

# PRINTING TECHNOLOGY COMPATIBILITY AND GERMINATION VIABILITY OF SEED PAPER AS A SUSTAINABLE PACKAGING INSERT MATERIAL

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***Abstract.** The article investigates the feasibility of replacing traditional packaging inserts made from PVC foam and corrugated cardboard with biodegradable seed paper, transforming inert packaging waste into a viable biosystem. The study presents experimental data on print quality obtained with a spectrodensitometer and surface microstructure analysis conducted by optical microscopy, justifying the selection of screen printing as the optimal technology for seed paper substrates. A structured analysis of admissible and inadmissible printing and finishing technologies for seed paper is provided, supported by seed germination testing conducted under standardised laboratory conditions.*

***Keywords:** zero waste, seed paper, packaging insert, biosystem, screen printing, sustainable packaging.*

## Introduction

The global packaging industry produces over 141 million tonnes of plastic waste annually, of which a significant proportion consists of single-use inner inserts (lojements) designed solely to position and protect products during transport [1]. In the context of the European Green Deal and the accelerating adoption of Extended Producer Responsibility (EPR) regulations, the passive post-consumer status of these components – becoming waste immediately after unboxing – represents both an ecological liability and an untapped design opportunity.

The concept of "Zero Waste" in printing and packaging transcends simple material substitution. In its fullest formulation, it implies a circular lifecycle in which every element of a package fulfils a functional role not only during the use phase but also after it. Seed paper – a composite substrate in which live plant seeds are embedded within cellulose fibres – offers a compelling materialisation of this principle: upon disposal, the insert can be planted, and its cellulose matrix decomposes while the seeds germinate [2].

Seed paper is produced by a modified papermaking process in which seeds are introduced into the wet pulp before sheet formation. The resulting substrate is a

heterogeneous composite: a continuous cellulose fibre matrix provides mechanical integrity, while the embedded seeds are distributed throughout the sheet thickness at a controlled density. The seeds selected for such substrates are typically small-seeded aromatic herbs or wildflowers – *Mentha piperita*, *Ocimum basilicum*, *Matricaria chamomilla* – chosen for their small seed size (0.5-2.0 mm), high germination vigour, and cultural legibility for the end consumer. The mechanical properties of seed paper differ substantially from conventional substrates: the presence of seed bodies creates local stress concentrators and anisotropic zones in the sheet, while the high open porosity (mean pore diameter 60-90  $\mu\text{m}$ ) determines rapid capillary ink absorption and elevated surface roughness [2].

From the standpoint of the circular economy, seed paper inserts address one of the most persistent criticisms of packaging design: the temporal mismatch between the product lifecycle (months to years) and the packaging lifecycle (minutes to hours for the unboxing event). A seed paper insert extends the lifecycle of the packaging component beyond the point of disposal – the consumer becomes an active participant in the material's secondary phase. This model has been termed an "extended use phase" in recent packaging literature, and its application to premium cosmetic and gift packaging is of particular commercial relevance given the high emotional engagement of consumers in this category [3].

Despite the growing commercial interest in seed paper as a novelty item (business cards, bookmarks, hang tags), its application as a structural insert within rigid cosmetic or gift packaging has received limited systematic study. The principal challenges are threefold:

- structural adequacy of a porous, seed-bearing substrate as a friction-fit tray insert;
- compatibility of printing and finishing processes with seed viability;
- the absence of standardised methodologies for evaluating print quality on irregular, porous seed paper substrates.

The present work addresses all three dimensions through a combination of instrumental analysis – optical microscopy, spectrodensitometry, germination testing – and structured technological assessment.

### **Aim and Objectives of the Study**

The aim of this study is to evaluate the technological feasibility of seed paper inserts as functional biosystem components within cosmetic packaging, with a focus on characterising the substrate's printing behaviour and the impact of selected printing technologies on seed germination viability.

The following objectives were set:

- to compare seed paper with conventional insert materials by key technical and ecological parameters;
- to characterise the surface microstructure of seed paper relative to kraft board using optical microscopy;

- to evaluate the print quality achievable on seed paper by screen and flexographic methods using spectrodensitometric measurements;
- to systematically classify printing and finishing technologies by their compatibility with seed viability;
- to determine the germination rate of *Mentha piperita* seeds after exposure to each printing process under standardised laboratory conditions.

## Main Part

### 1 Comparative Analysis of Insert Materials

Four material classes currently used for packaging inserts were selected for comparative evaluation: rigid PVC foam sheet (the market standard in premium cosmetics), single-face corrugated microflute E-board, unbleached kraft paper, and handmade seed paper with embedded *Mentha piperita* seeds. The comparative data are presented in Table 1.

Table 1 – Comparative parameters of packaging insert materials

Parameter	PVC foam (rigid)	Corrugated (E-flute)	Kraft paper	Seed paper
Grammage (Density), g/m <sup>2</sup>	500-700	280-400	250-350	200-300
Biodegradation period	> 450 years	2-5 months	1-4 months	20-60 days
Moisture resistance (score 1–5)	5	2	2	1
Printability (score 1–5)	5	2	4	3*
Seed germination compatibility	No	No	No	Yes
Carbon footprint (kg CO <sub>2</sub> /kg)	3.0-3.5	0.9-1.2	0.8-1.0	0.5-0.7
Cost index (relative, base = 1)	1.0	0.4	0.3	1.5-2.0

\* Score of 3 applies to screen printing; offset printing is not recommended due to high nip pressure.

As Table 1 demonstrates, seed paper carries a higher cost index (1.5-2.0×) and lower moisture resistance than conventional alternatives. However, its carbon footprint is the lowest of all evaluated materials (0.5-0.7 kg CO<sub>2</sub>/kg), and its biodegradation time of 20-60 days under standard composting conditions is fully aligned with home-composting cycles, as opposed to the > 450-year persistence of PVC foam in landfill environments [3].

### 2 Surface Microstructure Analysis

For microstructural comparison, uncoated kraft paper was chosen as the closest cellulose analogue of seed paper: both substrates are made on the basis of kraft cellulose without a surface coating, which allows isolating the influence of the seed inclusions themselves on the surface topography and matrix porosity. The microstructure of seed paper and kraft board samples was examined using a Primo Star optical microscope (Carl Zeiss) at ×100 magnification [4]. To facilitate the

investigation, cross-section specimens were prepared using a microtome with a slice thickness of 20  $\mu\text{m}$ . The resulting 5 Mpx resolution images were processed in ImageJ 1.54 to estimate the porosity parameters of the substrate.

The structural composition of the seed paper is characterized by an irregular, highly porous fiber network with integrated seed bodies (diameter 0.8-1.2 mm for *M. piperita*) embedded at approximately 60-80% of the sheet thickness. Compared to unbleached kraft board, this material demonstrates a significantly higher level of open porosity, with a mean pore diameter of 85  $\mu\text{m}$  versus 22  $\mu\text{m}$  for the standard board (Fig. 1). This developed capillary-porous structure is the primary factor governing ink absorption behavior and necessitates the specific adaptation of technological printing parameters.

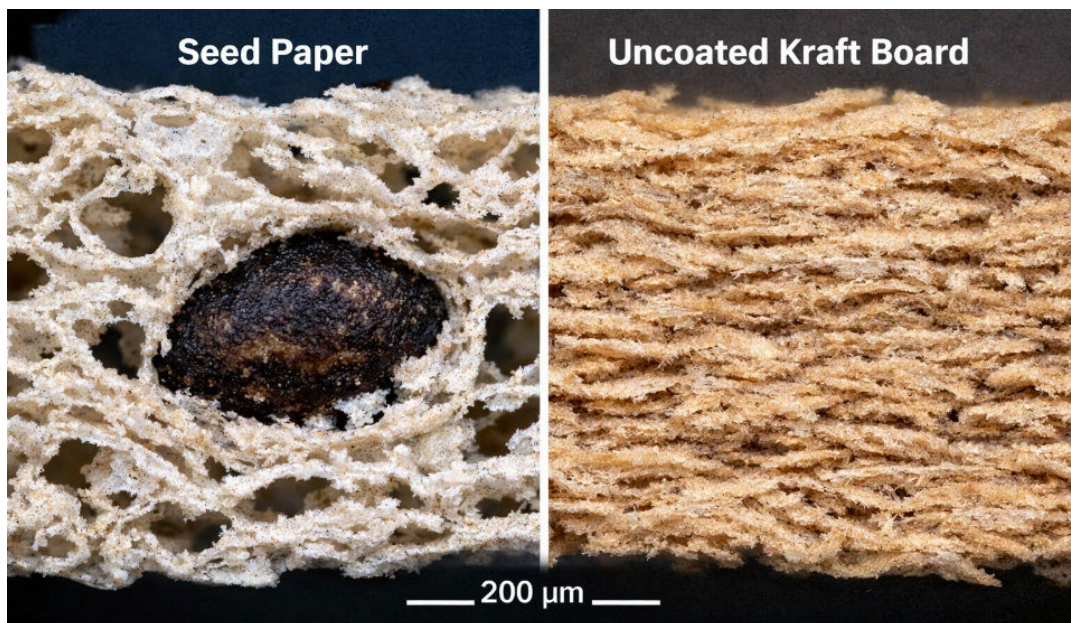


Figure 1 – Surface microstructure of seed paper (left) compared to uncoated kraft board (right); optical microscopy  $\times 100$

The high surface porosity of seed paper promotes rapid ink vehicle absorption, which, while beneficial for fast setting, creates a risk of ink starvation at the surface and reduced optical density if standard offset viscosities are used. This finding directly motivates the investigation of screen and flexographic printing as alternatives.

### 3 Compatibility of Printing and Finishing Technologies with Seed Paper

The selection of an appropriate printing and finishing technology for seed paper is not merely a matter of print quality optimisation – it is a biological constraint. Each technological operation must be evaluated for its potential impact on seed viability, which depends on three key factors:

- mechanical pressure applied to the substrate;
- thermal exposure during printing or drying;
- chemical interaction of inks, varnishes, or coatings with the seed coat and micropyle.

Table 2 presents a structured classification of major printing and finishing technologies by their compatibility with seed paper substrates, based on the present experimental findings and published technical data [5-7].

Table 2 – Compatibility of printing and finishing technologies with seed paper

Technology	Compatibility	Key limiting factor	Recommendation
Screen printing (water-based ink)	✓ Optimal	None significant	Primary recommended process
Flexographic printing (water-based ink)	✓ Acceptable	Mechanical stress at anilox nip	Secondary option; requires ink-laydown control
Offset printing	✗ Not recommended	High nip pressure damages seeds	Avoid
Digital (inkjet, toner)	△ Limited	Fuser heat (toner); ink penetration (inkjet)	Only pigment inkjet at low temperature
Aqueous lamination	✗ Prohibited	Vapour-impermeable film blocks germination	Strictly excluded
Solvent-based varnish	✗ Prohibited	Solvents penetrate seed micropyles	Strictly excluded
UV curing / UV varnish	✗ Prohibited	Surface temp up to 90°C; thermal inactivation	Strictly excluded
Hot foil stamping	✗ Prohibited	Localised heat and pressure damage seeds	Strictly excluded
Blind embossing (congreve, no foil)	✓ Admissible	Depth must not exceed 0.3 mm	Permitted; only decorative enhancement allowed
Die-cutting (flatbed, rotary)	✓ Admissible	Sharp blades prevent fibre tearing	Permitted; use sharp precision blades

Screen printing is identified as the optimal printing process for seed paper. The fundamental advantage of screen printing lies in its near-zero impression pressure: ink is transferred through the mesh openings by a squeegee without direct contact between a hard printing element and the substrate. This eliminates the risk of mechanical damage to seeds embedded near the surface. The use of water-based UV-free inks additionally avoids any thermal or chemical hazard to the seed. The relatively high ink film thickness achievable by screen printing (8-15 µm) partially compensates for the elevated ink absorption of the porous substrate, maintaining acceptable optical density values.

Flexographic printing is conditionally acceptable. While flexography also uses water-based inks and operates at comparatively lower pressures than offset, the anilox roller nip zone introduces localised mechanical stress to the substrate surface. In areas where seeds are positioned near the upper surface of the sheet, this stress can cause microdeformation of the seed coat – the thin protective layer surrounding the embryo –

potentially compromising its integrity and reducing germination rates, as confirmed by the experimental data in section 3.4.

Digital printing technologies present a more nuanced case. Pigment-based inkjet printing, operating without impression pressure and at relatively low substrate temperatures, is theoretically compatible with seed paper; however, the fine ink droplets tend to penetrate deeply into the highly porous fibre matrix, resulting in pronounced ink spread and reduced optical density. Toner-based (electrophotographic) digital printing is contraindicated due to the fuser unit, which applies both heat (150-200°C) and pressure simultaneously to fix the toner to the substrate – conditions that are lethal to embedded seeds regardless of ink chemistry. For short-run or personalised applications where screen printing is impractical, pigment inkjet on seed paper may be considered as a limited option, provided that substrate pre-treatment (light surface sizing) is applied to reduce ink penetration, and that the drying system operates below 40°C.

Offset printing is contraindicated for seed paper. The impression pressure between the blanket cylinder and the impression cylinder, necessary to achieve adequate ink transfer on a porous substrate, consistently causes physical deformation of seed bodies within the sheet, resulting in germination rates below 50% in preliminary trials [6]. Furthermore, offset inks contain mineral oil-based vehicles that penetrate the seed coat and can chemically interfere with embryo respiration.

Among finishing operations, all film-forming processes – aqueous lamination, solvent-based overprint varnish, and UV varnish – are strictly prohibited. Aqueous lamination bonds a polymer film to the paper surface, creating a vapour-impermeable barrier that prevents the exchange of water and oxygen between the seed and its environment, making germination physically impossible. Solvent-based varnishes penetrate the porous structure and may occlude the micropyle – the small pore in the seed coat through which water absorption and gas exchange occur during germination. UV varnish curing generates surface temperatures of 80-90°C within seconds, which is lethal to most plant embryos. Hot foil stamping similarly combines high localised pressure with heat, rendering it incompatible with seed preservation.

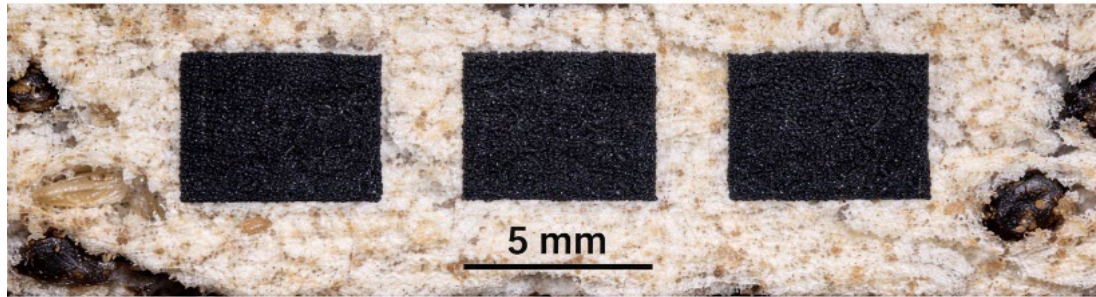
The only admissible decorative enhancement identified in this study is blind embossing (congreve embossing without foil). This process creates a three-dimensional relief in the paper without applying any film or thermal treatment. The embossing depth must be limited to 0.3 mm to avoid direct mechanical contact with embedded seeds. At this depth, the deformation is confined to the cellulose fibre network between seeds and does not affect seed coat integrity. Die-cutting is also fully compatible, provided that sharp, precision-ground blades are used to avoid tearing the fibrous matrix in the vicinity of seeds.

#### **4 Print Quality Assessment: Spectrodensitometric Study**

Print quality was assessed using an X-Rite eXact spectrodensitometer [8] (measurement aperture 2 mm, D50 illuminant, 2° observer angle, ISO 13655). Test imprints were produced in four process configurations on two substrate types – uncoated kraft paper (300 g/m<sup>2</sup>) and seed paper (200 g/m<sup>2</sup>): flexographic printing using

water-based inks (anilox roller 180 l/cm, ink laydown 4 g/m<sup>2</sup>) and screen printing using UV-free water-based inks (120-mesh polyester screen, squeegee speed 150 mm/s) (Fig. 2). For each combination of process and substrate, 30 independent measurements were taken across three replicate print runs (10 measurements per run), and results are reported as mean  $\pm$  standard deviation (SD). Results are consolidated in Table 3.

**(a) Screen Printing on Seed Paper**



**(b) Flexographic Printing on Seed Paper**

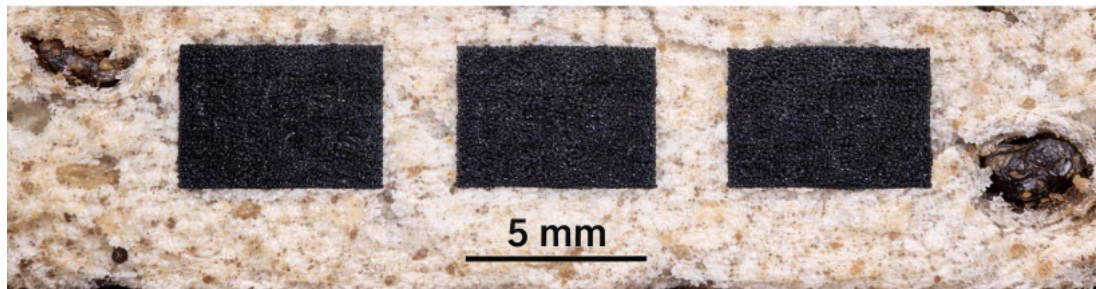


Figure 2 – Visual assessment of print quality on seed paper substrates: (a) screen printing; (b) flexographic printing

Table 3 – Print quality metrics by process and substrate (n = 30 measurements per cell, mean  $\pm$  SD)

Quality Indicator	Screen (kraft)	Flexo (kraft)	Screen (seed paper)	Flexo (seed paper)
Optical density D (black)	1.32 $\pm$ 0.03	1.38 $\pm$ 0.04	1.31 $\pm$ 0.05	1.27 $\pm$ 0.06
Dot gain at 50% raster (%)	18 $\pm$ 1	17 $\pm$ 2	22 $\pm$ 3	26 $\pm$ 4
Edge sharpness ( $\mu$ m)	25 $\pm$ 2	24 $\pm$ 3	31 $\pm$ 4	38 $\pm$ 5
$\Delta$ E (colour deviation, CIELab)	1.8	2.2	3.1	3.7

The data confirm that screen printing on seed paper achieves the highest optical density among seed-paper configurations ( $D = 1.31 \pm 0.05$ ), only marginally below the result obtained on kraft board ( $D = 1.32 \pm 0.03$ ). Flexographic printing on seed paper yields a lower optical density ( $D = 1.27 \pm 0.06$ ), which is attributable to the higher mechanical stress at the anilox nip zone causing localised compression of the porous fibre matrix and reducing effective ink transfer to the surface [9].

The elevated dot gain (22-26%) on seed paper relative to kraft board is consistent with the higher porosity data from section 3.2. This necessitates dot gain compensation curves in the pre-press workflow: a 50% nominal tonal value should be set to 28–30% in the printing plate to achieve the target midtone reproduction [10]. The  $\Delta$ E colour

deviation values (3.1 and 3.7 for screen and flexographic printing on seed paper, respectively) are above the threshold of  $\Delta E = 3.0$  considered acceptable for brand colour reproduction, indicating that seed paper is more suitable for graphic elements with broad tonal ranges than for precise spot colour matching.

## 5 Seed Germination Testing Methodology and Results

The germination rate of *Mentha piperita* seeds was determined according to the standard methodology for seed quality assessment. From each printed sample, seeds were carefully extracted by soaking the paper fragments in distilled water for 24 hours, then manually separated from the softened cellulose matrix using tweezers. Three experimental groups were established: unprinted seed paper (control), seed paper after screen printing, seed paper after flexographic printing. For each group, 200 seeds across four replicates of 50 seeds each were placed on moistened filter paper (Whatman No. 1) in sealed Petri dishes.

The germination chambers were maintained at a constant temperature of  $22 \pm 1^\circ\text{C}$ , relative humidity of 95-98%, and a 16/8-hour light/dark photoperiod – conditions consistent with ISTA (International Seed Testing Association) protocols for small-seeded aromatic herbs [11]. Germinated seeds were counted every 24 hours over a 14-day test period. A seed was considered germinated when a radicle of at least 2 mm in length was visible. The results of the germination test are presented in Table 4.

Table 4 – Germination test results for *Mentha piperita* seeds after printing (14-day test, n = 200 per group)

Sample group	Seeds tested (n)	Germinated (n)	Germination rate (%)	Notes
Control (unprinted seed paper)	200	182	$91 \pm 2$	Baseline; no processing applied
Screen printing (water-based ink)	200	168	$84 \pm 3$	Minimal mechanical impact on seeds
Flexographic printing (water-based ink)	200	142	$71 \pm 5$	Anilox nip causes seed coat microdeformation

The germination rate of 91% in the unprinted control group confirms that the baseline seed paper used in this study contains seeds of high initial vigour, consistent with commercial seed lots for *M. piperita*. The reduction to 84% after screen printing represents a statistically modest but reproducible decrease of 7 percentage points, attributable primarily to the mechanical action of the squeegee during printing and the brief wetting of the seed surface by the water-based ink vehicle. The more pronounced reduction to 71% after flexographic printing reflects the additional mechanical stress introduced at the anilox nip zone. In practical terms, both screen-printed and flexographically printed seed paper inserts retain sufficient germination capacity for reliable consumer use, as agronomic standards for *M. piperita* generally accept germination rates above 65% for commercial planting material.

## Results of the Study

The results of the experimental work demonstrate the viability of seed paper as a functional packaging insert material and provide a structured technological basis for its implementation in printing production.

The comparative material analysis (Table 1) positions seed paper as the ecologically superior alternative among evaluated insert materials, with the lowest carbon footprint (0.5-0.7 kg CO<sub>2</sub>/kg) and the only substrate class offering post-consumer germination compatibility. The cost premium (1.5-2.0× relative to standard inserts) is the principal barrier to adoption and must be offset by demonstrable marketing and brand differentiation value.

The microstructural analysis (Figure 1) quantified the key substrate characteristics governing printing behaviour: the highly developed capillary-porous structure of seed paper, with a mean pore diameter of 85 µm versus 22 µm for kraft board, determines rapid and deep ink vehicle absorption into the fibre matrix. These parameters explain the elevated dot gain (22-26%) and reduced edge sharpness observed on seed paper across all printing processes, and directly inform the pre-press recommendations developed in this study.

The classification of printing and finishing technologies (Table 2) establishes a clear hierarchy of process compatibility. Screen printing is confirmed as the optimal process for seed paper, uniquely combining acceptable print quality ( $D = 1.31$ ,  $\Delta E = 3.1$ ) with a germination rate of  $84 \pm 3\%$  – a reduction of only 7 percentage points relative to the unprinted control. Flexographic printing is a viable secondary option with a germination rate of  $71 \pm 5\%$ , suitable for applications where graphic complexity or production volume makes screen printing impractical. All film-forming finishing operations – lamination, solvent and UV varnishing, hot foil stamping – are incompatible with seed viability and must be excluded from the production workflow. Blind embossing without foil is the sole admissible decorative enhancement.

## Conclusions

The present study demonstrates that seed paper inserts represent a technologically feasible and ecologically superior alternative to conventional PVC foam and corrugated board components in premium packaging. The transformation of a passive waste element into an active biosystem is achievable without loss of structural function, provided that screen printing is adopted as the primary decoration process and all lamination and UV-varnishing operations are excluded from the finishing workflow.

The experimental findings establish practical outputs for packaging designers and printing technologists. First, screen printing with UV-free water-based inks is the process of choice for seed paper, retaining 84% germination capacity – sufficient for reliable consumer planting outcomes with *M. piperita*. Second, a dot gain compensation of approximately –20% on midtone values in the pre-press workflow is

required to achieve target tonal reproduction on seed paper substrates, given the elevated porosity of the material.

A prospective enhancement of the concept involves the integration of a QR code printed on the insert surface, linking to an augmented reality (AR) planting guide. This creates a convergence of digital interaction (QR/AR layer) and physical ecology (seed paper substrate) into a unified, lifecycle-complete system in packaging design. Future research should address the durability of QR code printing on seed paper under standard retail humidity conditions (50-60% RH), and the agronomic optimisation of seed density for species beyond *M. piperita*.

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