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Green supply chain management in the Southern Brazilian rice industry: A survey and structural analysis

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A R T I C L E I N F O

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A B S T R A C T

The purpose of this study is to evaluate the influence of Green Supply Chain Management (GSCM) dimensions on the performance of an agrifood supply chain, with a specific focus on the rice industry in southern Brazil. The region's rice industry produces a substantial amount of biomass, fostering circular economy practices that align with both economic and environmental objectives. Using Structural Equation Modeling with Partial Least Squares (SEM-PLS), this research analyzes data from a survey of 92 companies. The measurement model incorporates 21 input and 11 output indicators, organized into six constructs. The input constructs—green strategy, green innovation, and green operations—are instrumental in shaping industry competitiveness, the fourth construct. The output constructs measure results and reputation. The findings indicate that green innovation and green operations significantly enhance competitiveness, whereas green strategy exerts minimal influence. The scope is limited to the rice industry in southern Brazil. Practical implications include offering a strategic framework for agrifood industry practitioners to improve competitiveness by optimizing green practices within their supply chains. Theoretical implications suggest that while green strategy alone may not be sufficient to drive competitiveness, the integration of green innovation and operations can enhance it. The originality of this research lies in the development of a comprehensive measurement model for assessing competitiveness in agrifood businesses, which evaluates both operational outcomes and reputational impact.

1. Introduction

Environmental concerns in the supply chain (SC) aim to reduce environmental impacts, increase efficiency, and comply with legislation. Green practices can cut costs by reducing the need for virgin raw materials and energy sources while launching new products based on the reuse of waste from other industries (Ajamieh et al., 2016). In 2015, Jabbour et al. (2015) found that approximately 70% of managers or practitioners from leading companies in their industries included sustainability in their work agendas. Success relies on collaboration among SC actors in implementing eco-efficient and sustainable actions (Kalyar et al., 2020).

Focal companies and SC members that prioritize environmental concerns usually improve reputation and market share, driving the widespread adoption of Green Supply Chain Management (GSCM) practices. Chen et al. (2022) argue that sustainability in the SC requires addressing environmental, social, and economic factors. Laguir et al. (2021) observe that emphasizing environmentally conscious practices not only meets regulatory requirements but also enhances long-term competitiveness.

Hebaz and Oulfarsi (2021) define GSCM as the integration of environmental considerations throughout the entire product lifecycle. Reche et al. (2022) add that GSCM also focuses on product conception, design, future disposal, disassembly, transportation, and delivery. GSCM fosters

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partnerships across the SC, encouraging purchasing from suppliers with ISO 14000 certifications or those committed to reducing environmental impact (Machado et al., 2023).

GSCM incorporates internal practices within the company (Stekelorum et al., 2021) and external ones that involve suppliers, customers, and other external agents (Bag et al., 2022). GSCM enhances SC eco-efficiency by addressing environmental and economic issues, thereby increasing profits, market share, and environmental performance for the focal company and partners. GSCM extends beyond traditional SC goals like profitability, quality, and cooperation (Qalati et al., 2022), incorporating compliance with legislation, consumer demands, and new market development (Cousins et al., 2019). GSCM integrates with other SC management strategies focused on efficiency, agility, and resilience, collectively known as LARG (lean, agile, resilient, and green) (Sahu et al., 2022, 2023).

The relationship between GSCM and SC's long-term competitiveness encompasses investment in technology, cost reduction, regulatory compliance, customer demands, risk mitigation, product differentiation, and the pursuit of sustainability for both business and the environment (Sahu et al., 2018; Tan et al., 2019). GSCM enhances value addition and market expansion (Nureen et al., 2022), with key dimensions including greening strategy, innovation, and green operations (Herrmann et al., 2021). A Scopus search for "GSCM" and "Green Supply Chain Management" found 764 articles published in English from 2004 (just one) to 2023 (123), highlighting the growing importance of the field. A search within the initial results using the keywords "competitiveness" and "performance" yielded only 52 articles. When adding "dimensions," just one article remained (Santos et al., 2021), which is a theoretical study without empirical data. The result reveals a research gap and raises the research question: How can the relationships between GSCM dimensions and the competitive performance of the supply chain be evaluated within its industry?

The purpose of this study is to evaluate the influence of GSCM dimensions on the performance of an agrifood supply chain (AFSC), with a specific focus on the rice industry in southern Brazil. The study proposes a method for industry practitioners to evaluate the impact of green practices on AFSC performance. It also addresses a strategic flaw in the industry, offering insights to both local practitioners and society. Given the AFSC's economic, social, and environmental influence, the strategic changes recommended can be highly relevant and valued by local leaders. The local rice industry was selected for its role in circular economy activities, generating significant biomass from rice husk and rice straw. Two cement complexes, established due to the region's limestone deposits, previously used imported low-ash coal for clinker kiln operations. Now, they replace up to 35% of the coal's calorific value with biomass from the rice industry, significantly reducing the local ecological footprint due to the coal's transatlantic logistics (Sellitto et al., 2013). Thus, the biomass from the local rice industry drives circular economy activities in the region.

The research surveyed 92 companies in Southern Brazil, where rice is a prominent crop, particularly near the Uruguayan border. Company practitioners completed a questionnaire, and the results were analyzed using SEM-PLS (structural equations modeling-partial least squares) with SMART-PLS software. The measurement model, based on previous studies (Herrmann et al., 2021; Sellitto and Hermann, 2016; Sellitto et al., 2015), includes three dimensions: green strategy, green innovation, and green operations. Hermann et al. (2021) identified relevant measurement models, dimensions, and variables from the literature that supported this study. The rest of the article covers the hypotheses derivation, methodology, results, discussion, and conclusion.

2. Hypotheses derivation

2.1. Dimensions in GSCM

Hermann et al. (2021) outlined a comprehensive set of 64 green practices based on global database references. Their study also includes measurement models from the literature, outlining each practice's specifications, prerequisites, and outcomes. They introduced tree-like structures to organize green practices in supply chain management hierarchically, with GSCM at the top level. The top term is divided into latent constructs, which are measured by manifest variables at the third level. Drawing on prior empirical research (Sellitto and Hermann, 2016; Sellitto, 2018), this study employs three latent constructs—green strategy, green innovation, and green operations—supported by 21 manifest variables. In summary, based on previous AFSC contributions from the literature, seven indicators were selected to support each construct. Table 1 lists these indicators and references at least one empirical study for each, providing evidence of their role in GSCM.

Green practices are viewed as strategic resources that enhance organizational performance (Cankaya and Sezen, 2019). When aligned with a greening strategy, these resources can directly impact SC performance (Jabbour et al., 2014) and create a competitive advantage (Genovese et al., 2015). These considerations lead to the first hypothesis.

H1. A greening strategy positively impacts the competitiveness of companies in the South Brazilian rice industry (Jabbour et al., 2014; Genovese et al., 2015).

In SCs, the focal company typically drives innovation, influencing other members to invest in practices such as eco-design (Santos et al., 2019) and cleaner production technologies (Pan et al., 2021). Green products and processes support efficient structures, including reuse, recycling, and the avoidance of hazardous materials. Green marketing strategies also encourage consumers to seek information about products and organizations (Roh et al., 2022). Additionally, technological and organizational support is crucial for implementing green practices in supply chains (Feng et al., 2022). Innovation further enhances environmental sustainability through energy savings, pollution prevention, waste recycling, and green product projects, impacting the organization's economic performance (Assunção et al., 2022). These considerations lead to the second hypothesis.

H2. Green innovation positively impacts the competitiveness of companies in the South Brazilian rice industry SC (Feng et al., 2022; Assunção et al., 2022)

Green operations are linked to supply chains that adopt business strategies to minimize raw material use, weight, size, and energy consumption (Kazancoglu et al., 2020). They encompass green manufacturing, warehousing, distribution, reverse logistics, final disposal, and pollution reduction policies that focus on reducing, reusing, or properly disposing of operational waste (Sharabati, 2021). These green practices generally enhance efficiency (Govindan et al., 2016) and improve economic outcomes (Luthra et al., 2016). These considerations lead to the third hypothesis.

H3. Green operations positively impact the competitiveness of companies in the South Brazilian rice industry (Govindan et al., 2016; Luthra et al., 2016).

2.2. Impact of green practices on performance

Kushwaha and Sharma (2016), Jum'a et al. (2021), and Stekelorum et al. (2021) advocate that GSCM implementations enhance company performance and support sustainable development. GSCM practices impact SC's environmental, financial, and operational performance by lowering costs, inventories, risks, and waste while boosting quality, production scale, and investment returns (Carballo-Penela et al., 2023). They also help improve corporate image (Sharma and Kadiyan, 2020) and meet legal requirements (Jabbour et al., 2014). The link between GSCM and firm performance can be assessed through variables related to competition objectives (Sharabati, 2021; Alghababsheh et al., 2022),

Table 1
Constructs and indicators.

Dimension	Indicator	Description	Reference
Green strategy	Green strategy formulation	Method for formulating greening objectives and plans	Huo et al. (2021)
	Green performance measurement	Method for measuring the achievement of green objectives	Trujillo-Gallego et al. (2022)
	Communication	Structures and interconnected information systems in SC	Ajamieh et al. (2016)
	Green requirements	Set of green requirements demanded from suppliers	Nguyen et al. (2021)
	Cooperation with suppliers	Existence of shared strategies and information in SC	Assumpção et al. (2022)
	Cooperation with customers	Existence of shared strategies and information with customers	Tan et al. (2019)
	Recovery of investments	Resale, recycling, or reuse of leftovers, excess, scrap, and obsolete equipment	Machado et al. (2020)
Innovation	Environmental technology	Adopts cleaner production technology	Pan et al. (2021)
	Ecodesign	Assess and prevent environmental impacts during product design	Sellitto et al. (2017)
	Green Market	Knows the requirements of green niche markets	Borazon et al. (2022)
	Green marketing	Meets green market requirements	Kushwaha and Sharma (2016)
	Green product	Offers products with low material and energy consumption.	Kara and Edinsel (2023)
	Organizational structure	Leadership, material resources, and commitment of managers	Lutfi et aç. (2023)
	Green process	Operates processes with the reduction of waste, materials, and energy.	Wong et al. (2020)
Green operations	Green Manufacturing	Incorporates environmental requirements into the manufacturing strategy	Umar et al. (2023)
	Green Distribution	Incorporates environmental requirements into distribution	Sellitto et al. (2012)
	Green warehousing	Incorporates environmental requirements into warehousing	Sellitto et al. (2012)
	Pollution reduction	Reduces environmental damage and the use of hazardous materials.	Nureen et al. (2023); Purnomo et al. (2022)
	Pollution prevention	Anticipates and prevents environmental risks and the use of hazardous materials.	Rusmawati and Soewarno (2021); Nureen et al. (2023)
	Reverse logistic	Recovers value by reusing, remanufacturing, and recycling waste and packaging	Richnák and Gubová (2021); Beiler et al. (2020).
	Final disposal	Correctly dispose of non-reusable materials.	Richnák and Gubová (2021); Beiler et al. (2020).

such as cost reduction, quality, flexibility, and dependability (Teixeira et al., 2020). In specific SCs, such as AFSC, service excellence becomes a fifth priority (Kumar et al., 2022).

This study measures supply chain competitiveness using five indicators: cost, quality, flexibility, dependability, and services. Competitiveness manifests in the business environment through two constructs: result (tangible) and reputation (intangible) (Uddin, 2021). Therefore, the model includes two endogenous constructs to measure performance: (i) material result, assessed by ROI (Chotia et al., 2023), net profit (Kazancoglu et al., 2020), and customer satisfaction (Chavez et al., 2016); and (ii) reputation, evaluated by image (Uddin, 2021), market share (Nguyen et al., 2020), and compliance (Le et al., 2022). Such considerations lead to the two last hypotheses.

H4. Competitiveness positively impacts the results of companies in the South Brazilian rice industry (Sharabati, 2021; Alghababsheh et al., 2022).

H5. Competitiveness positively impacts the reputation of companies in the South Brazilian rice industry (Uddin, 2021).

Given the hypotheses and tree-like structures, Fig. 1 presents the measurement model.

The model is composed of three exogenous constructs, ξ1, ξ2, and ξ3, supported by 21 indicators, and three endogenous constructs, η4, η5, and η6, supported by 11 indicators. All constructs are reflexive, meaning the construct precedes and correlates with its indicators. For example, a company adopting environmental planning under the strategy construct is also likely to develop performance measurement methods, partner collaboration, and communication systems. Therefore, indicators within this construct are expected to correlate. This rationale applies to other constructs as well.

3. Methodology

The research method involves a survey conducted in the rice industry of southern Rio Grande do Sul, Brazil's top rice-producing state, which borders Uruguay. The region accounts for over 65% of Brazil's rice production, benefiting from a climate and geography well-suited for rice cultivation. Rice farming is a major economic activity and is integrated into local cultural heritage and history. Agricultural practices include flooded rice fields, or paddies, essential for irrigated rice farming. The sector faces challenges such as market price fluctuations, pest and disease issues, and the need for sustainable practices. Efforts to introduce modern farming techniques and technology are ongoing and are a key focus of local research.

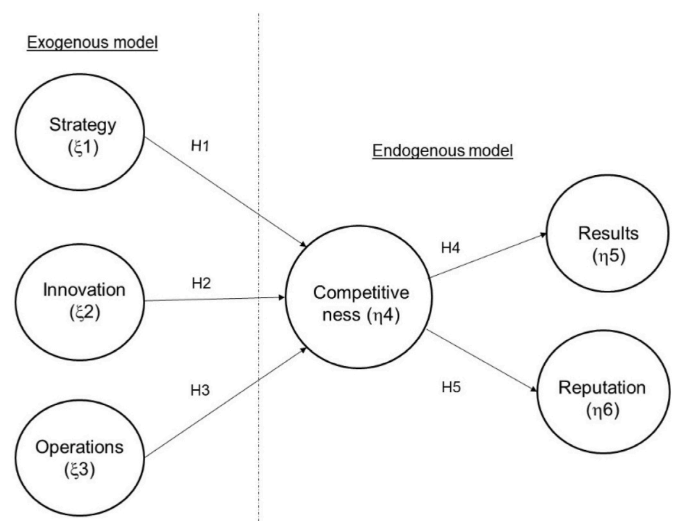

Fig. 1. Measurement model.

The research method is SEM-PLS (Structural Equations Modeling – Partial Least Squares), which involves two main phases. First, manifested variables are combined into weighted composites used in regression analyses to determine path coefficients (Rönkkö et al., 2016). Despite some criticisms, PLS-SEM is widely used for estimating path coefficients in exploratory studies focused on prediction rather than theory testing (Hair et al., 2011). SEM-PLS was chosen for its ability to handle small sample sizes, formative and reflexive latent constructs, and non-normally distributed data (Hair et al., 2013). Given the exploratory nature of our study, which uses a sample of 92 individuals and variables with skewness exceeding 1, thus violating normality assumptions (Ali et al., 2017), SEM-PLS is appropriate. Zeng et al. (2021) support the use of SEM-PLS in exploratory studies with small samples and non-normally distributed data. However, SEM-PLS has been criticized and faces limitations, especially beyond exploratory contexts (Rönkkö et al., 2016; Kono and Sato, 2023).

The research methodology encompassed the following steps:

- Literature review and development of a measurement model operationalized through a Likert scale questionnaire.
- Meeting with the rice industry union in Pelotas, Brazil, to ask for support.
- Pre-test with fifteen regional experts in sustainability in rice cultivation.
- Questionnaire distribution to 322 companies with an introductory letter from the union and assessed for non-response bias and common method variance.
- Collection and validation of 92 responses (28.5% response rate);
- Exploratory factor analysis (EFA) to refine the measurement model;
- Structural equation modeling using SEM-PLS operated by the Smart PLS software. and
- Presentation and discussion with local rice industry union leaders.

Fig. 2 summarizes the methodology.

3.1. Pre-test

The group of experts assessed the 21 indicators of Table 1 according to their relevance to the local rice industry using the Fuzzy Delphi Method (Tseng et al., 2022).

- Step 1: k experts expressed their opinions R_i on the importance of each indicator i on a scale [1–5];
- Step 2: Opinions were organized into Triangular Fuzzy Numbers (TFN) $O_i = (L_i, M_i, U_i)$, respectively the lowest, geometric mean, and highest ratings received by the indicator, according to Equations (1)–(3);
- Step 3: Equation (4) defuzzified the TFNs. Indicators with $G_i \geq 3.0$ (center of the scale) remain in the measurement model.

$$\boldsymbol{L_i} = \boldsymbol{Min}[\boldsymbol{R}_1, \ldots, \boldsymbol{R}_k] \tag{1}$$

$$\boldsymbol{M_i} = \left(\prod_{i=1}^{k} \boldsymbol{R_i}\right)^{1/k} \tag{2}$$

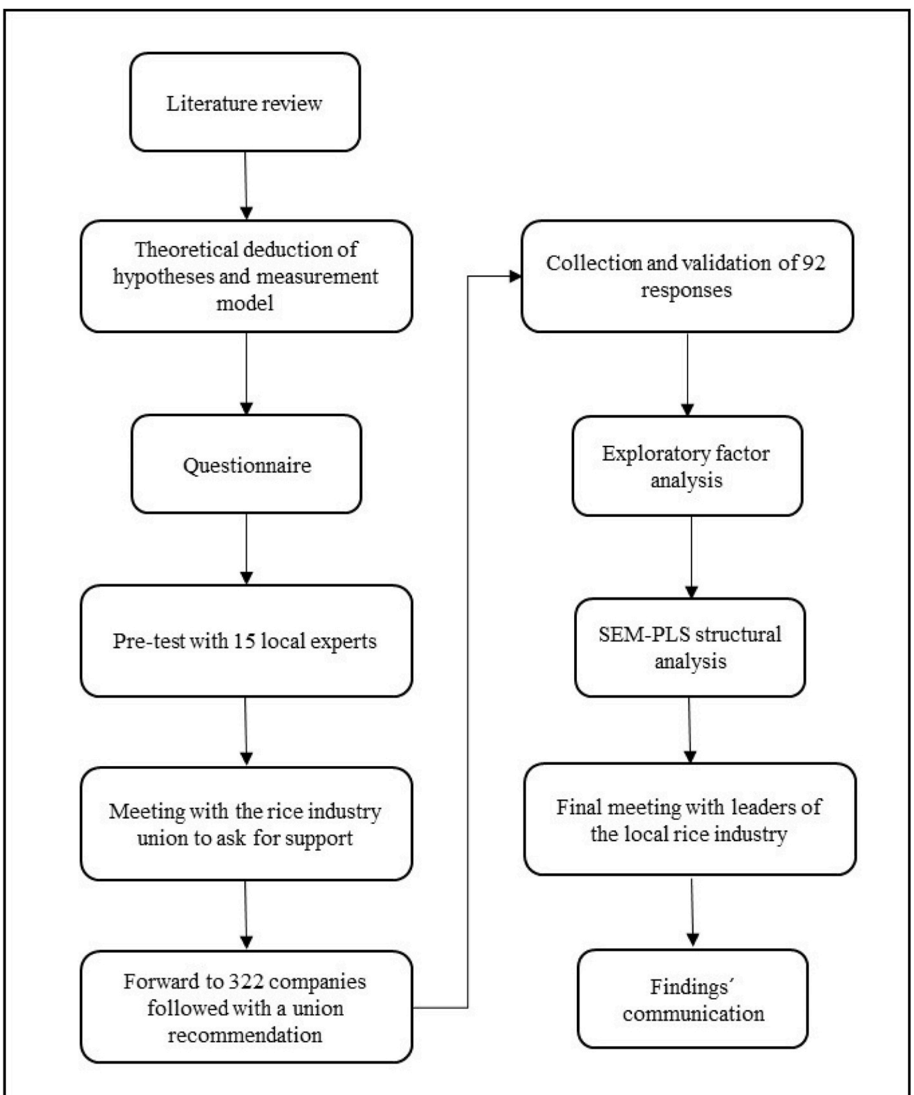

Fig. 2. Flow chart of the methodology.

$$U_i = \boldsymbol{Max}[R_1, \ldots, R_k] \tag{3}$$

$$G_i = \frac{(U_i - L_i) + (M_i - L_i)}{3} + L_i \tag{4}$$

Table 2 presents the *Gi*. All indicators remain after this stage.

3.2. Questionnaire and demographic information

Table 1 and TFN analysis results informed the development of a five-point Likert scale questionnaire. The final refined questionnaire and scale are shown in Table 3. Keywords were not provided to respondents.

Sheehan (2001) states that salience, or the relevance of the survey to the respondent's concerns, typically increases response validity. The endorsement by the sectorial entity enhanced the relevance. To test for non-response bias, early and late respondents were compared using a *t*-test, which found no significant difference in average values. For common method variance, an EFA showed that the first factor explained less than 50% of the variance, indicating no dominant factor (Tehseen et al., 2017). Barclay et al. (1995) state that a sample size is adequate if it is at least ten times the number of paths to a single construct. With a maximum of three paths, the sample size is sufficient. Fig. 3 presents the demographic information of the 92 respondents and companies, with over 60% having an active environmental management system, such as ISO 14000 or similar.

4. Results

4.1. Measurement model

Measurement quality was assessed using exploratory factor analysis (EFA) (Hair Jr. et al., 2020). SPSS version 22 evaluated sample adequacy with the Kaiser-Meyer-Olkin (KMO) and Bartlett's sphericity tests. KMO was 0.757 (threshold = 0.6), and Bartlett's test had a p-value of 0.000 (threshold = 0.01), indicating suitability for analysis (Hair et al., 2011). EFA revealed five factors with eigenvalues above 1, but only three showed significant loadings, validating the initial model with three constructs. Indicators with loadings <0.4 (Ford et al., 1986) or cross-loadings with differences <0.2 (Kim and Mueller, 1978) were removed, leaving 18 valid indicators. Oblique EFA, recommended by Yim (2019) for SEM, used a pattern matrix with Oblimin rotation. Rotation converged in 21 iterations. Table 4 displays the pattern matrix after Oblimin rotation and Kaiser normalization.

EFA recommends removing performance, recovery, and eco-design, as well as reallocating technology and manufacturing (from innovation to strategy) and process (from innovation to operations). The subsequent step involves SEM-PLS analysis using Smart-PLS version 3.3.9. Fig. 4 displays the software interface.

Before interpreting results, internal consistency (Cronbach's alpha,

Table 2
Degree of importance of measurement model indicators.

Indicators	G_i	Indicators	G_i	Indicators	G_i
Green strategy formulation	5,00	Environmental technology	5,00	Green Manufacturing	5,00
Green performance measurement	3,75	Ecodesign	4,00	Green Distribution	4,50
Communication	5,00	Greenmarket	4,25	Green warehousing	3,75
Green requirements	4,25	Green marketing	5,00	Pollution reduction	3,75
Cooperation with supplier	4,00	Green product	4,75	Pollution prevention	4,50
Cooperation with customers	4,75	Organizational structure	4,75	Reverse logistics	3,75
Recovery of investments	3,75	Green process	3,75	Final disposal	5,00

Table 3
Questionnaire.

My company:	
1. Possesses a well-defined strategy and shared plans aimed at environmental and energy conservation, along with reduced generated waste.	Formulation
2. Utilizes an appropriate methodology to measure and assess the outcomes of the environmental impacts it generates.	Performance
3. Implement effective methods to facilitate communication with business partners to manage the environmental impacts it generates.	Communication
4. Enforces suitable environmental requirements and demands commendable environmental performance from its suppliers.	Requirements
5. Fosters practical cooperation with suppliers to jointly manage the environmental impacts generated.	Suppliers
6. Promotes collaboration with customers to manage the collective environmental impacts.	Customers
7. Adheres to a defined and active policy for reusing unused equipment, materials, and inventories.	Recovery
8. Invests judiciously in innovative design and production technologies to diminish the environmental impact.	Technology
9. Establishes objectives and applies eco-design techniques to new products, minimizing environmental impact and enhancing processes' eco-friendliness.	Ecodesign
10. Discloses the environmental characteristics of its products and processes transparently, utilizing environmental arguments for advertising and sales.	Market
11. Proactively identifies and develops markets for environmentally friendly products that align with sustainability goals.	Marketing
12. Modifies existing products or introduces new ones with enhanced environmental characteristics compared to current offerings.	Product
13. Maintains a management structure and official documents that underscore the value of environmental preservation, such as ISO 14,000 certifications.	Organizational
14. Adjusts business processes appropriately to enhance environmental friendliness and reduce associated impacts.	Process
15. Understands and effectively controls the environmental impact resulting from manufacturing activities.	Manufacturing
16. Understands and adeptly controls the environmental impact associated with the distribution of its products.	Distribution
17. Understands and proficiently controls the environmental impact stemming from the storage of its products.	Warehousing
18. Organizes operational practices effectively to minimize pollution generation.	Reduction
19. Organizes operational practices to prevent pollution and mitigate the risks of environmental accidents.	Prevention
20. Implements a reverse logistics policy, efficiently repurposing waste and reutilizing waste from other companies.	Reverse
21. Disposes of generated waste in an environmentally responsible manner.	Disposal
22. Successfully reduces production costs through environmentally valorized policies.	Cost
23. Enhances the quality of products and services by embracing environmental valorization policies.	Quality
24. Increases the flexibility of products and services based on environmental valorization policies.	Flexibility
25. Enhances the punctuality and reliability of deliveries through environmental valorization policies.	Dependability
26. Diversifies services associated with the product based on environmental valorization policies.	Service
27. Maintains an excellent market image and reputation through environmental valorization policies.	Image
28. Demonstrates full compliance with current legislation and maintains high adherence to internal and external standards and regulations.	Compliance
29. Commands a substantial market share.	Share
30. Exhibits high profitability.	Profit
31. Realizes a high return on investment (ROI).	ROI
32. Records high customer satisfaction levels for the products and services provided.	Satisfaction

Scale: 1 = totally disagreed, 2 = partially disagreed, 3 = intermediate, 4 = partially agreed, 5 = totally agreed.

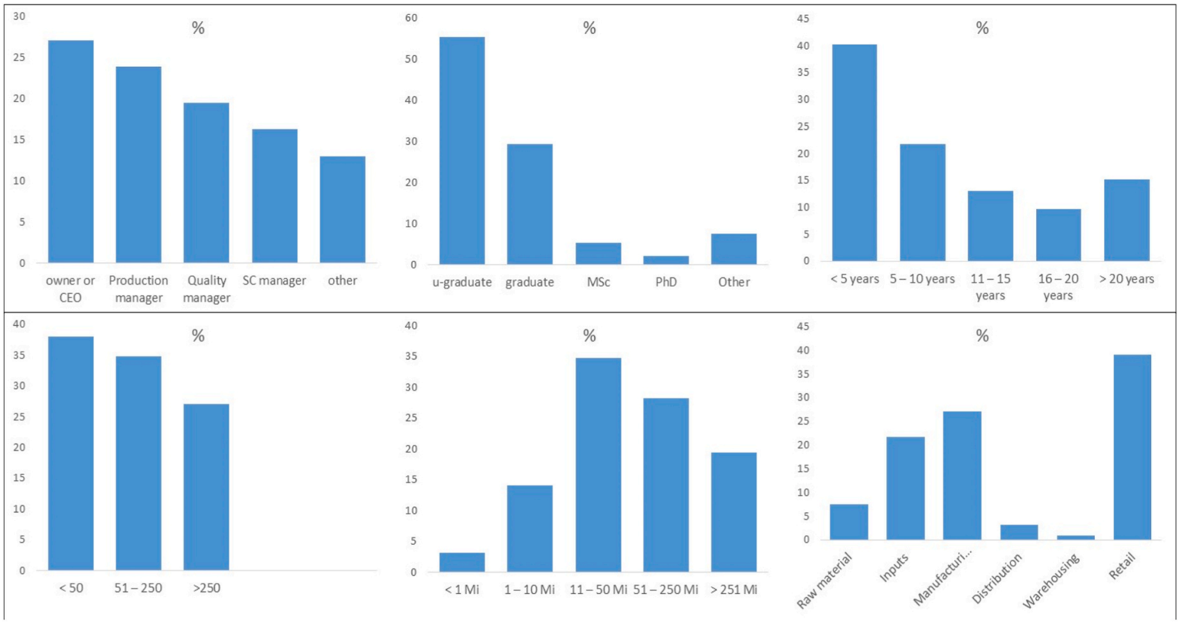

Fig. 3. Demographic information on respondents (a) position, (b) scholarly, (c) time in company and companies, (d) number of workers, (e) revenue in Brasilian currency in 2022, and (f) position in the FSC.

Table 4
Exploratory factors analysis of the dataset.

Keyword	(ξ1)	(ξ2)	(ξ3)	Major load	Second load	Diff.	OK?
Formulation	**0.600**	0.015	0.169	0.600	0.169	0.430	Yes
Performance	0.273	0.331	0.314	0.331	0.314	0.017	No
Communication	**0.614**	0.296	−0.246	0.614	0.296	0.318	Yes
Requirements	**0.570**	0.251	−0.040	0.570	0.251	0.319	Yes
Suppliers	**0.752**	−0.023	−0.124	0.752	−0.023	0.776	Yes
Customers	**0.467**	0.224	−0.054	0.467	0.224	0.243	Yes
Recovery	0.414	−0.224	0.323	0.414	0.323	0.091	No
Technology	**0.565**	0.054	0.301	0.565	0.301	0.264	Yes
Ecodesign	0.343	0.423	0.190	0.423	0.343	0.080	No
Market	0.185	**0.721**	0.049	0.721	0.185	0.536	Yes
Marketing	−0.019	**0.871**	−0.069	0.871	−0.019	0.890	Yes
Product	−0.066	**0.804**	0.088	0.804	0.088	0.716	Yes
Organizational	0.337	**0.537**	−0.044	0.537	0.337	0.201	Yes
Process	0.143	0.320	**0.527**	0.527	0.320	0.207	Yes
Manufacturing	**0.594**	−0.068	0.354	0.594	0.354	0.240	Yes
Distribution	0.114	0.181	**0.600**	0.600	0.181	0.420	Yes
Warehousing	0.285	−0.195	**0.629**	0.629	0.285	0.344	Yes
Reduction	−0.025	0.020	**0.334**	0.334	0.020	0.314	Yes
Prevention	−0.023	−0.159	**0.675**	0.675	−0.023	0.698	Yes
Reverse	−0.362	0.268	**0.691**	0.691	0.268	0.424	Yes
Disposal	0.092	−0.051	**0.680**	0.680	0.092	0.588	Yes

rho_A, and composite reliability), convergent validity (average variance extracted – AVE), and discriminant validity must be assessed (Hair et al., 2017). All parameters for internal consistency are satisfactory. Additionally, no composite reliability (CR) exceeds 0.95, indicating no excessive redundancy among indicators (Diamantopoulos et al., 2012). Convergent and discriminant validity are also confirmed. Tables 5 and 6 present the assessments and acceptance criteria.

Smart-PLS provides a cross-loading analysis to assess discriminant validity. Table 7 displays it, reinforcing discriminant validity and confirming that performance, recovery, and eco-design should be removed from the model.

The Heterotrait-Monotrait (HTMT) ratio also confirmed that there are no issues with discriminant validity. All values are below 0.765. The acceptance threshold is 0.85 (Henseler et al., 2015). However, AVE issues remain for strategy and operations. Removing communication and customers from the strategy construct refines it, though strategy's influence is minimal. Disposal and prevention are also removed to achieve a satisfactory AVE of 0.505. Eco-design has been reintegrated into the model despite its cross-loading with strategy. Other measurements remain unchanged. Fig. 5 displays the final configuration.

4.2. Structural model

Structural analysis requires six assessments (Hair et al., 2017) provided by Smart-PLS: (*i*) multicollinearity issues; (*ii*) size and significance of path coefficients; (*iii*) coefficients of determination R^2, (*iv*) predictive relevance Q^2, (*v*) f^2effect sizes; and (*vi*) q^2effect sizes.

The first analysis assesses collinearity using VIF (variance inflation factor). A VIF above 5 indicates collinearity; in this model, the highest VIF is 2.601, showing no collinearity issues. The second analysis evaluates path coefficients. Smart-PLS uses bootstrapping to determine standard deviations, 95% confidence intervals, t-statistics, and p-values.

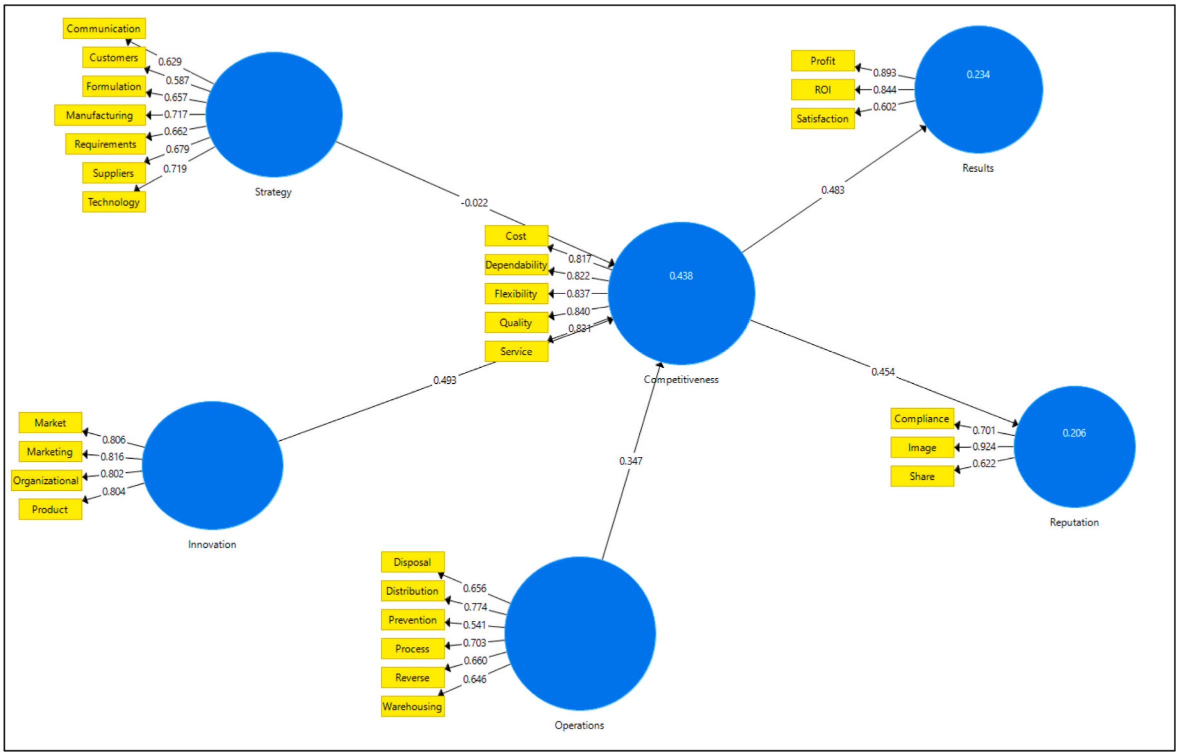

Fig. 4. Screen of the initial SEM-PLS run.

Table 5
Internal consistency and convergent validity.

	Cronbach's alpha	rho_A	Composite reliability (CR)	Average variance extracted (AVE)
ζ1	0.793	0.802	0.847	**0.443**
ζ2	0.823	0.828	0.882	0.652
ζ3	0.759	0.785	0.826	**0.445**
η4	0.887	0.887	0.917	0.688
η5	0.694	0.762	0.829	0.624
η6	0.687	1.037	0.799	0.577
Acceptance	>0.6[a]	>0.6[a]	>0.6[a]	>0.5[b]

[a] Dijkstra and Henseler (2015).
[b] Hair Jr. et al. (2020).

Table 6
Discriminant validity assessment.

	ζ1	ζ2	ζ3	η4	η5	η6
ζ1	**0.665**					
ζ2	0.488	**0.807**				
ζ3	0.456	0.270	**0.667**			
η4	0.376	0.576	0.470	**0.829**		
η5	0.336	0.294	0.485	0.484	**0.790**	
η6	0.552	0.480	0.603	0.454	0.461	**0.760**

Acceptance: The diagonal must be greater than the arriving lines (Fornell and Larcker, 1981).

Only the Strategy → Competitiveness path is insignificant, meaning only H1 is unsupported. Table 8 presents the assessment.

The next assessment focuses on the coefficient of determination R^2, which measures the variance explained by the construct. Competitiveness, results, and reputation have R^2 values of 0.446, 0.226, and 0.202, respectively, indicating moderate, weak, and weak explanatory power (Hair et al., 2017). The subsequent evaluation involves predictive relevance Q^2, which indicates prediction accuracy using data external to the model. A Q^2 greater than zero denotes predictive power (Hair et al., 2017). Smart-PLS calculates it via a blindfolding procedure. Competitiveness, results, and reputation have Q^2 values of 0.280, 0.089, and 0.141, respectively, showing predictive power for all constructs. The next step is to assess effect sizes by comparing changes in R^2 with the

Table 7
Cross-loading analysis.

	ζ1	ζ2	ζ3	η4	η5	η6
Communication	**0.629**	0.415	0.116	0.160	0.190	0.265
Customers	**0.587**	0.308	0.235	0.226	0.230	0.285
Formulation	**0.657**	0.301	0.330	0.199	0.239	0.360
Manufacturing	**0.717**	0.264	0.484	0.321	0.375	0.513
Performance	**0.627**	**0.475**	0.398	0.299	0.164	0.346
Recovery	**0.414**	0.073	**0.311**	0.096	0.079	0.309
Requirements	**0.662**	0.466	0.213	0.221	0.074	0.331
Suppliers	**0.679**	0.318	0.168	0.283	0.197	0.310
Technology	**0.719**	0.284	0.461	0.281	0.208	0.435
Ecodesign	**0.527**	**0.669**	0.401	0.418	0.133	0.263
Market	0.467	**0.806**	0.266	0.434	0.196	0.442
Marketing	0.475	**0.816**	0.167	0.383	0.254	0.282
Organizational	0.475	**0.802**	0.193	0.513	0.245	0.491
Product	0.305	**0.804**	0.252	0.500	0.252	0.314
Reduction	0.122	**0.486**	0.220	0.114	0.179	0.146
Disposal	0.304	0.093	**0.656**	0.180	0.251	0.351
Distribution	0.419	0.263	**0.774**	0.444	0.395	0.510
Prevention	0.167	0.010	**0.541**	0.189	0.290	0.399
Process	0.449	0.367	**0.703**	0.327	0.301	0.440
Reverse	0.083	0.139	**0.660**	0.354	0.336	0.313
Warehousing	0.377	0.061	**0.646**	0.242	0.339	0.390
Flexibility	0.342	0.406	0.362	**0.837**	0.380	0.392
Cost	0.257	0.426	0.470	**0.817**	0.426	0.323
Dependability	0.320	0.543	0.301	**0.822**	0.409	0.377
Quality	0.36	0.486	0.458	**0.840**	0.382	0.406
Service	0.322	0.540	0.361	**0.831**	0.405	0.392
Profit	0.245	0.245	0.446	0.461	**0.893**	0.387
ROI	0.257	0.239	0.305	0.398	**0.844**	0.366
Satisfaction	0.322	0.172	0.434	0.254	**0.602**	0.356
Compliance	0.284	0.154	0.435	0.198	0.384	**0.701**
Image	0.545	0.501	0.579	0.505	0.338	**0.924**
Share	0.361	0.344	0.292	0.161	0.487	**0.622**

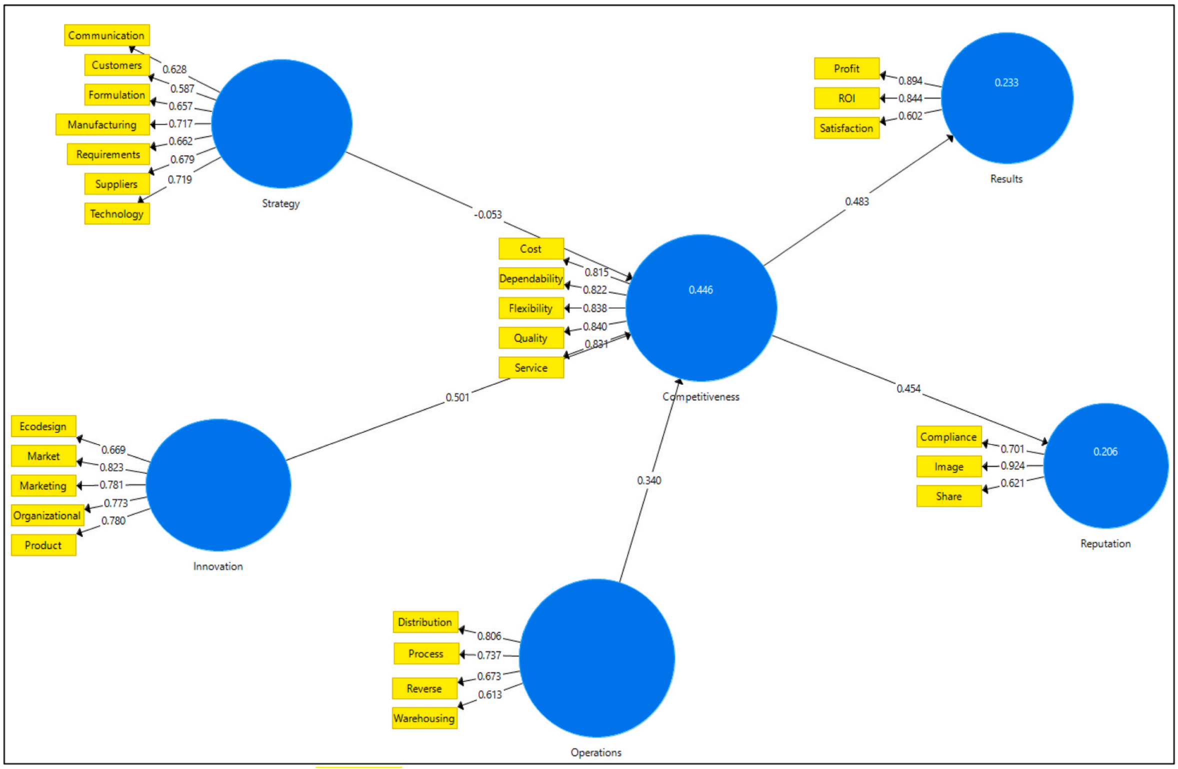

Fig. 5. Screen of the final SEM-PLS run.

Table 8
Path coefficient and hypotheses assessment.

Hypothesis/Path	Path coefficient	Standard deviation	*t*- statistics (>1.95)	*p*-value (<0.05)	Confidence interval 95%	Significant?	Hypothesis
H1: Strategy →Competitiveness	−0.053	0.099	0.534	0.593	[-0.260-0.112]	No	Not supported
H2: Innovation →Competitiveness	0.501	0.111	4.513	0.000	[0.293–0.705]	Yes	Supported
H3: Operations →Competitiveness	0.340	0.103	3.310	0.001	[0.099–0.515]	Yes	Supported
H4: Competitiveness →Results	0.483	0.093	5.192	0.000	[0.251–0.630]	Yes	Supported
H5: Competitiveness →Reputation	0,454	0.082	5.531	0.000	[0.257–0.577]	Yes	Supported

inclusion and exclusion of each exogenous construct. Equations (5) and (6) calculate the f^2 and q^2 size effect. Table 9 presents both.

$$f^2 = \frac{R^2_{included} - R^2_{excluded}}{1 - R^2_{included}} \tag{5}$$

$$q^2 = \frac{Q^2_{included} - Q^2_{excluded}}{1 - Q^2_{included}} \tag{6}$$

Finally, regarding circular economy concerns, local GSCM implementations have enabled the local cement industry to replace about 35% of coal's calorific value with biomass from the rice industry. This shift has brought significant economic and environmental benefits, reducing transatlantic logistics by 10%. Annually, around 20,000 tons of biomass, formerly sent to landfills, now fuel kilns. Excess biomass is used in local boilers for thermal energy, with ash employed as a mortar additive in regional construction.

Table 9
f^2 and q^2 size effect.

Path	f^2 effect	q^2 effect
Competitiveness →Reputation	0.259 (large)	–
Competitiveness →Results	0.304 (large)	–
Innovation →Competitiveness	0.312 (large)	0,146 (intermediate)
Operations →Competitiveness	0.161(intermediate)	0,078 (intermediate)
Strategy →Competitiveness	0.003 (null)	0,000 (null)

5. Discussion

5.1. Feedback from practitioners

Results were presented to local practitioners, as indicated by the union and experts who had previously refined the measurement model. Discussions addressed the eliminated variables and the model structure.

The excluded variables are performance, recovery, reduction, disposal, and prevention. Practitioners noted that companies lacked formal systems for measuring environmental performance. Many adhered only to mandatory standards without comprehensive monitoring systems for indicators, indices, historical data, trends, projections, and decision support. This gap presents an opportunity for sector improvement.

For recovery, there was concern about the question's clarity due to common industry practices like retrofitting and corrective maintenance of obsolete equipment. Future questionnaires should refine the wording to enhance clarity. For reduction and prevention, respondents found the questions similar and unclear. Reduction addresses existing pollution sources, while prevention focuses on avoiding new pollution sources. The industry demonstrates a strong commitment to pollution prevention, especially with rice husk waste, which is mostly used by local cement factories (Sellitto et al., 2013). Future applications should unify these questions for better clarity. For disposal, most waste is reused, with minimal landfill transfer. Future questions should emphasize non-industrial waste and specify disposal related to municipal solid waste management.

Regarding the model structure, a reevaluation of the hypotheses is necessary. Only H1, which posits that a greening strategy positively impacts competitiveness, is unsupported. Future research should explore why this hypothesis is not supported. The data substantiate the remaining hypotheses. Practitioners were initially surprised, given the widespread environmental concerns in most companies. A possible explanation is that companies may need to incorporate a greening strategy into their strategic planning explicitly. Consequently, environmentally favorable outcomes may not be seen as the result of targeted efforts but rather as byproducts of broader strategies, such as those addressing commercial, legal, and financial goals. Additionally, none of the seven original indicators within the construct show a loading greater than 0.707, suggesting potential ambiguity in the questions. Further research is needed to understand why this construct does not contribute to competitiveness in the industry, and new indicators should be identified to improve its reliability.

5.2. Comparison with the literature and implications

The use of rice husks as secondary fuel in the cement industry aligns with circular economy principles. The practice was observed in the study and examined through a database search, which identified twelve recent high-impact articles. Notably, among others, Kahawalage et al. (2023) discuss the application of rice husks and other biomass types sourced by the AFSC, highlighting their role in reducing the industry's ecological footprint. The study reinforces our results.

Regarding the constructs, prior studies (Herrmann et al., 2021; Sellitto and Hermann, 2016) suggest using a tree-like structure with three constructs—strategy, innovation, and operations—as measurement models for GSCM analysis in AFSC. However, during discussions, participants observed that the terms 'innovation' and 'operations' might no longer accurately reflect their content due to changes in variable allocation. They proposed renaming both to 'Customer Relationships' and 'Logistics.' This study, therefore, suggests an alternative structure that broadens the constructs and is better suited for future research: strategy, customer relationships (encompassing more than innovation), and logistics (more focused than operations). While these changes fit the rice industry's specific context, their relevance in other industries remains uncertain.

Regarding the relationship between GSCM, competitiveness, the rice industry, and circular practices, only one recent high-impact study was found (Nguyen et al., 2021). This study used three constructs—internal green processes, customers, and suppliers—which align with our constructs of green strategy, customer relationships, and logistics. However, Nguyen et al.'s model focuses solely on environmental performance, omitting financial and reputational outcomes. A practical implication is the development of a framework to help agrifood industry practitioners enhance competitiveness by optimizing green practices within their SCs.

Participants highlighted the unconfirmed hypothesis, suggesting leaders may be unaware of the effectiveness of a specific greening strategy. A key implication of the study emphasizes the need for a dedicated strategic plan for AFSC greening, including clear objectives, methodologies, resource allocation, assigned personnel, and a system for measuring environmental performance, along with historical data storage for informed decision-making. Establishing a consistent database could aid in integrating AI and machine learning techniques currently recognized in agribusiness (Schmidt et al., 2024). The four confirmed hypotheses reinforced the importance of customer relationships and logistics operations for industry competitiveness. Additionally, the audience was not surprised with the material and immaterial outcomes reflected in the results and reputation constructs.

An additional implication suggests enhancing visibility for ongoing industry initiatives focused on pollution prevention and reduction, such as using biomass waste for renewable energy. Beyond reducing pollution, adopting biomass as a secondary fuel in the industry decreases dependence on fossil energy sources like coal.

Finally, a theoretical implication is the potential use of customer relationships and logistics constructs instead of innovation and operations in future AFSC applications, with some indicators possibly requiring updates. Another theoretical implication suggests that while a green strategy alone may not drive competitiveness, integrating green innovation and operations can enhance it.

6. Conclusion

The purpose of this study was to evaluate the influence of Green Supply Chain Management (GSCM) dimensions on the performance of the agrifood supply chain, with a specific focus on the rice industry in southern Brazil.

The research method involved surveying industry companies. A questionnaire was sent to 322 companies, yielding 92 valid responses (28.5% return rate). The findings support all but one hypothesis. The unsupported hypothesis suggests that a green strategy does not necessarily enhance competitiveness in the industry. In contrast, the confirmed hypotheses show that green innovation and green operations positively contribute to competitiveness. Additionally, competitive companies are linked to positive outcomes and a strong reputation within the industry.

Further efforts should focus on addressing the unsupported hypothesis. The hypothesis's refutation indicates that green practices currently do not lead to improved outcomes and reputation, possibly due to disorganized or absent implementation of key GSCM pillars by individual companies. Two strategic initiatives are recommended under the local industry union's guidance. The first should provide technical support for implementing green practices, as outlined in Herrmann et al. (2021), involving strategy development, green requirements, supplier collaboration, green manufacturing, and cleaner production technologies. The second should promote the importance of a circular economy to enhance the industry's image. These initiatives can significantly improve both outcomes and reputation. The primary managerial implication is the need for theoretical support for these strategic movements within the industry.

The study opens avenues for further research. Case studies should explore why companies lack or fail to perceive the integration of greening strategies in their operations and examine the prerequisites for formulating and implementing formal greening strategies. Additionally, a similar survey should be conducted in another significant AFSC in southern Rio Grande do Sul, specifically the peach AFSC. Pair-wise results are expected due to the overlap in retailing and distribution between these industries.

CRediT authorship contribution statement

Miguel Afonso Sellitto: Writing – review & editing, Methodology, Conceptualization. **Felipe Fehlberg Herrmann:** Writing – original draft, Investigation, Data curation. **Marcelo Fernandes Pacheco Dias:** Data curation. **Gislene Salim Rodrigues:** Visualization, Validation. **Maria Angela Butturi:** Writing – review & editing, Visualization, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPTin and Grammarly to improve readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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