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Research on Investment and Financing Management and Risk Control in the Green Transformation of Small and Medium-Sized Textile Enterprises

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ABSTRACT

The green transformation toward sustainable development poses significant challenges for the textile industry, particularly for Small and Medium-Sized Textile Enterprises (SMTEs) involved in resource-intensive chemical operations such as the dyeing and finishing of cotton yarn and fabrics. These firms often face financing gaps for upgrading textile mills, machinery, and equipment, which is critical for processing both natural and synthetic fibers. This study proposes an integrated decision-support framework, merging Multi-Criteria Decision Analysis (MCDA) and Monte Carlo simulation, to evaluate and prioritize green investments in textile processing technology. An evaluation of three retrofit plans identified that a comprehensive switch to waterless digital-printing equipment—a key advancement in textile technology—is the optimal solution for processing fiber products with minimal water and organic compound usage. A hybrid financing structure was optimized to fund the acquisition of this new equipment, and a digital Green Investment and Risk Coordination System (GIRCS) was designed for real-time risk tracking. The findings offer a replicable methodological blueprint for investment appraisal in the textile industry, aiding firms across the supply chain—from weaving to finishing—and contributing a novel approach at the intersection of materials science and engineering management.

KEYWORDS

textile industry, sustainable development, green finance, textile finishing, Multi-Criteria Decision Analysis

INTRODUCTION

The green and low-carbon transformation has become a binding mandate for China's manufacturing sector, driven by the nation's dual-carbon targets of peaking emissions before 2030 and achieving carbon neutrality by 2060 [1,2]. Within this transition, the textile industry faces significant challenges, contributing roughly 6% of China's total carbon emissions while employing nearly 20 million workers [3]. Although large state-owned firms have begun piloting green technologies, the sector is dominated by over 300,000 Small and Medium-Sized Textile Enterprises (SMTEs) [4,5]. These firms typically operate on thin margins, lack the scale to absorb large upfront capital costs for green retrofits, and rely on relational financing networks.

Statistics reveal that over 70% of SMTEs report difficulty obtaining green loans, and nearly half have never commissioned a formal energy audit [6,7]. This creates a cycle of non-compliance, where firms face either recurring environmental penalties or delisting by international apparel brands enforcing stricter environmental standards. This financial paralysis not only threatens regional industrial decline but also the ecological health of the manufacturing hubs. The urgency is compounded by international market pressures, such as the European Union's Carbon Border Adjustment Mechanism (CBAM) and tightening life-cycle disclosure requirements from major brands, which risk excluding non-compliant SMTEs from premium export markets [8,9].

Scholarly attention to green financing for SMEs has evolved across several streams, yet significant gaps remain [6]. The first stream examines macro-level policies like green bonds and tax incentives [10]. However, studies show that only a marginal share of green credit reaches smaller enterprises due to stringent collateral requirements and high transaction costs, with banks often applying a "double-risk premium" to SMTE projects [11]. A second stream focuses on corporate-level determinants of green investment, but its findings, often based on large, listed firms, are difficult to extrapolate to unlisted, owner-centric SMTEs [12]. A third stream has applied Multi-Criteria Decision Analysis (MCDA) to sustainable projects [13]; however, its application to the textile SME sector is scarce, and existing models lack integration with a closed-loop financing architecture that feeds real-time performance data back to lenders. While digital ESG monitoring platforms exist, they largely function as historical reporting utilities rather than as forward-looking decision-support engines. Consequently, the literature lacks an end-to-end solution that addresses the specific context of SMTEs, integrates fragmented metrics, and provides a feedback loop between ex-ante assessment and ex-post performance to mitigate risks such as greenwashing.

To address these deficiencies, this paper develops and validates a novel, integrated framework that provides a holistic, data-driven pathway for SMTE green transformation. Our contribution is threefold. First, we extend the Delphi–AHP tradition by using a diverse expert panel—including financiers, engineers, carbon-audit professionals, and SME owners—to balance methodological rigor with industry pragmatism. Second, we operationalize a four-dimensional MCDA model that couples quantitative financial metrics with qualitative criteria for environmental performance, policy compliance, and risk-management capacity. Third, we embed this evaluation engine into a conceptual digital platform, the Green Investment and Risk Coordination System (GIRCS), designed to mitigate information asymmetry by providing standardized project validation and real-time risk assessment. The theoretical value of this research lies not in proposing a new standalone theory but in its architectural and applied innovation. By translating the management concept of "dynamic capabilities" into a concrete methodological blueprint and extending static evaluation models into a dynamic system, this framework provides an end-to-end solution connecting the traditionally siloed tasks of risk identification, project prioritization, financing, and digital supervision.

METHODOLOGY

The research design followed the mixed-methods paradigm [14], integrating qualitative expert elicitation with quantitative simulation in a sequential explanatory fashion. The workflow consisted of six main stages, which are detailed below.

Stage 1: Stakeholder Mapping and Risk Factor Identification

Following Freeman's stakeholder theory, we first mapped actors with potential influence over or interest in SMTE green projects, including bank credit officers, venture capital (VC) analysts, textile-equipment suppliers, local environmental regulators, and international brand representatives. Semi-structured interviews (n = 32) were conducted to surface 28 candidate risk factors distributed across the project life-cycle. These factors were then categorized into financial, technological, policy, and market domains, serving as inputs for the ensuing Delphi exercise.

Stage 2: Delphi–AHP Weighting

A purposive sample of 15 experts was assembled: five financial experts from state-owned banks, joint-stock banks, and venture capital firms; four textile-engineering consultants with over ten years of plant-retrofit experience; three certified carbon-audit professionals; and three SMTE general managers. To justify the selection and mitigate potential bias, experts were identified through nominations from key industry bodies, including the China National Textile and Apparel Council (CNTAC), and the research team's professional networks. A deliberate strategy was employed to ensure geographical and institutional diversity. The panel included representatives from both the Yangtze River Delta and the Pearl River Delta, and financial experts were sourced from state-owned banks, joint-stock banks, and venture capital to capture a spectrum of lending and investment philosophies. This multi-stakeholder composition was intentionally designed to enhance the robustness of the resulting weights beyond what is captured by statistical consensus metrics alone. The composition of the expert panel is summarized in Table 1.

In the first Delphi round, experts rated each factor’s importance on a five-point Likert scale; factors with a mean score below 4.0 or a standard deviation above 0.8 were discarded as non-critical. The second round asked experts to re-rate after viewing the anonymized group statistics, which led to substantial convergence (Kendall’s W increased from 0.63 to 0.79). Twenty-four factors were retained and hierarchically arranged. Using Saaty’s 1–9 scale, we then elicited pairwise comparisons within each level of the hierarchy, and consistency ratios were computed to ensure reliability.

Table 1. Expert Panel Composition

Role	Count
Green-finance managers	5
Textile-engineering consultants	4
Carbon-audit professionals	3
SME general managers	3

Stage 3: Definition of Investment Alternatives and Data Collection

Drawing on field visits to the Shaoxing and Foshan textile clusters, we designed three archetypal retrofit plans that differ in capital intensity, technological novelty, and policy incentive alignment. Plan A entailed a comprehensive switch to waterless digital printing, costing CNY 12 million and yielding an estimated 78% reduction in water consumption and a 32% energy-saving ratio. Plan B combined a heat-recovery steam system with low-liquor dyeing, requiring CNY 9.8 million upfront but enjoying a higher government subsidy intensity (25% of CAPEX). Plan C involved a rooftop PV installation of 1.2 MW capacity at a cost of CNY 9 million, offering tariff offsets but facing intermittent shading risks.

Primary data for these plans were obtained from multiple sources. Cost parameters were collected from machinery suppliers and cross-checked against industry association quotations. Operation and maintenance (O\&M) costs were derived from supplier contracts and supplemented with government benchmark reports. Process-based environmental data were drawn from ecoinvent v3.8 and local environmental-impact assessment reports, with factors localized for regions such as Shaoxing and Foshan. Energy-price scenarios followed National Development and Reform Commission (NDRC) forecasts, and subsidy parameters were modeled according to provincial incentive catalogs. All monetary values were normalized to 2025 real terms using the Producer Price Index (PPI). Financial projections employed a ten-year horizon and a 7% discount rate. Non-financial indicators were sourced from LCA databases and local assessments. To mitigate bias, technical coefficients were cross-validated by independent engineers, and a rigorous audit trail was maintained using NVivo 14 with data triangulation performed wherever possible.

Stage 4: Multi-Criteria Decision Analysis

Five MCDA experts—none of whom took part in the Delphi exercise—scored each plan against the 24 sub-criteria on a 1–5 scale. To ensure scoring consistency and transparency, each expert was provided with a detailed evaluation handbook that defined all criteria and provided qualitative anchor descriptions for each score level. The experts performed the initial scoring independently, followed by a moderated focus group where they could discuss their rationale without being forced to reach a consensus. The final score for each criterion was the arithmetic mean of the five experts' ratings. Raw scores were normalized via linear min–max scaling, then multiplied by sub-criterion weights and aggregated to derive composite scores. Rank-reversal tests confirmed that the ranking remained invariant, satisfying MCDA robustness requirements.

Stage 5: Monte Carlo-Based Sensitivity Analysis

Acknowledging the subjectivity inherent in expert weighting, we performed a Monte Carlo simulation with 10,000 iterations using @Risk 8.0. Dimension weights were perturbed using a triangular distribution (lower −15%, mode 0%, upper +15%). The choice of distribution and ranges was based on expert feedback and empirical studies to represent uncertainty realistically. For each iteration, the composite score of each plan was recalculated; ranking frequencies and Spearman correlations between weights and scores were recorded. To further triangulate the results, we conducted a post-hoc robustness check using an alternative weighting method—Shannon entropy—on the same normalized score matrix.

Stage 6: Financing Structure Optimization and Digital Platform Design

Leveraging the MCDA outputs, we applied a constrained optimization model to allocate financing instruments—bank credit, policy subsidies, internal equity, and venture capital—subject to cost-of-capital and risk-allocation constraints. The model was formulated as a linear program designed to minimize the project's Weighted Average Cost of Capital (WACC). The model is formally defined as follows:

Objective Function:

The primary goal is to minimize the WACC:

$$Minimise\ WACC = \sum_{i=1}^{n} r_i \cdot w_i$$

where r_i is the cost of capital for each financing source *i* and w_i is the weight (proportion) of source *i* in the total financing package.

Subject to the following key constraints:

- Total Funding Requirement: $\sum_{i=1}^{n} w_i = 1$
- Policy Subsidy Limit: The proportion of financing from ESG-linked subsidies ($w_{subsidy}$) cannot exceed the maximum percentage stipulated by government incentive policies.
- Debt Service Coverage Ratio (DSCR): To meet lender requirements and ensure financial solvency, the project's forecasted DSCR must be maintained above a minimum threshold, which is typically 1.3 for such projects.

$$DSCR = \frac{\text{Projected EVITDA}}{\text{Annual Debt Service (Principal +Interest)}} \geq 1.3$$

- Internal Capital Limit: The amount of internal equity (w_{equity}) cannot surpass the maximum capital the SMTE is able or willing to invest in the project.
- Non-negativity:

$$w_i \geq 0 \text{ for all } i$$

This model was solved to find the optimal financing structure, and scenario analyses were conducted to test project resilience under financial shocks. Finally, we translated the framework into the conceptual architecture of the Green Investment and Risk Coordination System (GIRCS), which consists of four modules designed to interface with external registries and banks via RESTful APIs.

RESULTS

Risk Factor Weights

The Delphi-AHP process yielded weights for the four primary dimensions: Economic Return (E1) 0.32, Environmental Performance (E2) 0.26, Policy Compliance (E3) 0.18, and Risk-Management Capacity (E4) 0.24. This reflects the experts' view that financial feasibility remains paramount, yet environmental credentials and risk safeguards are highly influential. Key statistics from the Delphi process are presented in Table 2.

Table 2. Delphi Round-2 Risk Factor Statistics (excerpt)

Risk Factor	Mean Importance	Std. Dev.
Policy risk	4.5	0.30
Technological risk	4.3	0.35
Market risk	4.1	0.40
Financial risk	4.4	0.28

Project Evaluation Scores and Ranking

The MCDA evaluation of the three plans yielded the following composite scores: Plan A scored 4.13, Plan B scored 4.01, and Plan C scored 3.93. Consequently, Plan A (waterless digital printing) emerged as the top-ranked alternative. The raw expert scores for each plan are detailed in Table 3, and the final ranking is in Table 4. Figure 1 visualizes the MCDA scores across the four dimensions.

Table 3. Raw Expert Score Matrix (mean ± SD, n = 5)

Plan	E1	E2	E3	E4
A	4.2 ± 0.3	3.8 ± 0.4	3.9 ± 0.2	4.5 ± 0.3
B	3.5 ± 0.4	4.7 ± 0.3	4.0 ± 0.2	3.6 ± 0.4
C	4.0 ± 0.2	4.0 ± 0.3	3.7 ± 0.3	3.9 ± 0.3

Table 4. Final Weighted Scores and Ranking

Plan	Composite Score	Rank
A	4.13	1
B	4.01	2
C	3.93	3

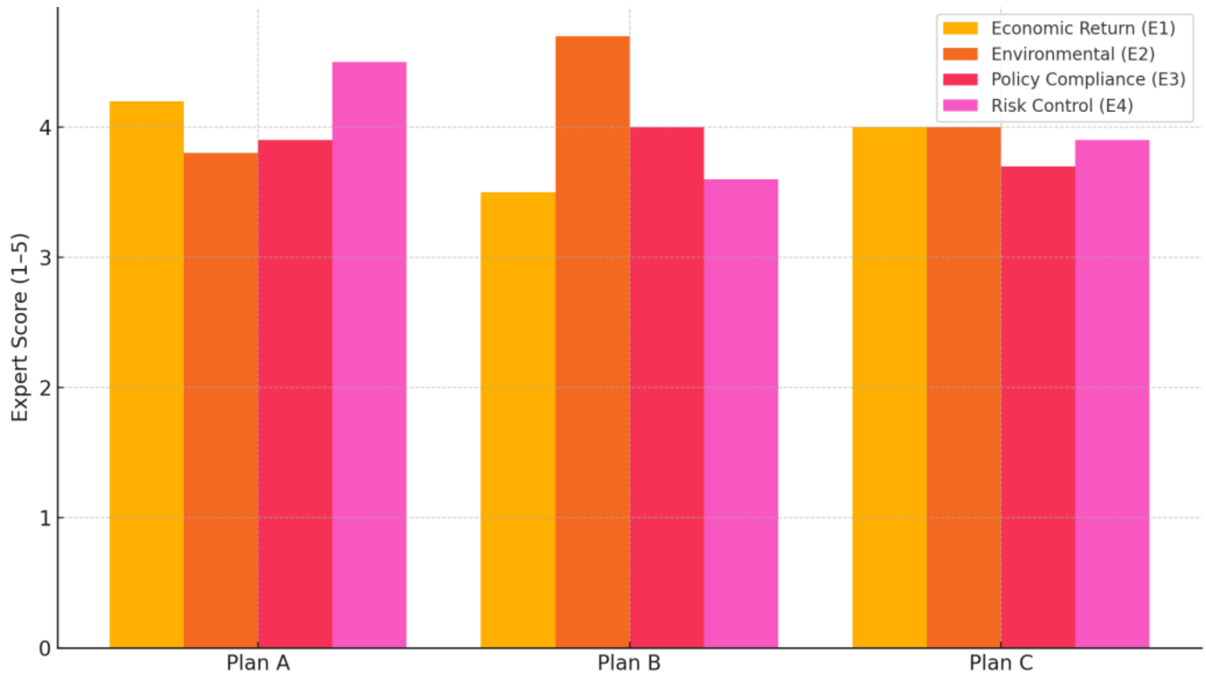

Figure 1. MCDA Scores of Investment Alternatives

Sensitivity Analysis

The Monte Carlo simulation confirmed the robustness of the ranking: Plan A maintained the top position in

87.4% of iterations, Plan B in 11.8%, and Plan C in 0.8%. Table 5 shows that Economic Return (E1) was the most influential driver of score variability (Std. Reg. Coefficient = 0.42), followed by Environmental Performance (E2) (0.35) and Risk-Management Capacity (E4) (0.30). Policy Compliance (E3) was the least sensitive driver (0.15).

Table 5. Top Sensitivity Drivers from Monte Carlo Simulation

Criterion	Std. Reg. Coefficient
Economic return (E1)	0.42
Environmental performance (E2)	0.35
Risk-management capacity (E4)	0.30
Policy compliance (E3)	0.15

Optimal Financing Structure and Stress-Testing

For the top-ranked Plan A, the financing optimization suggested a mix of 40% green credit, 20% ESG-linked subsidy, 25% internal funds, and 15% venture capital. A stress-test under a 300-basis-point interest-rate increase reduced the project's IRR from 16.2% to 13.5% but kept the DSCR above the conservative threshold of 1.3, indicating financial resilience.

Robustness Check of Weights

The post-hoc robustness check using Shannon entropy confirmed the stability of the expert-derived weights. The entropy-derived weights differed by less than ±0.04 from the Delphi–AHP outcomes, and the resulting project ranking remained unchanged, reinforcing confidence in the chosen weighting scheme.

DISCUSSION

The results demonstrate that a comprehensive green retrofit, as exemplified by Plan A (waterless digital printing), offers the most balanced value proposition for SMTEs. Its top ranking was not based on a single metric but was driven by the synergistic effects of superior water and energy savings, which translated into significant, tangible cost reductions. A deeper inspection reveals the importance of a life-cycle perspective; while Plan B was attractive due to a higher subsidy rate, its weaker environmental performance penalized its overall rank. This illustrates a critical insight for decision-makers: maximizing short-term subsidies does not guarantee a project's overall desirability or long-term competitiveness.

The sensitivity analysis provided a crucial finding regarding stakeholder priorities. After the paramount importance of economic returns, Environmental Performance (E2) emerged as a stronger differentiator among projects than Policy Compliance (E3). This suggests that for investors and experts, tangible environmental outcomes and resource efficiency are becoming more influential in defining a high-quality green project than simply meeting basic compliance standards or securing available grants.

The optimized financing structure, particularly its inclusion of a 15% venture capital (VC) component, warrants discussion. Although unconventional for SMTEs, this is justified by emerging trends where 'cleantech' and impact-focused VCs target transformative technologies such as waterless digital printing, which offer disruptive efficiency gains. The proposed Green Investment and Risk Coordination System (GIRCS) plays a pivotal role here. By offering standardized project validation and real-time, data-driven risk tracking, it is designed to reduce the information asymmetry and transaction costs that typically deter VCs from engaging with SMTEs. While significant practical barriers remain—such as stringent collateral requirements from banks, complex subsidy applications, and SMTE reluctance to cede equity—the GIRCS platform with its matchmaking function is specifically designed to mitigate these hurdles and make such hybrid financing structures more attainable.

From a managerial viewpoint, the analysis underlines the necessity for SMTEs to bundle complementary retrofit actions rather than pursuing isolated upgrades. The synergistic environmental and financial gains from combining energy-efficiency and water-saving technologies, as seen in Plan A, far outstrip the additive benefits of stand-alone measures. On the policy front, the findings suggest that grant schemes should be tied to verified carbon-reduction milestones rather than blanket CAPEX subsidies, a strategy that would better incentivize sustained performance. The GIRCS platform enables such dynamic oversight by alleviating information asymmetry and allowing lenders and policymakers to modulate credit lines and subsidies dynamically based on verified performance, rather than relying on static, upfront covenants.

Feedback on the GIRCS prototype from stakeholders was constructive. Bankers valued the auto-generated risk reports and loan-covenant compliance dashboards, whereas SME owners appreciated the one-click subsidy-eligibility checker. However, both groups requested enhanced data-privacy features, particularly for commercially sensitive production metrics. This insight will directly inform the next iteration of the platform’s design and highlights the pathway from academic research to practical technology transfer.

To lend external validity to the findings, Plan A's performance was benchmarked against national data from the China National Textile and Apparel Council (CNTAC). Its CO_2 abatement cost and water-saving cost are more efficient than national averages, positioning the plan favorably for inclusion in national Best Available Techniques (BAT) catalogs. Furthermore, a scenario analysis using Guangdong's different grid emission factor confirmed that the ranking order of the plans remained unchanged, further reaffirming the model's robustness across regional contexts.

This study has several limitations. First, the reliance on a 15-person expert panel means the derived weights are representative of this specific cohort's opinion and should be generalized with caution. Second, the dataset is specific to Chinese textile clusters; extending the model to other sectors, such as leather tanning, could reveal context-specific variations. Third, the GIRCS platform is currently a prototype, and issues of data cybersecurity, interoperability, and long-term maintenance costs require further investigation. Finally, the MCDA framework assumes that the evaluation dimensions are preferentially independent, which may not fully capture real-world complexities where, for example, strong risk management positively influences economic returns.

Future research could address these limitations in several ways. Promising avenues include exploring adaptive weighting algorithms using machine learning to update criteria weights based on real-time data and integrating blockchain-based smart contracts to automate subsidy disbursement upon verified ESG milestones. Comparative studies across different countries could also provide valuable insights into how risk priorities differ across regulatory landscapes. Methodologically, to address the limitation of criteria independence, future work could employ more advanced techniques such as the Analytic Network Process (ANP) or Bayesian network models. Finally, field experiments that randomly assign SMTEs to use the GIRCS versus traditional financing advice could causally identify the framework's real-world impact on investment uptake, addressing the increasing emphasis in the academic field on providing evidence of practical effectiveness beyond model validation.

CONCLUSION

This article contributes to the discourse on SME green finance not by advancing a single method, but by proposing and validating a novel, integrated decision-support framework that synthesizes Delphi-AHP weighting, MCDA ranking, Monte Carlo sensitivity testing, and financing-structure optimization. The theoretical contribution of this work is its architectural innovation: creating a replicable, end-to-end pathway that translates abstract sustainability theories into an actionable, dynamic, and data-driven tool for a critical, under-researched sector.

The empirical application to three textile-sector retrofit options demonstrates that comprehensive waterless digital printing (Plan A) offers the most balanced portfolio of economic gains, environmental benefits, and policy alignment. The findings confirm the value of combining expert elicitation with probabilistic simulation, which helps bridge the gap between heuristic-based decision-making and rigorous analytical models. By embedding the evaluation engine within the GIRCS digital platform, the study charts a feasible route to real-time risk supervision and adaptive financing. This end-to-end pathway is poised to help SMTEs navigate the complexities of China's dual-carbon era. Furthermore, the open-data stance adopted here enhances transparency, enabling replication and cross-sector extrapolation. In a policy landscape marked by rapid change and data proliferation, such integrated, data-driven frameworks may well become the standard for sustainable investment appraisal across a broad swath of engineering domains.

Looking forward, scaling the framework beyond pilot use will require collaborative governance models where financial regulators set uniform green-credit taxonomies, technology vendors supply verified performance data through IoT sensors, and third-party auditors certify ESG outcomes in near real-time. Such an ecosystem promises not only to unlock affordable capital for SMEs but also to accelerate China's progress toward its nationally determined contributions under the Paris Agreement.

Author Contributions

Jiang Yuan and Anbalagan Marimuthu designed the study; all authors conducted the study; Lingfeng Cheng and Anbalagan Marimuthu collected and analyzed the data. Jiang Yuan and Lingfeng Cheng participated in drafting the manuscript, and all authors contributed to critical revision of the manuscript for important intellectual content. All authors gave final approval of the version to be published. All authors participated fully in the work, took public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or completeness of any part of the work were appropriately investigated and resolved.

Conflict of Interest

The authors declare no conflict of interest.

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Availability of Data and Materials

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

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Not applicable.

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