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Integrating Artificial Intelligence in the Design of Sustainable and Smart Packaging: Challenges and Perspectives in Graphic Engineering

ABSTRACT

Sustainability has become a central requirement in graphic engineering and packaging design, driven by environmental regulation and the shift towards a circular economy. At the same time, machine learning and other Artificial Intelligence (AI) methods are being applied across production workflows, material selection and quality control in the printing industry. This paper examines how these methods can support the design and production of environmentally conscious, interactive packaging, treating sustainability and consumer experience as related rather than separate problems. The first part deals with graphic materials: recycled paper substrates and eco-friendly inks are discussed in terms of colour stability and ink penetration during printing, and a machine-learning-based approach is proposed for selecting ink–substrate combinations at the prepress stage. The second part addresses the design process itself: Design Thinking, AI-assisted colour management, and Augmented Reality (AR) are discussed as complementary tools for turning packaging into a channel that also carries traceability and product information. This paper draws on published evidence from graphic engineering, printing science, and consumer research to assess which parts of the proposed framework are already supported by experimental results and which still need testing. The paper ends with a concrete plan to validate the framework on a defined set of substrates, inks, and AR content.

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Packaging design, artificial intelligence, sustainability, graphic materials, smart packaging, colour management

1. Introduction

Packaging is a multidisciplinary field that combines graphic engineering, materials science, manufacturing technologies, and consumer communication (Davidescu et al., 2025). Beyond protecting products and supporting brand identity, modern packaging is increasingly expected to meet sustainability requirements linked to circular economy principles and environmental regulations (International Organization for Standardization, 2013).

Within the European Union, this context is now shaped by the Packaging and Packaging Waste Regulation (PPWR), Regulation (EU) 2025/40, which applies from 12 August 2026. It establishes life-cycle requirements for packaging and packaging waste, including provisions related to prevention, recyclability, labelling, reuse, and resource efficiency, with several technical obligations phased in on later dates (European Union, 2025).

Adopting recycled substrates, renewable materials, and eco-friendly inks has become an important strategy for reducing packaging's environmental impact (Strižić et al., 2024). However, these materials often show greater

variability in surface properties, absorbency, and colour reproduction than conventional alternatives, creating challenges for maintaining print quality and production efficiency (Tomašegović et al., 2021; Svanes et al., 2010).

Recent developments in AI have created new opportunities to address these challenges. Machine learning techniques can support material selection, predict print-quality characteristics, optimise production parameters, and reduce waste throughout the printing workflow (Basak et al., 2025; Abusaq et al., 2023). At the same time, AI applications are increasingly used in packaging design to support decision-making and more sustainable, user-centred solutions (Jin et al., 2024).

In parallel, Design Thinking methodologies have emerged as effective frameworks for developing packaging concepts that integrate technical requirements with consumer needs (Bijitkar & Moule, 2024). Furthermore, Augmented Reality (AR) technologies are transforming packaging into an interactive communication medium by providing access to digital content such as product information, traceability data, and sustainability guidance. Previous studies have demonstrated that AR can enhance consumer engagement and perceived value (Accardi et al., 2025; Gu et al., 2023).

While advances in sustainable substrates, machine learning, and interactive design are well documented, the literature often treats them as distinct disciplines. Consequently, a clear need remains for a workflow that connects AI-driven prepress decisions directly to physical production and digital consumer interfaces.

Building on these complementary approaches, this study proposes a conceptual framework that integrates predictive modelling of ink-substrate interactions, AI-assisted colour management, Design Thinking methodologies, and AR technologies. The objective is to show how these complementary approaches can simultaneously contribute to sustainability, production efficiency, improved print quality, and consumer engagement.

The remainder of the paper is organised as follows. Section 2 reviews the relevant literature, Section 3 presents the proposed framework and its experimental validation plan, Section 4 discusses its feasibility, potential benefits, and limitations, and Section 5 concludes the study and outlines future research directions.

2. Related work

The literature review followed a structured narrative approach. Scopus, Web of Science, and Google Scholar were searched for English-language publications from 2010 to September 2026 using combinations of the terms “sustainable packaging”, “recycled paper”, “eco-friendly inks”, “flexographic printing”, “print quality”, “machine learning”, “colour management”, “Design Thinking”, “augmented reality”, and “smart packaging”. Priority was given to peer-reviewed studies directly addressing packaging engineering, printing processes, colour measurement, resource efficiency, or AR-enabled packaging. We included standards and official regulatory sources where necessary, while excluding sources without a clear methodological or technological connection to the proposed framework.

The packaging industry has evolved from a system focused primarily on product protection and marketing into a multidisciplinary field that integrates sustainability, technological innovation, and digital communication (Bolanča et al., 2018). Sustainable packaging design has become increasingly important because of growing environmental concerns and the transition toward circular economy principles.

Svanes et al. (2010) proposed a holistic approach to sustainable packaging design that considers material reduction, transportation efficiency, product protection, and end-of-life recovery as interconnected parameters. This perspective aligns with circular economy objectives and is further supported by standards such as ISO 18604, which define requirements for material recycling and recovery (International Organisation for Standardisation, 2013).

At the production level, research has highlighted the challenges associated with recycled and environmentally friendly substrates, whose physical properties can significantly influence print quality. Tomašegović et al. (2021) demonstrated that substrate roughness and absorbency affect key flexographic printing characteristics, including dot gain and colour consistency. These findings emphasise the need to predict and optimise material-process interactions accurately.

Recent advances in Artificial Intelligence (AI) have provided effective solutions to address these challenges. Basak et al. (2025) compared several machine-learning techniques for predicting dot gain in flexographic printing and reported prediction accuracies of up to 98% using artificial neural networks. Similarly, Abusaq et al. (2023) demonstrated the potential of AI-assisted analysis to improve energy efficiency and reduce waste in printing production. These studies indicate that machine learning can significantly support process optimisation and sustainable manufacturing.

AI applications have also expanded into packaging design and colour management. Jin et al. (2024) used deep-learning techniques to support sustainable and user-centred packaging development, while Azarenkov and Deineko (2025) investigated neural-network-based approaches to generate colour profiles directly from measurement data. Such meth-

ods are particularly relevant for packaging printed on recycled substrates, where colour behaviour may vary considerably between production batches.

Beyond production processes, research has increasingly focused on human-centred design and digital interaction. Design Thinking provides a structured framework for developing packaging solutions that balance technical requirements with consumer needs through iterative design and evaluation processes (Bijitkar & Moule, 2024). At the same time, Augmented Reality (AR) technologies enable packaging to become an interactive communication medium, delivering product information, traceability data, and immersive consumer experiences. Studies by Accardi et al. (2025) and Gu et al. (2023) demonstrated that AR-enhanced packaging can improve consumer engagement, perceived interactivity, and overall product evaluation.

Although individual technologies like machine learning and AR have proven their value in printing science, they are rarely integrated into a single production pipeline. The intersection of material sustainability, AI-based process control, and digital consumer interaction currently lacks a cohesive methodological structure.

Consequently, the proposed framework integrates AI-driven print-quality prediction, colour management, Design Thinking methodologies, and AR technologies to support the development of sustainable and smart packaging solutions that enhance production efficiency, environmental performance, and consumer engagement.

3. Proposed Framework and Experimental Validation Plan

3.1. Graphic materials: recycled substrates and eco-friendly inks

The proposed framework focuses on recycled paper substrates and environmentally friendly inks as key components of sustainable packaging production. Recycled fibre-based materials, water-based inks, and low-migration UV-curable inks can reduce environmental impact and VOC emissions and support recycling processes. However, recycled substrates often exhibit greater surface roughness, porosity, and variability than virgin-fibre materials, affecting ink transfer, absorption, colour reproduction, and overall print quality (Tomašegović et al., 2021). Colour stability and ink penetration are therefore critical prepress parameters, as they directly influence optical density, colour saturation, and tonal reproduction. These properties depend on interactions among substrate characteristics, ink composition, and printing conditions, including ink viscosity, anilox line screen/cell density and volume, halftone screen ruling, dot percentage, and drying conditions. Because conventional trial-and-error evaluation is time-consuming and resource-intensive, data-driven methods offer a more efficient approach to material selection, process optimisation, and waste reduction.

3.2. Predictive model for ink–substrate interaction

To address the complexity of material-process interactions, the proposed framework incorporates a machine-learning-based predictive model designed to support prepress decision-making. The objective of the model is to estimate the expected performance of different ink-substrate combinations before physical printing takes place, enabling more informed and sustainable production choices.

The model will use material and process parameters as input variables, including substrate properties, ink formulation, anilox line screen/cell density, anilox volume, halftone screen ruling, dot percentage, ageing condition, and selected production settings. Based on these inputs, it will predict print-quality responses, resource-consumption indicators, and waste-related indicators. Resource consumption and waste generation will be treated as bounded sustainability-related proxies within the printing process, rather than as comprehensive measures of environmental sustainability.

Drawing upon previous studies in machine learning for print-quality prediction, several supervised learning techniques can be considered, including linear regression, random forests, gradient boosting algorithms, and artificial neural networks (Basak et al., 2025). These methods offer different capabilities in modelling non-linear relationships between printing variables and production outcomes.

Because ΔE_{00}, resource consumption, and waste generation have different units and numerical ranges, the weighted objective will use normalised values:

$$F(x) = w_1 \cdot \widehat{\Delta E}_{00}(x) + w_2 \cdot \hat{R}(x) + w_3 \cdot \hat{W}(x), \quad \text{with} \quad w_1 + w_2 + w_3 = 1 \tag{1}$$

where each objective is scaled to [0,1], for example $\hat{z}(x) = [z(x) - z_{min}]/[z_{max} - z_{min}]$, using limits defined by the experimental design or an agreed production baseline:

- x represents the vector of material and process parameters;
- $\widehat{\Delta E}_{00}(x)$ is the normalised predicted colour difference;
- $\hat{R}(x)$ is the normalised resource-consumption indicator;
- $\hat{W}(x)$ is the normalised waste-generation indicator;

- w_1, w_2, and w_3 are non-negative weighting coefficients representing the agreed relative priorities.

R(x) will comprise ink, substrate, and energy consumption per accepted production unit. W(x) will comprise makeready waste, rejected sheets or packages, and other process waste generated within the stated system boundary. The coefficients w_1, w_2, and w_3 will be selected transparently through stakeholder-defined priorities, sensitivity analysis, or an analytic decision procedure, and the effect of alternative weight sets will be reported. Pareto-based multi-objective optimisation may also be used to identify non-dominated solutions without imposing a single fixed weighting scheme. The recommendations will be interpreted as decision support for balancing print quality, resource efficiency, and waste reduction.

Table 1

AI and complementary technologies/methodologies integrated into the proposed packaging workflow

Production stage	Technology / methodology	Primary target	Expected contribution to resource efficiency / waste reduction
Material & ink selection (prepress)	Supervised machine learning (regression, ensemble methods, neural networks)	Colour stability, ink penetration	Reduced trial prints, lower resource and ink consumption
Design ideation	Design Thinking supported, where appropriate, by AI-assisted tools	User-centred, iterative prototyping	Fewer design iterations, material-aware concepts
Colour management	AI-assisted spectral / colour prediction and profiling	Cross-substrate colour consistency	Fewer reprints, waste reduction
Consumer interface	Augmented Reality (complementary digital technology)	Traceability, engagement	Extended product lifecycle information, reduced need for extra printed inserts.

3.3. Proposed experimental validation plan

A structured experimental framework is proposed to evaluate the predictive model's effectiveness and investigate relationships between material properties, printing parameters, and print-quality outcomes. The primary objective of this validation process is to generate a representative dataset for training and evaluating machine-learning algorithms while also examining the suitability of sustainable materials for smart packaging applications.

The experimental design focuses on recycled paper substrates and environmentally friendly ink systems commonly used in the packaging industry. Multiple combinations of material and process parameters are considered to ensure that the collected data adequately capture the variability encountered under real production conditions. This approach enables the investigation of both individual parameter effects and interactions among variables that may significantly influence colour reproduction, print quality, resource consumption, and sustainability performance.

To evaluate the proposed framework comprehensively, the proposed validation study will adopt a hierarchical (split-plot/mixed) experimental design. In this design, substrate, ink system, anilox line screen/cell density, anilox volume, halftone screen ruling, and other press settings are assigned at production-run level; dot percentage is evaluated as a within-form test-patch factor, because the different tonal values are patches of the same printed form rather than separate production runs; and ageing condition (or ageing time) is treated as a post-print repeated-measurement factor applied to the same or corresponding printed samples, not as a new production condition. Print run/batch is used as a blocking and grouping variable. Consequently, the full combination of factor levels does not correspond to a comparable number of fully independent production conditions: only the production-level factors define independent press setups. Actual anilox specifications will be selected from commercially/experimentally available roller configurations; line screen and volume combinations will therefore be constrained to physically available engravings. Nominal anilox volume is a characteristic of the cell geometry and engraving, whereas actual ink transfer is additionally influenced by ink rheology and viscosity, surface tension, doctoring, and dynamic printing conditions, effects that become particularly important in high-line-screen engravings where the cells are very small (Savickas et al., 2020). Ink transfer will therefore be treated as a measured response (for example, ink film weight) rather than being inferred from nominal volume alone. Measured response variables will include colour difference (ΔE00), dot gain, print density, tonal reproduction, ink absorption, drying behaviour, AR recognition performance, resource consumption, and waste generation. The experimental unit is a printed test sample produced under a given experimental condition within a given print

run/batch; repeated measurements taken from the same sample are not treated as independent observations. Multiple independent print runs will be performed, with their number selected to permit grouped cross-validation during model development and a genuinely independent run-level test set (at least five runs are planned: four for model development and one held out for final testing). Each independent print run constitutes an independent production replicate. Within each run, each experimental condition will be produced in three within-run production replicates, which assess repeatability and are not regarded as independent replicates. Experimental and measurement order will be randomised, while print run/batch will be treated as a blocking and grouping variable. This structure will permit estimation of main effects and relevant interactions while separating systematic run-to-run variability. Table 2 presents the proposed factors, levels, responses, replication, and blocking structure.

As shown in Table 2, the proposed design separates controllable factors and levels from measured responses. Print quality will be assessed through spectrophotometric and microscopic measurements. Colour performance will be evaluated using CIE L*a*b* coordinates and ΔE00, while ink penetration, print density, dot gain, and tonal reproduction will be measured to assess reproduction accuracy and consistency (Yılmaz et al., 2022). Resource consumption will be recorded as ink, substrate, and energy used per accepted production unit, whereas waste will include makeready material, rejected sheets, and other process waste within the defined printing boundary. The dataset generated during validation will first be separated, at print-run level, into a model-development set and an independent test set. Within the development set only, models will be trained and compared through grouped k-fold cross-validation, with print run/batch as the grouping variable, and hyperparameter selection. The final test set will consist of one or more genuinely independent print runs that have been used neither for training nor for model selection; only after model selection will final performance be estimated on it. All observations from the same print run/batch, including within-run replicates, will remain within the same fold or partition and will never be allocated simultaneously

Table 2

Experimental factors, proposed levels, responses, replication, and blocking for validation of the predictive model

Experimental factor	Proposed levels	Measured response variable(s)	Role in design
Substrate	FSC-certified recycled kraftliner (250 g/m²); recycled coated duplex board (300 g/m²)	Surface roughness, baseline colour, ink absorption	Production-level factor
Ink system	Water-based ink; low-migration UV-curable ink	Drying/curing behaviour, print density, ΔE00	Production-level factor
Anilox line screen / cell density	800 lpi; 1000 lpi	Ink transfer, print density, dot gain	Production-level factor
Nominal anilox volume / volumetric capacity	2.5 cm³/m²; 3.5 cm³/m²	Ink film weight, print density, resource consumption	Production-level factor
Halftone screen ruling	133 lpi; 150 lpi	Dot gain, tonal reproduction, print contrast	Production-level factor
Dot percentage	10% to 100%, in 10% steps	Tonal reproduction curve, dot gain	Within-form test-patch factor
Ageing condition	Standard indoor storage; accelerated ageing	Change in ΔE00 and AR recognition performance	Post-print repeated-measurement factor
Print run / batch	Multiple independent runs (at least five planned)	Run-to-run variability	Blocking/grouping variable
Within-run production replicates	Three per condition within each run	Repeatability and uncertainty	Replication
AR recognition	Controlled illumination, distance, and viewing-angle conditions	Recognition success rate, acquisition time, maximum distance, robustness	Response assessment

to training and test partitions, to prevent data leakage. Model performance will be reported using RMSE, MAE, R^2, and uncertainty intervals where appropriate.

3.4. Design Thinking applied to packaging concept development

While material optimisation is fundamental for sustainable packaging, successful solutions must also address consumer needs and market expectations. To support this objective, the proposed framework integrates Design Thinking as a human-centred methodology for packaging concept development.

The Design Thinking process follows the established sequence of empathise, define, ideate, prototype, and test. In the initial stages, the team collects information on consumer expectations, sustainability concerns, usability requirements, and information accessibility, then translates it into design criteria. This approach keeps technical decisions aligned with user needs throughout development.

During ideation and prototyping, designers generate and evaluate multiple packaging concepts. At this stage, the AI model's predictions can help designers identify material and printing configurations that meet both sustainability targets and visual requirements before producing physical prototypes. This integration shortens development cycles and supports evidence-based decision-making.

The testing phase combines visual evaluation, functional assessment, and the verification of digital features incorporated within the package. Through iterative refinement, Design Thinking facilitates the development of packaging solutions that balance environmental performance, production feasibility, and user experience.

3.5. AI-assisted colour management

Colour consistency remains one of the most critical quality requirements in packaging production. However, maintaining stable colour reproduction across production batches is particularly challenging with recycled substrates because of variations in fibre composition, surface characteristics, and absorption behaviour.

Established colour-management workflows rely on device characterisation targets, spectrophotometric measurements, ICC or spectral profile generation, profile validation, process control, and recalibration when substrate or production conditions change. These procedures remain essential, but their measurement and maintenance burden increases when recycled substrates exhibit substantial batch-to-batch variability.

Within the proposed framework, AI/ML is not intended to replace established ICC-based or spectral colour-management workflows. Instead, machine-learning models will operate as a complementary decision-support layer that learns from characterisation and production measurement data, predicts substrate-specific colour behaviour, and indicates when additional characterisation or recalibration may be required.

This complementary approach may support faster substrate-specific adjustments, identify drift between print runs, and reduce corrective print iterations while preserving compatibility with established colour standards and validation practices. Its effectiveness will be evaluated against the baseline ICC/spectral workflow rather than against an assumed absence of colour management.

3.6. Augmented Reality integration

The final component of the framework concerns integrating AR technologies into sustainable packaging systems. As consumer expectations increasingly shift towards personalised and interactive experiences, packaging is evolving from a static physical medium into a dynamic communication platform.

In the proposed approach, printed visual elements such as markers, logos, QR codes, or image-recognition features serve as triggers that connect physical packaging with digital content accessible through mobile devices. The resulting AR experience may provide product traceability information, sustainability instructions, recycling guidelines, usage recommendations, or interactive brand communication elements.

Beyond marketing applications, AR may reduce the need for some additional printed information by providing digital access to traceability, recycling, and usage guidance (Rani & Ramlie, 2023). This potential contribution is treated as a resource-efficiency opportunity rather than as evidence of comprehensive environmental sustainability.

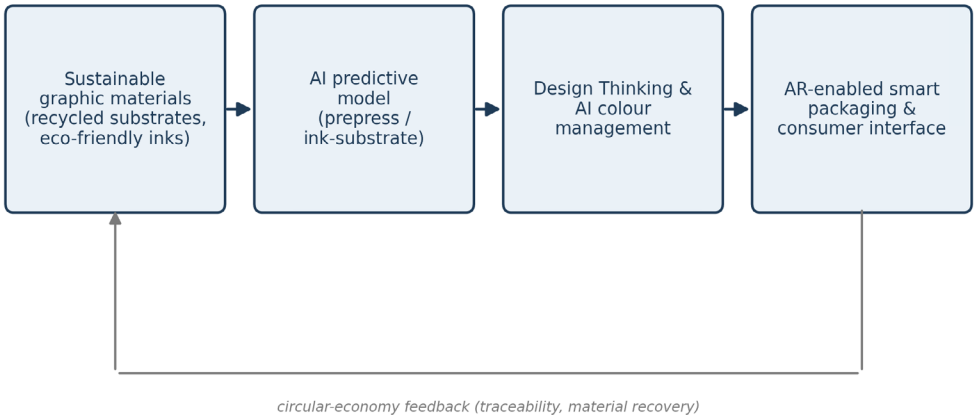
From a graphic engineering perspective, successful AR functionality depends strongly on the printed trigger and its interaction with the substrate. During validation, AR performance will be quantified through recognition success rate, acquisition time, maximum recognition distance, and robustness under controlled changes in illumination and viewing angle. These outcomes will be analysed in relation to ΔE00, print contrast, dot gain, substrate roughness and colour, and ageing-induced degradation. This analysis will connect AR reliability directly with print-quality and process variables, strengthening the graphic-engineering dimension of the framework.

4. Discussion

Figure 1 illustrates the workflow connecting the components described in Section 3: material selection feeds the

predictive model, the predictive model supports Design-Thinking-based concept development and AI-assisted colour management, and the resulting package carries AR content that returns traceability and material-recovery information to the consumer, which in turn can influence the material choices made in the next design cycle.

that its accuracy depends on how the network is configured; this is consistent with the proposal in Section 3.5, though it also means that the colour-management step needs its own, separate tuning and is not simply inherited from the predictive model in Section 3.2.



» **Figure 1:** *Proposed framework connecting AI-based material selection, colour management and AR-enabled interaction in sustainable packaging design*

4.1. Feasibility of the material and predictive-model components

The material and predictive-model components rest on the most direct evidence of the four. Basak et al. (2025) reported prediction accuracies of 95–98% for a neural-network model of flexographic dot gain trained on a comparable set of variables to those proposed in Table 2. Tomašegović et al. (2021) showed that ecologically favourable substrates can reach acceptable print quality once their absorption and roughness are accounted for at the prepress stage. Both results support the assumption in Section 3.2 that colour deviation and dot gain can be predicted from substrate, ink and process parameters with a useful degree of accuracy; what has not yet been shown, and is left for the experimental plan in Section 3.3, is whether the same accuracy holds once resource consumption and waste are added as joint objectives rather than treated as a single response variable.

4.2. Feasibility of Design Thinking and AI-assisted colour management

Bijitkar and Moule (2024) reported that a Design-Thinking-based process produces more technically grounded and better-received packaging concepts than a purely theoretical design process, supporting its use as the organising structure for Section 3.4 rather than treating AI-based screening as a stand-alone step. For colour management, Azarenkov and Deineko (2025) demonstrated that a neural-network-based profile can be built directly from measured colour-target data and

4.3. Feasibility of the AR-enabled consumer interface

The consumer-facing component is supported mainly by marketing and consumer-behaviour research rather than by graphic engineering studies. Accardi et al. (2025) found, using physiological measurements rather than self-report alone, that immersive AR content produces stronger engagement than static AR content; Gu et al. (2023) found, with a much larger sample, that AR reduced negative evaluations of take-away food packaging. Neither study addressed how print quality on the physical marker affects AR recognition rates, which is the specific graphic-engineering question raised in Section 3.6 and is not answered by the consumer-research literature reviewed here.

4.4. Limitations

Several limitations follow from assembling the framework from separate strands of published work rather than testing it as a whole. The predictive model must be trained on data specific to the substrates, inks, anilox specifications, screening conditions, and press technology used by a given converter, and its accuracy outside that domain is unknown. The Design Thinking and colour-management steps require skills in data handling, colour science, and interaction design that are not yet standard across all graphic-engineering settings. The AR component depends on print quality in ways the literature reviewed here has not yet quantified, and its printed trigger must remain compatible with the package's material and recycling

constraints. The framework does not perform a complete Life Cycle Assessment (LCA). Resource consumption and waste generation are therefore sustainability-related indicators or proxies within a defined production boundary, not comprehensive measures of environmental sustainability. Finally, none of the components has yet been tested together on the same samples; Section 3.3 defines the validation plan required to address this limitation.

5. Conclusions and Future Work

This paper proposes an integrated framework for applying Artificial Intelligence and complementary methodologies to resource-efficient and smart packaging development. At the production level, machine learning is proposed to support prediction of ink-substrate interactions and prepress decision-making. At the design and communication levels, Design Thinking, AI-assisted colour management, and Augmented Reality are combined to support packaging concepts that integrate print-quality requirements, traceability, and access to digital information. The principal contribution is a unified workflow and an explicit validation plan rather than a completed experimental demonstration or a comprehensive environmental assessment.

Future work will validate the framework through controlled printing trials using recycled substrates, environmentally preferable ink systems, and clearly separated anilox and halftone-screen parameters. The resulting measurements will support grouped model development, cross-validation, model selection, and independent testing, while a functional AR prototype will be evaluated using measurable recognition metrics. The validation will determine whether the workflow can improve material selection, colour consistency, production efficiency, and waste-related indicators without overstating these outcomes as a full LCA or comprehensive sustainability assessment.

6. Acknowledgments

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