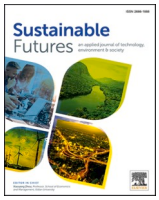
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Strategic green supplier selection to mitigate supply chain emissions: A Sustainability multidimensional approach

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ABSTRACT

Companies are increasingly required to reduce emissions across their supply chains, making green supply chain management practices – such as sustainable supplier selection – crucial for improving environmental performance. However, obtaining reliable supplier-level emissions data is often costly and limited, creating the need to identify alternative, publicly available sustainability indicators that may serve as preliminary screening signals.

This study addresses this gap by analysing a multidimensional dataset including economic, social, governance, and emissions metrics from 684 suppliers of an Italian ceramic company. Methodologically, the study combines a disjoint Principal Component Analysis, which extracts four conceptually distinct dimensions that jointly account for 67.4 per cent of the total variance, with a Generalized Additive Model (GAM) to examine the relationship between sustainability dimensions and emissions across different supplier sectors, allowing for a non-linear specification of the economic dimension.

The findings provide novel evidence that these relationships are sector-dependent within the same supply chain. The economic dimension is associated with emissions through a non-linear form common to all sectors, and its positive association is significantly stronger among material-processing suppliers ($\beta = 2.597$, $p < 0.01$). Stronger governance is associated with lower emissions in services ($\beta = –0.280$, $p < 0.01$), whereas social sustainability shows no significant association in logistics and an unexpected positive association in services.

These results highlight that the association of ESG dimensions with emissions is not uniform but varies systematically by sector, offering more precise insights for sustainable supplier management. Overall, the study contributes to the literature by proposing a sector-sensitive analytical approach and providing actionable implications for firms facing pressure to reduce supply chain emissions under data constraints. These dimensions are proposed as first-order screening heuristics that complement, rather than replace, direct supplier-level emissions measurement.

1. Introduction

Stakeholders, such as clients and regulators, pressure companies to assume responsibility for the emissions of their entire supply chains [1–5]. Indeed, in an Environmental, Social, and Governance (ESG) perspective [6–9] there is increasing awareness that most global emissions do not originate from single companies' production activities but rather from their (globalised) supply chains [10].

Green Supplier Selection [11,12] is a strategy that, through the measurement of environmental performance, allows for the identification of suppliers with lower emissions. Green supplier selection requires data on suppliers' emissions and, in exchange, enables the purchasing company to reduce the overall emissions of its supply chain [3,13–15].

However, most existing literature on green supplier selection [3, 13–15] assumes the public availability and easy accessibility of supplier emissions data. In reality, obtaining reliable emissions data from suppliers is often hampered by technical and political challenges, resulting in high difficulty or cost for the buying company [16,17].

Economic, social and governance sustainability data, on the other hand, are largely more available on public databases compared to emissions data [18].

This paper aims to explore the effects (if any) of economic, social and governance sustainability on emissions in order to analyse possible alternative variables that the buying company can implement to select

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green suppliers [19,20], when suppliers' emissions are not available [16,17]. The paper focuses on sustainability dimensions, such as economic, social, governance and environmental, supported by a vivid stream of literature that has been studying the existing interconnections between sustainability dimensions [16,21,22].

In addition, the paper considers suppliers' industrial sectors separately to capture the possible variability in emissions [23] and to identify sector-specific patterns on suppliers' emissions.

To address the aim of the paper, a unique longitudinal dataset was compiled with economic, social, governance, and emissions data for 684 suppliers of a large Italian ceramic company. The ceramic supply chain is increasingly focused on the issue of emissions, driven by the regulatory framework established by the European Union's Climate Change and other Sustainability initiatives [1]. The Italian case is relevant as Italy and Spain are the most significant EU ceramic tile producers [24].

The data were analysed in two steps. First, an exploratory factor analysis [25] was conducted to identify composite indicators (factors) for economic, social, and governance dimensions. In the second, a generalized additive model was estimated to analyse the association of economic, social, and governance dimensions with emissions in each sector, such as logistics, material processing and services.

Findings reveal that economic sustainability is associated with higher emissions in the material-processing sector, while stronger sustainable governance is associated with lower emissions in the services sector. Social sustainability, by contrast, shows no statistically significant association with emissions in the logistics sector. These findings suggest that the multidimensional approach of sustainability evaluation can identify different effects on suppliers' emissions in the ceramic supply chain depending on the suppliers' industrial sector.

Given its findings, this study contributes to green supplier selection theory and practices in three main ways.

First, from a theoretical point of view, this paper suggests the literature on the role of green supplier selection in reducing supply chain emissions [3,13–15] that suppliers' emissions data can be unavailable to the buying company in many cases. Since green supplier selection requires reliable data [14], the lack of suppliers' emissions data could prevent the buying company from benefiting from green supplier selection.

Second, from a conceptual standpoint, this paper introduces a multidimensional sustainability framework where economic, social, and governance performances are associated with the emissions levels of suppliers and, consequently, can be implemented when emissions data are unavailable. The framework highlights that these effects are sector-contingent where economic sustainability serves as a screening heuristic in material processing, and governance sustainability in services, while social sustainability does not show a significant association in logistics. Furthermore, using sector-specific sustainability metrics can enhance supply chain sustainability disclosure required by recent reporting regulations [1].

Third, the paper confirms the relevance of considering the mutual interdependencies of sustainability dimensions [16,21,22] and of considering the suppliers' sector [23] when implementing suppliers' selection.

From a decision-support perspective, the paper offers preliminary screening heuristics that buying companies can employ when direct emissions data are unavailable. These heuristics should be understood as first-order approximations that complement, rather than replace, direct emissions measurement [18]. Furthermore, using sector-specific sustainability metrics can support supply chain sustainability disclosure required by recent reporting regulations [1].

The rest of the paper is structured as follows. The second section introduces the literature on supply chain emissions management. The third section presents hypothesis development. Subsequently, the fourth section illustrates the materials and methods of the paper. The fifth section describes the analysis results, while the last section collects the discussion and the conclusions.

2. Literature review: supply chain emissions management

Emissions, which include carbon dioxide (CO2), methane (CH4), and ammonia (NH3) produced by human activities, are a significant contributor to the deterioration of the atmospheric ecosystem, leading to climate change and global warming [26]. Moreover, emissions are linked to severe health issues, including cancer, threatening human well-being [27].

In recent years, the awareness of the importance of ESG practices has increased [6–9]. ESG roots in stakeholder theory [2] and the Triple Bottom Line approach [7] and evaluates how companies manage environmental impacts, social responsibilities, and corporate governance practices. Research has shown that strong ESG performance is associated with superior long-term organisational outcomes [6], positive financial performance [8], and enhanced value creation when sustainability issues are material to the business [9].

Moreover, the public and stakeholders' pressure has extended to companies' supply chains' emissions reduction [3–5]. Indeed, it has been studied that most global emissions do not originate from single companies but from their supply chains [10,28]. The growing recognition that a substantial share of global emissions originates not from individual firms but from their upstream and downstream supply chains [10,28] has intensified pressure on companies to extend their environmental accountability beyond organisational boundaries.

Stakeholders, such as clients, and the regulation [1] require companies to activate due diligence processes to identify and resolve adverse impacts on the human and the environment of their worldwide suppliers.

One possible approach to address this requirement is to design and adopt green supplier selection [3,13–15]. This approach is based on the idea that managerial practices, such as supplier selection [11,12], can contribute not only in providing the company with economic performance but also to address legitimacy objects such as the supply chain emissions reduction.

Green Supplier Selection [11,12] has emerged as a prominent supply chain management strategy aimed at improving environmental sustainability by incorporating environmental performance criteria into supplier evaluation and selection processes. Through the systematic assessment of suppliers' environmental performance, firms can identify and prioritise business partners characterized by lower levels of greenhouse gas emissions and reduced environmental impacts. Although the implementation of green supplier selection practices requires the availability of reliable emissions-related information from suppliers, such practices can significantly contribute to the reduction of the overall carbon footprint of the supply chain and support the achievement of broader corporate sustainability objectives [3,13–15].

Despite the growing body of research on green supplier selection, the existing literature largely assumes that suppliers' emissions data are readily available, transparent, and easily accessible to buying firms [3, 13–15]. Such an assumption may not adequately reflect the realities faced by organisations in practice. The collection of accurate and comparable emissions data often presents substantial challenges due to technical limitations, inconsistencies in reporting methodologies, varying levels of supplier disclosure, and potential political or strategic reluctance to share sensitive environmental information. Consequently, obtaining reliable emissions data may entail significant costs and resource commitments for buying firms, thereby limiting the practical applicability of emissions-based supplier selection approaches [16,17].

In contrast, sustainability-related information concerning economic, social, and governance dimensions is generally more widely available through public databases, sustainability reports, and ESG disclosure platforms than direct emissions data [18]. This greater availability raises an important research question regarding the extent to which these sustainability dimensions may be associated with suppliers' environmental performance. Accordingly, this study investigates the relationship between economic, social, governance, and environmental

sustainability indicators and suppliers' emissions levels. The objective is to assess whether publicly available sustainability information is related to emissions data and therefore support buying firms in identifying environmentally responsible suppliers when direct emissions information is unavailable or difficult to obtain [19,20].

The analysis is grounded in a well-established stream of sustainability literature that highlights the interdependencies and mutual influences among different sustainability dimensions. Previous studies have increasingly emphasized that economic, social, governance, and environmental performance should not be considered in isolation, as improvements in one dimension may be related to outcomes in others [16,21,22]. Building on this perspective, the present research explores whether these interconnections can provide useful insights for supplier evaluation and selection decisions.

Furthermore, the study explicitly accounts for sectoral heterogeneity by analysing suppliers across different industrial sectors. This distinction is particularly relevant because emissions profiles, production processes, regulatory pressures, and sustainability practices often vary considerably among industries. By examining suppliers on a sector-specific basis, the research aims to capture these differences and identify whether the relationship between sustainability dimensions and emissions is contingent upon industry characteristics. Such an approach contributes to a more nuanced understanding of suppliers' environmental performance and may facilitate the development of more effective and context-sensitive green supplier selection practices [23].

3. Hypotheses development

The study explores possible effects on suppliers' emissions [19] by considering the various suppliers' industrial sectors [23]. The analysis concentrates on the ceramic industry and proposes a segmentation of the ceramic supply chain, including sectors such as material processing [29], logistics and services [30].

3.1. The effect of the economic performance on emissions in the ceramic tiles supply chain

The existing research indicates a correlation between increased economic activity and high emissions levels [31–33]. However, the relationship between firms' economic sustainability and emissions levels strongly depends on the sector to which firms belong [23]. We expect that economic sustainability is decoupled from emissions in those sectors where the value added is not connected with producing or processing materials. For example, the delivered output is intangible and based on services and knowledge in the services and logistics sector. Differently, in the material-processing sector [34,35], it can be expected that economic performance and emissions are somehow more connected [36]. In material-processing industries, economic growth is mechanically linked to emissions through the throughput mechanism (Fig. 1): higher production volumes require greater energy consumption and raw material transformation [37,38].

Therefore, we hypothesise that the economic sustainability dimension is positively related to emissions levels for suppliers operating in the material-processing sector of the ceramic tiles supply chain. Differently, we expect economic performance to be decoupled from, or even inversely related to, emissions in the services and logistics sectors, where value added is not tied to material processing.

Drawing on the presented arguments, the following research question is developed:

H1: Economic sustainability is positively associated with emissions for material-processing suppliers within the supply chain.

3.2. The effect of social sustainability on mitigating emissions in the ceramic tiles supply chain

The significance of social sustainability in contemporary supply chains is a prominent theme in academic research [11,39–41]. Industries such as fashion and food have faced demands to disclose the social conditions of workers within their extensive global production and logistics networks [42]. However, there remains a limited understanding of the social factors affecting sustainable supply chain management practices [43].

Amid heightened awareness of the social impacts of logistics operations [44–46], stakeholders within and outside organisations advocate for logistics practices that adhere to socially sustainable development [47].

From a theoretical perspective, the social license to operate framework [48] suggests that logistics firms facing heightened social scrutiny over working conditions tend to adopt broader operational improvements that simultaneously address environmental performance. Firms that invest in employee welfare, reduce turnover, and improve working conditions typically also invest in operational efficiency improvements such as route optimisation, fleet modernisation, and load consolidation that reduce emissions as a co-benefit [49]. Conversely, firms characterised by exploitative social practices (high turnover, low wages, excessive productivity demands) tend to prioritise short-term cost reduction over operational efficiency, leading to higher emissions intensity (Fig. 2).

The market pressure to reduce shipping prices has been imposed on delivery companies, causing significant stress on their employees [50]. Thus, the logistics industry has recently been concentrating more on social aspects than on the issue of emissions reduction [49].

For this reason, we hypothesise that social sustainability in the logistics sector is associated with lower emissions:

H2: Social sustainability practices are associated with lower emissions of logistic suppliers within the supply chain.

3.3. The effect of governance sustainability on mitigating emissions in the ceramic tiles supply chain

The service sector, often regarded as having relatively low emissions, demonstrates significant responsiveness to environmental challenges, notably in emissions mitigation [51]. For example, Microsoft Corporation has sustained efforts to quantify and manage its carbon footprint

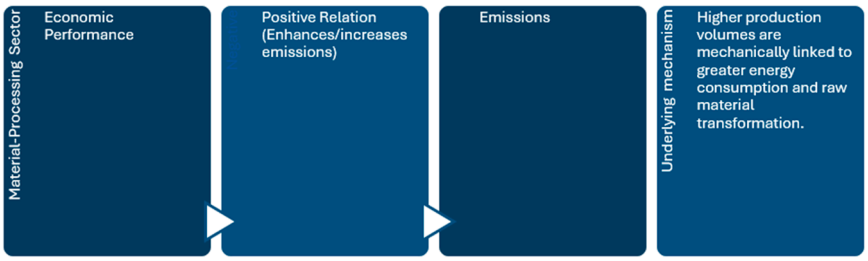


Fig. 1. Conceptual diagram explaining the relationship between economic performance and emissions in the material-processing sector. Source: Authors' elaboration.

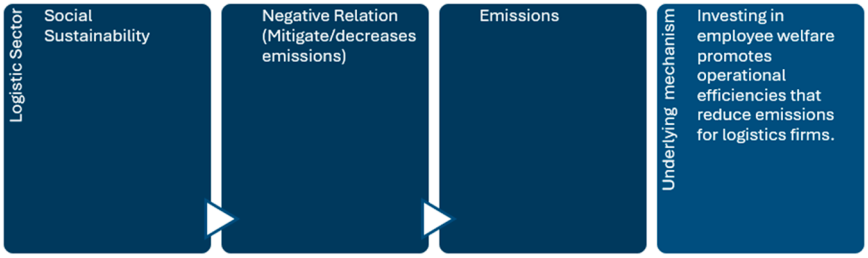


Fig. 2. Conceptual diagram explaining the relationship between social sustainability and emissions in the logistic sector. Source: Authors' elaboration.

[52]. Indeed, some authors advance the idea that the "decoupling relationship between emissions and the economic development in the services sector is conducive to promoting sustainable development" ([53], p. 63). The decoupling between economic output and emissions in services [53] creates space for strategic discretion as service firms' environmental footprint is substantially shaped by managerial decisions regarding energy procurement, office operations, and supplier management.

The current attention of the services sector on emissions-related issues is connected with top managers' accumulated knowledge, attitudes and culture regarding the relevance of these issues [32,54,55]. Studies investigating this relationship include various aspects of corporate governance, including the size and independence of the board [56] and gender diversity [57]. Adequate governance fosters improved decision-making processes [58], encompassing deliberations on capital expenditure and the disclosure of carbon emissions [32]. Drawing on the corporate governance–environmental disclosure literature [32,56], governance quality in service firms reflects top management commitment to environmental responsibility. Board diversity [57], managerial oversight [59], and institutional longevity [60] foster decision-making environments that integrate environmental considerations into strategic planning (Fig. 3).

Based on this argumentation, we develop our third hypothesis:

H3: Governance sustainability practices are negatively associated with emissions levels for service suppliers within the supply chain.

Finally, Fig. 4 summarises the research hypothesis.

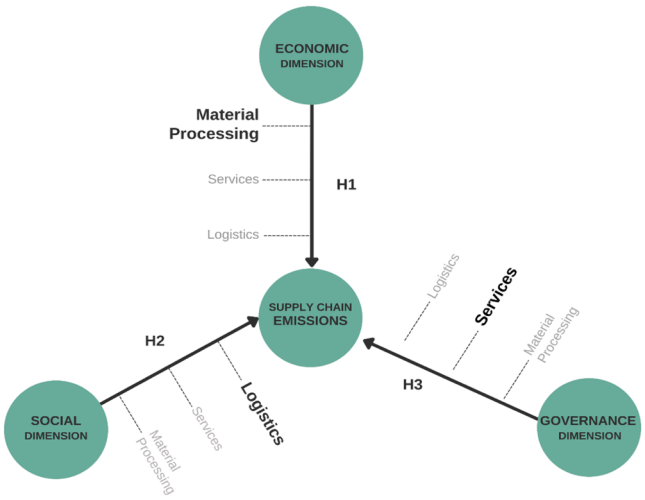


Fig. 4. Summary of the research hypotheses.

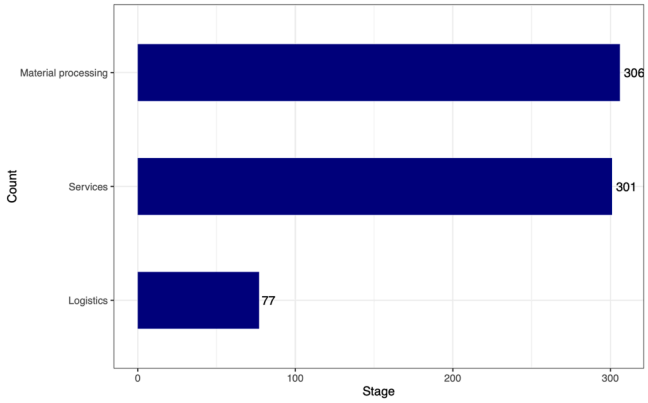


Fig. 5. Suppliers of the sample are divided by sector.

4. Material and methods

4.1. Context

The empirical data is represented by a primary dataset collected by the authors. In particular, the dataset includes economic, social, governance and environmental sustainability data related to all the suppliers, divided by sector (see Fig. 5) of the supply chain of a large Italian ceramic tiles company, covering the entire life cycle of the product [34].

The choice to concentrate on the ceramic supply chain was driven by the fact that the ceramic industry is considered a high-carbon industry [61], and companies are increasingly under pressure from stakeholders, such as clients and regulators, to extend emissions measurement and management to all their suppliers. Like other sectors, the ceramic industry is currently pressured to reduce supply chain emissions by the

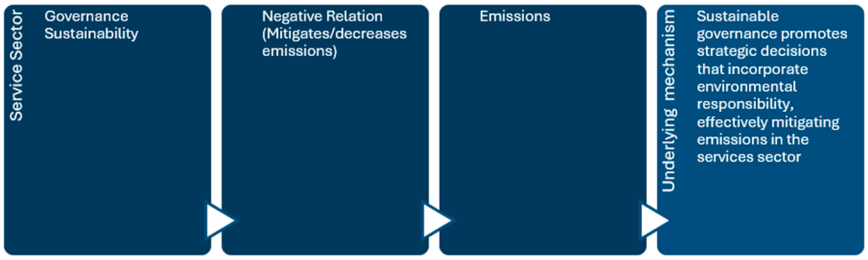


Fig. 3. Conceptual diagram explaining the relationship between governance sustainability and emissions in the service sector. Source: Authors' elaboration.

regulatory framework established by the European Union's Climate Change and other Sustainability initiatives ([1]; 2003/87/EC, 2009/29/EC, and 2012/27/EU). The specific Italian case is relevant as Italy and Spain represent the largest European producers of ceramic tiles [24].

The ceramic production chain involves several suppliers due to the complexity of the process, which includes specialised phases. In the first phase, raw materials, such as clay and minerals, are extracted and processed. Most of these suppliers focus on transforming raw materials into ceramics through specific processing techniques. In addition, other suppliers in the second phase provide services such as planning/management activities, assisting with tile-lying projects and marketing. Finally, distribution involves logistics companies that handle the transportation of the final products.

4.2. Sample and data source

A total of 684 suppliers were identified through the ceramic company's management system (System Applications and Products in Data Processing - SAP). The supplier population represents the complete set of active suppliers recorded in the company's procurement system for the fiscal year 2021, ensuring comprehensive coverage of the supply chain rather than a sample subset. As shown in Table 1, descriptive statistics, suppliers analysed in this study are represented by companies characterised by broad heterogeneity in terms of economic size and performance.

Specifically (Fig. 5), suppliers involved in the material extraction and processing are identified as "Material processing" [29,30,34], suppliers involved in planning, financial accounting, personnel recruitment, product promotion and after-sales activities as "Services" [62], and suppliers involved in inbound and outbound logistics as "Logistics" [63]. It is important to note that these industrial sectors are mutually exclusive, meaning each supplier belongs to only one category.

The sample includes 15 data variables for each supplier regarding their economic, social, governance, and environmental performance.

Two primary sources were used to populate the variables of the dataset: the first one is Aida - Bureau van Dijk for social, governance and economic data and I.STAT for the carbon emissions data.

Specifically, concerning carbon emissions data, the computational methodology adopted is called NAMEA (National Accounting Matrix including environmental accounts), which collects the amount of emissions for various pollutants directly caused by each Standard Industrial Classification (SIC) code. All extracted data relate to the year 2021. This specific year was chosen to avoid any COVID-19-related exogenous shocks that might impact the considered variables.

4.3. Measures and variables

Given the research hypothesis, for each supplier, we have collected data on economic (ECO), employees' social sustainability practices (SOC), governance data (GOV), and carbon dioxide (CO2), methane (CH4) and ammonia (NH3) emissions (EM) as detailed in Table 2.

The economic dimension (ECO) is associated with widely established measures in the literature employing public accounting data [65]. As shown in Table 2, Rossi et al. [65] advanced a set of indicators concerning the economic dimension; the variables adopted can be divided into four main blocks: cost reduction, revenue generation, profitability and investment in technological innovation. Similarly, Braccini and Margherita [64] examined a manufacturing company's economic sustainability by considering EBITDA, sales and net profit.

Social dimension (SOC) is identified through some social responsibility variables. The systematic literature review of Luthin et al. [76] identifies employee-related social dimension variables among six human-centred sub-categories of social impact. In addition, other studies [68] have focused on social responsibility and wealth distribution (Table 2). For example, a higher cost per employee [SOC1] generally signals greater investment in the workforce and is associated with higher corporate social sustainability [67]. Similarly, a positive change in the added value per employee [SOC2] indicates improving labour productivity and value distribution toward employees, while a negative change typically signals that the social practices toward employees are deteriorating. Meanwhile, employee growth [SOC3] captures the firm's capacity to expand and retain its workforce, with positive growth generally reflecting more sustainable employment practices [68].

As for the governance dimension (GOV), the average age of the board of directors [GOV1] captures the experience and oversight capacity of

Table 2
Variables summary, description and theory-related features.

Variables	Computation	Group	Reference (s)
EBITDA [ECO1] *continuous variable*	EBITDA	ECO	[64–66]
Value added [ECO2] *continuous variable*	Value Added	ECO	[64–66]
Production costs [ECO3] *continuous variable*	Production costs	ECO	[64–66]
Cost per employee [SOC1] *continuous variable*	(Cost per employee 2021)	SOC	[67]
Δ Added value per employee *continuous variable* [SOC2]	(Added value per employee $_{t}$ – Added value per employee $_{t-1}$)	SOC	[67]
Employee growth [SOC3] *continuous variable*	(N. employees $_{t}$ – N. employees $_{t-1}$)	SOC	[68]
Average age of BoD members *continuous variable* [GOV1]	Average age of the members of the Board of Directors	GOV	[59]
N. of women on BoD [GOV2] *continuous variable*	N. of women on the Board of Directors	GOV	[32,69]
Firm longevity [GOV3] *continuous variable*	(2026 – Year of company foundation)	GOV	[60]
CO2 Emissions [EM1] *continuous variable*	CO2	EM	[70,71]
CH4 Emissions [EM2] *continuous variable*	CH4	EM	[72]
NH3 Emissions [EM3] *continuous variable*	NH3	EM	[73]
Control variables			
Revenues *continuous variable.*	Revenues		[74,75]
Industry *categorical variable*	1* = Logistics [LOG]; 2 = Material Processing [MP]; 3 = Services [SERV]		

Note(s): BoD = Board of Directors; Industry = 1 (Logistics) is the reference category.

Table 1
Summary of the suppliers.

	Obs.	Mean	St. Dev.	Min	Median	Max
Employees	684	273.5	1898.0	0.0	23.0	34,529.0
Total Assets (thousands of €)	684	70,440.3	742,118.6	–2897.2	1776.1	16,564,381.0
Total Value of Production (thousands of €)	684	105,959.2	702,456.5	105.3	6429.5	13,027,589.0
Profit / Loss for the year (thousands of €)	684	102,837.5	680,193.4	95.9	6159.1	12,396,902.0

the leadership team, since more mature boards are generally associated with greater managerial prudence and a longer-term strategic orientation [59]. Similarly, the number of women on the board of directors [GOV2] reflects the relevance of greater diversity in corporate decision-making, acknowledging that diverse perspectives can lead to better outcomes and higher sustainability [32,69]. Simultaneously, company longevity [GOV3] indicates its resilience and long-term perspective [60].

Emissions (EM) variables, considering their relevance for humans [77], include not only carbon dioxide but also methane (CH4) and ammonia (NH3). CH4 combustion, which occurs during the firing process of ceramic tiles, contributes substantially to emissions [72]. Moreover, NH3 is used as a chemical reagent in various phases of ceramic production, including synthesising ceramic materials and applying coatings. The use of ammonia in such chemical processes can lead to higher levels of emissions [78]. According to the United States Environmental Protection Agency (EPA), although CO2 emissions [EM1] are the leading cause of climate change, methane [EM2] and ammonia [EM3] play a crucial role in the environment and on human health. Methane was considered since, although it persists in the atmosphere for about ten years [79], it hurts nature and humans.

Descriptive statistics are reported in Table 3.

4.4. Data analysis

The richness of the sample allowed for the implementation of a two-step analytical procedure: (i) Disjoint Principal Component Analysis (disjoint PCA) and (ii) a Generalized Additive Model (GAM). The two techniques and their respective scopes are outlined below.

(i) Disjoint PCA: a constrained variant of PCA in which each observed variable is allowed to load on one, and only one, component, so that the resulting components do not share any underlying variable [80]. Unlike classical PCA, where loadings are generally non-zero across all components, disjoint PCA imposes a block-diagonal structure on the loading matrix, which substantially improves the interpretability of the extracted components when the aim is to synthesise conceptually distinct constructs, such as the Economic, Environmental, Social and Governance dimensions considered here. The number of components to retain within each conceptual block was determined according to the Kaiser criterion (eigenvalue > 1).

(ii) GAM: a flexible extension of the generalized linear model in which one or more predictors may enter through smooth, non-parametric functions rather than simple linear terms, while the remaining predictors retain a standard linear (parametric) specification [81]. The decision to model the Economic dimension through a smooth term, while retaining a linear specification for the Social and Governance dimensions, was guided by a preliminary bivariate inspection of each sustainability dimension against the emissions outcome (Fig. 6). As shown by the locally estimated (LOESS) trend lines, the Economic dimension displays a markedly non-monotonic, curvilinear relationship with emissions, departing substantially from the corresponding linear fit, whereas the Social and Governance dimensions closely track their respective linear fits, providing no clear evidence of non-linearity. This pattern motivated the asymmetric specification in which only the Economic dimension enters through a non-parametric smooth term (see Eq. (1)). The smooth was specified to capture only the nonlinear (curvature) component, with the linear component of the Economic dimension retained as a separate parametric term, avoiding concurvity between the two. Models were estimated via Restricted Maximum Likelihood (REML), and the smooth term was specified using a thin-plate regression spline.

To assess the out-of-sample performance of the adopted specification, we conducted repeated 10-fold cross-validation (50 repetitions) on the estimation sample, comparing the smooth model against an otherwise identical model in which the Economic dimension entered linearly. Both models were evaluated on identical folds (paired design), and predictive accuracy was summarised through the Root Mean Squared Error (RMSE) and the Mean Absolute Error (MAE).

$$EM_i = \beta_0 + f(ECO_i) + \sum_{j=1}^{p} \beta_j x_{ji} + \varepsilon_i,\ \ \varepsilon_i \sim N(0, \sigma^2) \tag{1}$$

where EM_i is emissions for supplier i (the dependent variable); β_0 is the intercept; $f(\cdot)$ captures the nonlinear component of the Economic dimension, whose linear component is retained as a separate parametric term (*ECO*); x_{ji} are the remaining parametric predictors – the linear Economic term (*ECO*), the Social (*SOC*) and Governance (*GOV*) dimensions, Revenues (*REV*), and the sector dummies for Material processing (*MP*) and Services (*SERV*), with Logistics (*LOG*) as the reference category – and β_j are the corresponding linear coefficients; ε_i is the error term, assumed Gaussian with zero mean and variance σ_2. Unlike a conventional linear regression, in which each predictor enters through a single slope coefficient, the Economic dimension enters through the smooth function $f(\cdot)$, whose shape is estimated directly from the data rather than imposed a priori. The smooth is specified to capture only curvature, so that the linear economic effect is identified solely by the parametric term ECO and its sector interaction, avoiding concurvity between the two.

Preliminary diagnostic checks on a linear baseline specification, together with the bivariate inspection reported above, indicated a departure from linearity in the Economic dimension. A smooth term for the Economic dimension was therefore introduced; an F-test confirmed that this significantly improved model fit over the linear baseline ($F = 90.69$, $p < 0.001$), justifying the use of a generalized additive model (GAM) framework for the stepwise specifications (Models 1–5). Using component scores as predictors within this framework requires adherence to specific assumptions, namely the absence of concurvity and the adequacy of the basis dimension [81]. Because the components extracted through disjoint PCA are constructed from non-overlapping sets of

Table 3
Descriptive statistics of the variables.

	Obs.	Mean	SD	Min	Median	Max
EBITDA	684	18,567.2	141,028.5	–16,642.0	757.8	2585,169.0
Value Added	684	38,713.7	236,429.7	–785.2	2312.7	5038,134.0
Production Costs	684	132,452.8	796,325.9	30.9	8348.9	17,558,309.0
Cost per employee	684	5747.7	9834.3	–35,720.0	4660.0	70,060.0
Δ Added value per employee	684	23,884.4	40,119.3	–260,870.0	16,485.0	282,590.0
Employee growth	684	341.6	1879.1	0.0	31.0	34,529.0
Average age of BoD members	684	55.4	9.2	0.0	55.3	85.0
N. of women on BoD	684	0.5	1.0	0.0	0.0	11.0
Firm longevity	684	29.2	18.2	3.0	26.0	106.0
CO2 Emissions	684	12,941.8	68,148.8	0.0	206.4	1397,021.1
CH4 Emissions	684	12.6	109.8	0.0	0.0	2554.5
NH3 Emissions	684	0.3	1.3	0.0	0.0	19.2

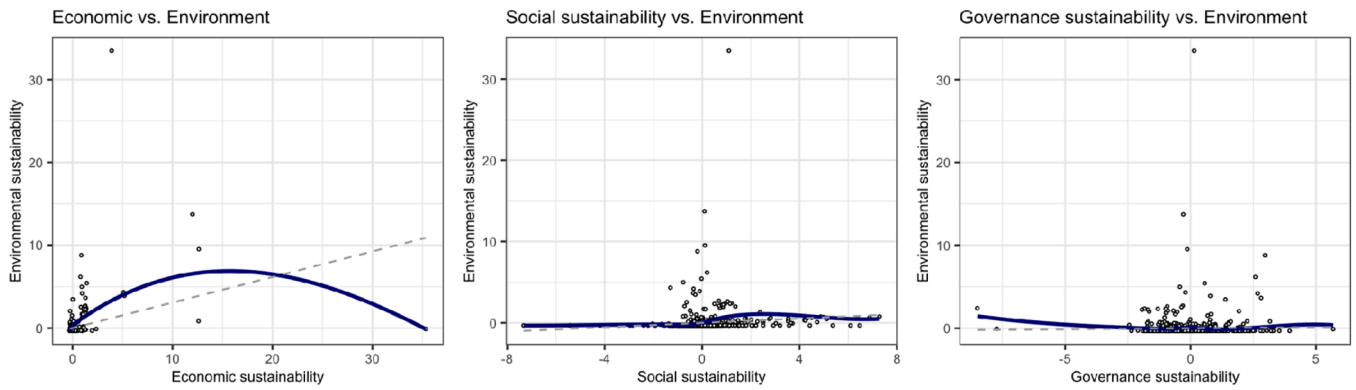


Fig. 6. Bivariate relationships between each sustainability dimension (Economic, Social, Governance) and environmental sustainability.
Notes: Solid dark blue lines show locally estimated (LOESS) trends; dashed grey lines show the corresponding linear fit.

variables, collinearity among them is negligible by construction. Accordingly, diagnostics confirmed that the smooth term for the Economic dimension was not explainable by the remaining parametric predictors (estimated concurvity = 0.00). Finally, the basis dimension of the smooth term was verified via gam.check(), which indicated an adequate number of basis functions (k-index = 1.06, $p = 0.94$). These diagnostic assumptions were consistently checked and met throughout the analysis.

H1 was tested through the following model (Model 3):

$$EM_i = \beta_0 + f(ECO_i) + \beta_1 ECO_i + \beta_2 SOC_i + \beta_3 GOV_i + \beta_4 REV_i + \beta_5 MP_i + \beta_6 SERV_i + \beta_7 (ECO_i \times MP_i) + \varepsilon_i \quad (2)$$

H2 was tested through the following model (Model 4):

$$EM_i = \beta_0 + f(ECO_i) + \beta_1 ECO_i + \beta_2 SOC_i + \beta_3 GOV_i + \beta_4 REV_i + \beta_5 MP_i + \beta_6 SERV_i + \beta_7 (ECO_i \times MP_i) + \beta_8 (SOC_i \times LOG_i) + \beta_9 (SOC_i \times SERV_i) + \varepsilon_i \quad (3)$$

H3 was tested through the following model (Model 5):

$$EM_i = \beta_0 + f(ECO_i) + \beta_1 ECO_i + \beta_2 SOC_i + \beta_3 GOV_i + \beta_4 REV_i + \beta_5 MP_i + \beta_6 SERV_i + \beta_7 (ECO_i \times MP_i) + \beta_8 (SOC_i \times LOG_i) + \beta_9 (SOC_i \times SERV_i) + \beta_{10} (GOV_i \times SERV_i) + \varepsilon_i \quad (4)$$

5. Results

5.1. Disjoint principal component analysis results

The disjoint Principal Component Analysis extracted four components, one for each conceptual block (Economic, Environmental, Social and Governance), in line with the Kaiser criterion applied separately within each block. The four components jointly account for 67.4 per cent of the total variance of the twelve underlying variables (Table 4). Unlike classical PCA, each component is constructed exclusively from the variables belonging to its own conceptual block, so that PC1 (Economic) is defined only by EBITDA, value added and production costs; PC2 (Environment) only by CO2, NH3 and CH4 emissions; PC3 (Social) only by cost per employee, added value per employee and employee growth; and PC4 (Governance) only by the average age of the board of directors, the number of women on the board, and firm longevity.

Table 4
Disjoint PCA – explained variance by block.

	PC1 (Economic)	PC2 (Environment)	PC3 (Social)	PC4 (Governance)
Proportion of total variance	0.228	0.220	0.123	0.104
Cumulative variance	0.228	0.448	0.571	0.674

The disjoint loading matrix shows that, by construction, each variable loads exclusively on the component corresponding to its conceptual block, with all other loadings constrained to zero (Fig. 7). The Economic component (PC1) is defined by EBITDA, value added and production costs, with loadings of 0.571, 0.600 and 0.560 respectively. The Environmental component (PC2) is defined by CO2, NH3 and CH4 emissions, with loadings of 0.610, 0.561 and 0.560. The Social component (PC3) is defined by cost per employee, added value per employee and employee growth, with loadings of 0.590, 0.580 and 0.561. The Governance component (PC4) is defined by the average age of the board of directors, the number of women on the board, and firm longevity, with loadings of 0.522, 0.531 and 0.668, all positive, indicating that higher scores on this component consistently reflect more mature, gender-diverse and longer-established governance structures.

Overall, the four extracted components provide a parsimonious and interpretable representation of the underlying Economic, Environmental, Social and Governance dimensions, and are retained for the subsequent GAM analysis (Fig. 7).

As shown in Fig. 7, the block-diagonal structure of the loading matrix indicates that the Economic (ECO) dimension encompasses three economic variables (EBITDA, value added and production costs), associated with higher levels of financial performance. The Governance (GOV) dimension encompasses three variables (average age of the board, number of women on the board, and firm longevity) that can contribute to sustainable governance practices. Within the Social (SOC) factor, three variables (cost per employee, added value per employee and

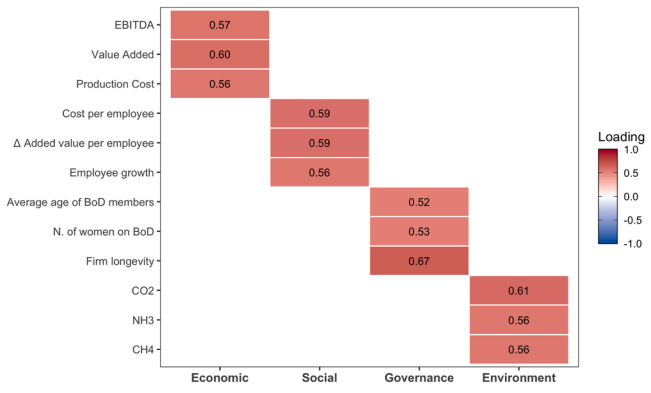


Fig. 7. Disjoint PCA component loadings.

employee growth) are synthesised, reflecting practices concerning employees [68]; all three variables load with a positive sign, indicating that the social dimension captures more sustainable practices towards employees. Lastly, the Environmental dimension (EM) encompasses three distinct emissions measures (carbon dioxide, methane and ammonia), indicating their contribution to general emissions in the air.

5.2. Regression results

In this section, the results of the hierarchical GAM analysis are presented. The GAM analysis served to test our hypotheses H1, H2 and H3. The effect of each sustainability dimension (ECO, GOV, SOC) on supply chain emissions levels (EM) was tested within the three different suppliers' industrial sectors. The model is estimated hierarchically across five specifications: Model 1 includes the parametric main effects of the three sustainability dimensions, with the Economic dimension entered as a smooth term; Model 2 adds the suppliers' sector dummies; Model 3 adds the interaction between the Economic dimension and the material-processing sector; Model 4 adds the interactions between the Social dimension and the logistics and service sectors; and Model 5 adds the interaction between the Governance dimension and the service sector.

Consistent with the preliminary diagnostic checks detailed in Section 4.4, the smooth specification provided a superior fit compared to a linear baseline, achieving a substantially lower Akaike Information Criterion (AIC – 2222.36 versus 2452.87). Beyond in-sample fit, the smooth specification also outperformed its linear counterpart out of sample on both criteria. Averaged across repetitions, cross-validated errors were lower for the smooth model (RMSE = 0.69; MAE = 0.26) than for the linear model (RMSE = 0.97; MAE = 0.37). The paired smooth-minus-linear differences were stable and consistently favourable: their 95% intervals lay entirely below zero for both metrics (ΔRMSE: median –0.27, 95% interval [–0.40, –0.15]; ΔMAE: median –0.10, 95% interval [–0.12, –0.08]). This indicates that the non-linear specification of the Economic dimension not only improves in-sample fit but also generalises to held-out observations, corroborating the choice of a smooth functional form over a purely linear one (see Fig. 8).

Having established the robustness of the GAM specification, Table 5 reports the estimation results used to test the research hypotheses. Note that across all specifications, one of the three supplier sector dummies was excluded from the regression equation to avoid perfect multicollinearity [82]. Table 6.

H1 states that economic sustainability is positively associated with emissions for material-processing suppliers within the supply chain. The GAM output (Model 5) shows that the economic–emissions association is markedly more positive in material processing than in the reference (logistics) sector, as captured by a positive and significant interaction ($\beta = 2.597$, $p < 0.01$). This result supports H1. The linear component of the economic dimension is itself negative and significant (β = –0.640, $p < 0.01$): because the economic slope is allowed to differ in material processing through the interaction term, this coefficient reflects the linear economic–emissions association in the non-material-processing sectors, where, net of the smooth term, stronger economic sustainability is associated with lower emissions. Combined with the positive interaction in material processing, the total linear economic slope thus reverses across sectors: negative outside material processing and positive within it, consistent with the throughput logic motivating H1 (Fig. 1).

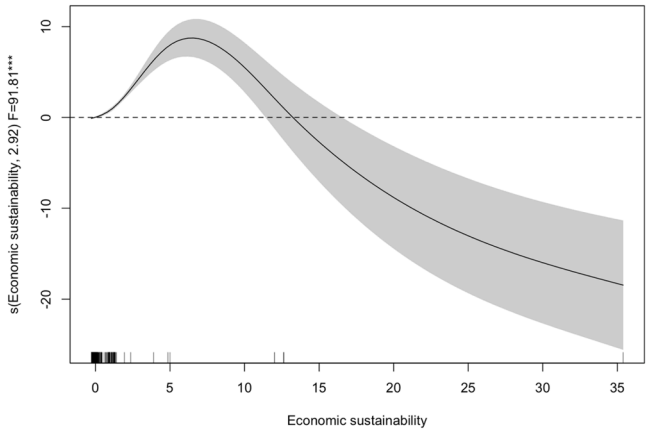


Fig. 8. Estimated smooth term for the Economic dimension (Model 1), with 95% confidence band.
Note: The dashed horizontal line marks a null effect; rug marks on the x-axis show the distribution of observed values.

H2 states that social sustainability practices mitigate emissions of logistic suppliers within the supply chain. The interaction between the social dimension and the logistics sector (Model 5) is not statistically significant ($\beta = 0.035$, n.s.). By contrast, the interaction between the social dimension and the service sector is positive and significant ($\beta = 0.124$, $p < 0.05$), indicating that within services stronger social sustainability is associated with higher emissions, contrary to the co-benefit logic behind H2, an unexpected pattern we treat as exploratory. A plausible reading is that, in service activities, the social construct, driven by cost per employee, added value per employee and workforce growth, proxies for firm scale and operational expansion rather than environmental restraint: service suppliers that invest more in their workforce tend to be larger and more active, with a correspondingly greater operational footprint. The social main effect is positive and significant in Models 1 through 4 ($\beta = 0.057$, $p < 0.1$ in Model 4), but this effect is no longer significant once the Governance × Service interaction is added in Model 5 ($\beta = 0.047$, n.s.). Overall, H2 is not supported: social sustainability is not associated with lower emissions among logistics suppliers.

Finally, H3 states that governance sustainability practices are negatively associated with emissions levels for service suppliers within the supply chain. The GAM reported in Table 5 (Model 5) shows that the interaction between the governance dimension and the services sector is statistically significant and negative ($\beta = –0.280$, $p < 0.01$). The association indicates that, within the services sector, stronger governance sustainability is associated with lower emissions. This result confirms our H3 and indicates that governance sustainability is associated with service suppliers' emissions levels. For service suppliers' assessment, higher governance sustainability can be used to select suppliers with lower emissions and enhance sustainable supply chain management.

Taken together, the GAM results reveal a clear hierarchy across the three sustainability dimensions. The economic dimension shows a significant and non-linear relationship with emissions across all phases, being significant both as a smooth main effect across sectors and especially in the material-processing interaction. Governance shows a significant but comparatively small relationship, non-significant as a main effect in most specifications but significant and negative in the service-sector interaction, consistent with the hypothesised direction. The social dimension shows no significant relationship with emissions in the logistics interaction; in the service interaction, however, it displays an unexpected positive and significant association, which we interpret cautiously as it was not hypothesised.

6. Discussion

This paper addresses a well-documented challenge in sustainable supply chain management, namely the difficulty of collecting reliable supplier-level emissions data required for green supplier selection [3, 13–15]. This limitation is widely acknowledged in the literature, particularly in contexts where environmental disclosure remains incomplete or inconsistent [17]. Building on this gap, the present study proposes a multidimensional sustainability-based approach as an alternative screening mechanism for supplier emissions when direct

Table 5
Hierarchical GAM results.

	Model 1	Model 2	Model 3	Model 4	Model 5
Constant	–0.124**	–0.305***	–0.690***	–0.686***	–0.698***
	(0.054)	(0.103)	(0.069)	(0.069)	(0.068)
Economic	0.195	0.209	–0.525***	–0.530***	–0.640***
	(0.147)	(0.147)	(0.100)	(0.100)	(0.102)
Social	0.101**	0.101**	0.087***	0.057*	0.047
	(0.040)	(0.040)	(0.026)	(0.033)	(0.032)
Governance	0.003	−0.002	0.016	0.016	−0.066**
	(0.043)	(0.043)	(0.029)	(0.029)	(0.034)
Revenues	0.00***	0.00***	0.00***	0.00***	0.00***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Material processing_1		0.294**	0.509***	0.505***	0.510***
		(0.120)	(0.079)	(0.079)	(0.078)
Service_1		0.143	0.122	0.119	0.148
		(0.128)	(0.084)	(0.084)	(0.083)
Economic × Material processing			2.555***	2.563***	2.597***
			(0.086)	(0. 086)	(0. 085)
Social × Logistics				0.038	0.035
				(0.105)	(0.104)
Social × Service				0.086	0.124**
				(0.054)	(0.054)
Governance × Service					–0.280***
					(0.062)
R^2 adjusted	0.437	0.441	0.760	0.760	0.767
N	684	684	684	684	684
AIC	2222.36	2220.13	1643.88	1645.31	1627.07

Notes: Material processing (1= yes, 0 = Logistics); Service (1= yes, 0 = Logistics). * $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

Table 6
Smooth terms.

Model 1		Model 2		Model 3		Model 4		Model 5	
EDF	F	EDF	F	EDF	F	EDF	F	EDF	F
2.920	91.81***	2.919	93.03***	2.979	133.2***	2.979	133.8***	2.979	131.9***

Note: Models 1–5 refer to the different GAM specifications in Table 5. EDF = effective degrees of freedom.

environmental data are not available.

The findings contribute to existing research by demonstrating that economic, social, and governance (ESG) dimensions can serve as statistically significant predictors of emissions, consistent with prior studies highlighting the role of sustainability integration in environmental outcomes [16,21,22]. In line with broader evidence on ESG–environment relationships [51,57,83], the results confirm that sustainability dimensions are not homogeneous in their environmental effects and must be interpreted within their operational context. Importantly, the empirical evidence extends this literature by showing that these relationships are sector-dependent within the same supply chain, reinforcing the idea that governance and operational structures are related to sustainability outcomes [54,60].

From a managerial perspective, the results provide actionable implications for green supplier selection under data constraints. Economic sustainability in material-processing suppliers is positively associated with emissions ($\beta = 2.597$, $p < 0.01$), suggesting that strong economic performance may be linked to higher production intensity and therefore higher environmental impact. This finding aligns with evidence that industrial efficiency and growth patterns can generate unintended environmental trade-offs in manufacturing contexts [24,64]. Consequently, procurement managers should not interpret economic strength as a proxy for environmental performance in this sector, but rather apply it cautiously as part of a broader screening heuristic.

Conversely, social sustainability shows no significant association with emissions among logistics suppliers ($\beta = 0.035$, n.s.); in services, by contrast, the association is positive and significant ($\beta = 0.124$, $p < 0.05$), an unanticipated pattern that we interpret cautiously and treat as exploratory. Two considerations help to interpret these results. First, the social component is built exclusively on employee-related indicators, namely cost per employee, added value per employee and employee growth, which capture the workforce facet of social sustainability but not the community, supplier and wider stakeholder facets that the social license to operate framework [48] associates with broader operational improvements; the null association in logistics ($\beta = 0.035$, n.s.) may therefore reflect this measurement scope rather than a genuine absence of a social-environmental relationship. Second, the positive association in services ($\beta = 0.124$, $p < 0.05$) may arise because, in service activities, gains in employee-related metrics accompany an expansion of activity and resource use rather than emission-reducing operational change. These results diverge from the co-benefit expectation that investments in employee welfare are accompanied by emission-reducing efficiency improvements [49], but they are consistent with evidence that social and environmental outcomes in supply chains are not necessarily aligned [11] and with the limited and still unclear understanding of how social factors shape sustainable supply chain practices [43]. They also contrast with the systematic associations observed here for the economic and governance dimensions. The logistics result does not support the expectation that workforce practices and organisational responsibility improve environmental outcomes in logistics operations, an expectation emphasised in prior research [5,45,50]. In this sample, social performance does not provide a reliable criterion for emissions-based supplier evaluation in transport-intensive segments.

Similarly, stronger governance sustainability is associated with lower emissions in service suppliers ($\beta = –0.280$, $p < 0.01$), consistent with studies emphasizing the environmental relevance of corporate governance mechanisms [51,56,57]. Strong governance structures may enhance transparency, accountability, and environmental monitoring,

thereby contributing to improved emissions performance in service-based activities.

A key contribution of this study lies in demonstrating the advantage of a sector-sensitive, multidimensional ESG approach within a real industrial supply chain context. Unlike traditional approaches that treat ESG indicators as uniform predictors, the proposed model highlights heterogeneity across supplier sectors, offering a more nuanced and operationally applicable decision-support tool. This orientation is consistent with recent work on sustainability-oriented decision support and integrated sustainability assessment, which shows that evaluating interconnected sustainability dimensions jointly, rather than in isolation, reveals long-term trade-offs that single-dimension assessments overlook [84]. Our sector-sensitive screening approach applies the same integrated logic to supplier assessment by treating the economic, social and governance dimensions as complementary signals within a structured decision-support framework. In the context of the Italian ceramic supply chain analysis, this approach enables firms to approximate emissions-related insights even when direct environmental data are unavailable, thereby supporting preliminary supplier screening under real-world information constraints.

Overall, the findings suggest that ESG dimensions can function as effective screening heuristics rather than deterministic decision rules. This interpretation aligns with recent calls in the literature for more flexible and context-aware sustainability assessment frameworks in supply chain management [1,18,21]. The proposed approach therefore contributes both theoretically, by refining the understanding of ESG–emissions relationships, and practically, by offering a structured yet adaptable method for sustainable supplier evaluation.

Regarding generalizability, the proposed framework can be extended to other industries by recalibrating the ESG–emissions relationships using sector-specific data, as the observed relationships are likely to vary with production intensity and operational structure. In multi-tier supply chains, the same approach can support preliminary supplier screening where direct emissions data are unavailable, provided that consistent ESG indicators are accessible. Furthermore, while the empirical setting is the Italian ceramic sector, the methodology is transferable across geographical contexts under comparable reporting standards such as Corporate Sustainability Reporting Directive (CSRD) and European Sustainability Reporting Standards (ESRS) [1,21], which enhance data comparability across regions. That said, because the empirical evidence rests on the Italian ceramic sector and on a single year (2021), these extensions should be read as conditional and exploratory directions rather than as demonstrated transferability. The sector-specific patterns reported here, including the stronger economic effect in material processing ($\beta = 2.597$) and the governance effect in services ($\beta = –0.280$), are likely to differ in industries with different production intensity, operational structure and institutional setting, and they would require recalibration and validation on independent, multi-firm and multi-industry data before the framework can be considered broadly applicable.

7. Conclusions: contribution and limitations

The insights from the paper's results contribute within an ESG perspective [6–9] to green supplier selection theory and practices in three main ways.

First, this paper contributes, from a theoretical perspective to the literature regarding the role of green supplier selection [3,13–15] by pointing out the evidence that suppliers' emissions data can be unavailable and inaccessible to purchasing companies [16,17]. The lack of suppliers' emissions data makes green supplier selection difficult and costly.

Second, this paper shows that emissions depend on other sustainability dimensions, such as economic, social and governance sustainability, representing publicly available data in public databases [18].

The paper highlights that suppliers' sectors [23] are a relevant variable in identifying the effects on emissions. To our knowledge, this paper represents the first attempt to study the effects of sustainability variables on supply chain sector-specific emissions with the aim to support green suppliers selection. These insights recommend that evaluating suppliers through a multidimensional sustainability approach based on their sector is essential while implementing green supplier selection [3,13–15] strategies and reduce supply chain emissions.

Third, building on the literature that explores the interrelationships among sustainability dimensions, the research empirically confirms that economic, social, and governance factors are associated with environmental outcomes [16,21,22]. It advances the theoretical discourse by demonstrating how these interdependencies vary across sectors. This contribution deepens the understanding of sustainability interactions and suggests new pathways for leveraging these interdependencies in emissions mitigation strategies.

In addition, the paper advances practical implications and recommendations in particular for buying companies [11,12] seeking to reduce their supply chain emissions [1] through suppliers' strategic assessment. The analysis highlights the association of economic, social, and governance sustainability with emissions within different suppliers' industrial sectors. It recommends that companies operating in the ceramic industry assess their suppliers' emissions by categorising them into services, logistics, and material-processing sectors. Specifically, in the material-processing sector, suppliers should be evaluated on the basis of their economic performance as it is significantly associated with their emission levels. Within the logistics sector, by contrast, social sustainability does not show a statistically significant association with emissions, so it cannot be recommended as a reliable emissions-based selection criterion for this segment. Finally, emission assessment in the service sector can be implemented by analysing governance sustainability measures.

Limitations

This study presents several limitations that should be acknowledged when interpreting the results and assessing their broader applicability. First, the analysis is based on the supply chain of a single firm, which may limit the generalizability of the findings to organisations operating in different industries, markets, or institutional environments. Supply chain structures, supplier relationships, and sustainability practices can vary significantly across firms, potentially affecting the transferability of the proposed approach. Second, the study relies exclusively on data from the year 2021. As a result, it does not capture temporal dynamics, changes in supplier performance, or the effects of evolving environmental regulations and sustainability strategies over time. To enhance the analysis, it would be beneficial to collect data from additional years [16], allowing for more comprehensive panel studies. Third, greenhouse gas emissions were estimated using sector-level emission factors and proxy measures rather than direct firm-level emissions data. While this approach enables preliminary screening and analysis, it may not fully reflect the actual environmental performance of individual suppliers. Fourth, the cross-sectional nature of the study restricts the ability to identify causal relationships or evaluate the long-term impact of sustainability initiatives. The results therefore represent a snapshot of the supply chain under investigation rather than a dynamic assessment. Finally, the proposed framework has not yet undergone external validation using independent datasets, alternative industries, or different geographical contexts. Consequently, additional empirical testing is needed to confirm its robustness, reliability, and practical applicability. In addition, the social dimension is proxied exclusively through employee-related variables, such as cost per employee, added value per employee and employee growth, which capture only the workforce facet of social sustainability. Future research should identify and implement broader social proxies that also embrace other stakeholders and the wider community, so that the social dimension is represented more comprehensively. Future research should address these limitations

through multi-firm studies, longitudinal analyses, firm-specific emissions data, and comprehensive validation procedures across diverse supply chain settings.

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CRediT authorship contribution statement

Girardi Andrea: Writing – original draft, Investigation, Conceptualization. **Kocollari Ulpiana:** Funding acquisition. **Fabio Demaria:** Formal analysis. **Laura Merzi:** Methodology, Formal analysis.

Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose.

Data availability

The authors do not have permission to share data.

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