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Prioritization of e-traceability drivers in the agri-food supply chains

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Abstract

Electronic traceability (e-traceability) is a growing trend in the agri-food industry, offering improved transparency, accountability, and reduced risk of foodborne illnesses through the use of electronic systems to trace products throughout the entire supply chain. E-traceability drivers in the agri-food supply chain encompass diverse factors motivating companies to adopt electronic systems for product tracking, aiming to enhance visibility, minimize risk, ensure compliance, and promote safety, sustainability, and efficiency through clear and verifiable records of product origins, quality, and sustainability, building consumer trust and loyalty. By identifying the main drivers of e-traceability, this research aims to shed light on the factors that motivate companies to implement electronic systems for tracking and monitoring products. For solving this problem of multi-criteria decision-making (MCDM), this study proposes a hybrid MCDM model. The model combines "Factor Relationship" (FARE) and "Axial Distance-based Aggregated Measurement" (ADAM) methods in the fuzzy environment. The results indicate that the most important drivers are supply chain efficiency, technology development and sustainability. These drivers are critical and they significantly impact the successful implementation and adoption of e-traceability strategies in the agri-food sector.

Keywords: E-traceability, Drivers, Agri-food, Supply-chain, Fuzzy FARE, Fuzzy ADAM, MCDM

Introduction

Electronic traceability, also known as e-traceability, implies using electronic systems to monitor and track products throughout their entire supply chain, from raw materials to finished goods (Schuitemaker and Xu 2020). This approach has become increasingly popular in recent years, particularly in the agri-food industry, to improve transparency and accountability and reduce the risk of foodborne illness outbreaks (Cocco and Mannaro 2021). Despite some challenges related to data privacy and security, cost and coordination among stakeholders, e-traceability offers a range of benefits for stakeholders throughout the supply chain, including improved efficiency, product safety, transparency, and accountability (Brun et al. 2020). E-traceability has the potential to transform supply chain management and improve the sustainability and resilience of global food systems. These are the main reasons why e-traceability, based on the implementation of more advanced technologies, the improvement of data quality and interoperability, has become one of the main tools of companies seeking to achieve higher efficiency and better competitiveness in the market (Corallo et al. 2020).

E-traceability drivers refer to the factors that motivate and incentivize companies to adopt electronic systems for tracking and monitoring products throughout the supply chain (Srivastava and Dashora 2021). These drivers can include a wide range of factors, such as consumer demand for transparency and traceability, regulatory requirements, certifications and standards, brand reputation and advances in technology. Ultimately, the goal of e-traceability is to provide a clear and verifiable record of product origins, quality and sustainability practices (Zhang et al. 2022). By improving the visibility and traceability of products, companies can reduce the risk of errors and fraud, ensure compliance with global regulations and build consumer trust and loyalty. E-traceability is therefore an important tool for promoting safety, sustainability and efficiency in the agri-food supply chain (Nguyen et al. 2022).

Having this in mind, the aim of this study is to identify main drivers of e-traceability in the agri-food supply chains. This aim leads to several research questions (RQ) addressed in the study: What are the potential drivers of e-traceability in agri-food supply chains? (RQ1); Which criteria could be used for the evaluation and prioritization of the drivers? (RQ2); What framework could be appropriate for solving the defined problem? (RQ3); What are the main implications of developing a prioritization framework and identifying the most important drivers? (RQ4).

Ten drivers were identified along with the corresponding criteria for their prioritization. The established multi-criteria decision-making (MCDM) method was solved using the newly developed hybrid model which combined "Factor Relationship" (FARE) and "Axial Distance-based Aggregated Measurement" (ADAM) methods in the fuzzy environment. The results indicate that the most important drivers are supply chain efficiency, technology development and sustainability. It can be concluded that these drivers are critical and that they significantly impact the successful implementation and adoption of e-traceability strategies in the agri-food sector. The identification and prioritization of these drivers offer valuable insights for policymakers, industry practitioners and researchers to develop strategies and frameworks that foster efficient, advanced and sustainable e-traceability systems.

The main contributions of the study are a comprehensive analysis and definition of a broad set of e-traceability drivers in agri-food supply chains, a systematic overview of criteria for evaluating and prioritizing them and the development of a novel hybrid MCDM model for solving the established problem.

The following section provides a literature review regarding the main aspects of the problem, i.e., e-traceability in the agri-food sector and MCDM methods that make up the model. The third section explains the methodology, i.e., the novel MCDM model. This is followed by a section dealing with solving the problem, i.e., obtaining the results, validating them and checking their stability. The fifth section provides a discussion of the contributions, limitations and implications of the problem, methodology and results. The last section offers concluding remarks and outlines directions for future research.

Literature review

In recent years, e-traceability has become a critical issue in the agri-food sector and thus the focus of numerous research. The following provides the context for the problem dealt with in this study, as well as the overview of the methods used to solve the defined problem.

E-traceability in the agri-food sector

E-traceability offers a range of benefits to stakeholders throughout the supply chain. For example, it can help to improve efficiency by reducing the time and resources required to track products manually (Jiang and Lei 2022). It can also enhance product safety by enabling rapid recall of contaminated or defective products, reducing the risk of food-borne illness outbreaks (Zrnić, 2020). Furthermore, e-traceability can improve transparency and accountability, building trust and confidence among consumers, thereby enhancing brand reputation and customer loyalty (Chiu and Hsieh 2018).

Despite its many benefits, e-traceability poses several challenges. One of the main challenges is data privacy and security (Zhang et al. 2022). Electronic systems can be vulnerable to hacking and other forms of cyber-attacks, which can compromise the confidentiality and integrity of sensitive data. Another challenge is the cost of implementing and maintaining e-traceability systems (Liu and Gao 2016), which can be prohibitive for small and medium-sized enterprises. In addition, e-traceability requires a high level of coordination and collaboration among stakeholders, which can be difficult to achieve in practice (Gooch et al. 2017).

Current research on e-traceability is focused on several key areas, including the development of new technologies, the improvement of data quality, interoperability and the assessment of the economic and environmental impacts of e-traceability. For example, recent studies have explored the use of blockchain technology to enhance the security and transparency of e-traceability systems (Li et al. 2022). Other studies have focused on the standardization of data formats and the development of data exchange platforms to facilitate data sharing among stakeholders (Bühler et al. 2023). Some research on e-traceability focuses on the development of more advanced technologies, such as artificial intelligence and the Internet of Things (IoT), to improve the efficiency and effectiveness of e-traceability systems (Wang 2022). Research has also addressed the emerging issues related to data privacy and security and the development of policies and regulations to ensure the responsible use of e-traceability systems (Corallo et al. 2020). In addition, some studies consider the socio-economic and environmental impacts of e-traceability to ensure that it is sustainable and equitable for all stakeholders (Srivastava 2022).

E-traceability has become an increasingly important topic in the agri-food industry as consumers demand more transparency and accountability from food producers. The literature on e-traceability in the agri-food supply chain has focused on the benefits and challenges of implementing traceability systems, as well as the different technologies and standards used for traceability. Some of the most recent studies highlighted the potential benefits of e-traceability, such as improving supply chain efficiency, reducing food waste, enhancing food safety and quality and increasing consumer trust (Skalkos et al.

2021; Rana 2020; Brun et al. 2020). For example, e-traceability systems can help food producers and retailers quickly identify the source of a food safety issue and implement a targeted recall, minimizing the impact on consumers and reducing the financial burden on the industry (Magalhaes et al. 2021). Traceability systems can also help identify where food waste is occurring in the supply chain, allowing for targeted interventions to reduce waste (Arora et al. 2023). The literature has also identified several challenges associated with implementing e-traceability in agri-food supply chains. One major challenge is the high cost of implementing and maintaining traceability systems (Conti 2022). Additionally, there is a lack of interoperability between different traceability systems, making it difficult to share data across the supply chain (Compagnucci et al. 2022). Resistance from some actors in the supply chain, such as small-scale farmers who may lack the resources to implement e-traceability systems, is also a significant challenge (van der Pijl 2014). Furthermore, there are concerns about data privacy and ownership, as well as the potential for e-traceability systems to be used as a tool for market domination by larger players in the industry (Xue and Wang 2022). Finally, some studies have explored the impact of e-traceability on food safety, quality and sustainability (e.g., Rana 2020). These studies have generally found that traceability can improve food safety by allowing for more targeted recalls and better tracking of foodborne illness outbreaks. Additionally, traceability can enhance food quality by allowing producers to identify and address quality issues in a more timely manner. Finally, traceability can promote sustainability by reducing food waste and improving supply chain transparency.

In spite the vastness of the literature, as far as the authors are aware, no existing studies in the literature have explored the factors driving e-traceability in the agri-food sector. This research study aims to fill this research gap.

MCDM methods encompassed by the model

This study proposes a novel hybrid MCDM model which combines the fuzzy FARE (FFARE) method for obtaining criteria weights and the fuzzy ADAM (FADAM) method for ranking the alternatives. The main reason for selecting both of the methods was their simplicity and reliability, which was needed due to the large number of experts involved in the decision process and large number of criteria against which the alternatives were compared.

The FARE method was developed by Ginevičius (2011) as a tool to establish criteria weights in decision-making problems. It is based on the idea that the criteria weights should be determined by the relationships between the criteria rather than by the decision maker's subjective judgment and involves several steps. Firstly, the decision problem is defined and the criteria and alternatives are identified. Then, the decision maker evaluates the relationships between the criteria using a pair-wise comparison matrix. In this matrix, each criterion is compared to every other criterion in terms of its relative importance. Once the pair-wise comparison matrix has been constructed, the FARE method calculates the geometric mean of the rows in the matrix. This calculation produces a vector of weights that reflects the relative importance of each criterion in the decision-making problem. Some of the strengths of the FARE method, compared to the other pair-wise comparison methods such as AHP, ANP, etc., are that it provides a systematic approach to establishing criteria weights that are based on the relationships between the criteria, significantly reduces the number of expert evaluations required and its consistent comparison matrix ensures more reliable and stable results without needing to be revised (Krstić et al. 2023a; Chatterjee et al. 2017; Kazan et al. 2015). This approach can help reduce the bias and subjectivity that may be introduced by the decision maker's subjective judgment. In addition, the FARE methodology is transparent and easily interpretable. The criteria weights are derived based on the relationships specified by experts, making it clear how each weight is influenced by the relationships among criteria. This enhances the transparency of the decision-making process. However, it also has some limitations. For example, it assumes that the relationships between the criteria are linear, which may not always be the case. Additionally, the method may require a lot of information and data to make an accurate evaluation of the relationships between the criteria. To address the subjective and uncertain nature of the decision-making process based on the opinions of decision-makers, the FARE method is extended to the fuzzy environment by Roy et al. (2020). The conventional FARE or the fuzzy FARE method has recently been used in the literature to solve problems such as: the selection of appropriate handling equipment for an intermodal terminal (Krstić et al. 2023a), the evaluation of sustainable last mile solutions (Krstić et al. 2021), evaluation and selection of third party logistics providers (Roy et al. 2020), the evaluation of the university competitiveness (Girdzijauskaitė et al. 2019) and the evaluation and selection of the most appropriate non-traditional machining process (Chatterjee et al. 2017).

The ADAM method was developed by Krstić et al. (2023b) as a representative of a completely new group of MCDM methods, namely geometric methods. In this approach, the ranking of alternatives relies on evaluating the aggregated measurement of complex polyhedra defined by vertices established on the basis of values of criteria weights and alternatives. The ADAM method is simple, user-friendly and easily understandable, with a low risk of rank reversal and an intuitive graphical representation based on volume calculations of polyhedra (Krstić et al. 2023b). The method remains stable and changes in criteria weights have an insignificant impact on the results, making it a reliable and easily interpreted decision-making tool for a large number of criteria (Krstić et al. 2023b). In addition, the results obtained with this method indicate a high level of conformity with the results of other MCDM methods. The average correlation indices of this method are among the highest when comparing them to the most used MCDM methods (Krstić et al. 2023b). This is one of the newest MCDM methods and has been used so far for the evaluation of business models (Krstić et al. 2023b) and for ranking circularity boosting strategies (Agnusdei et al. 2023).

Until now, the ADAM method has not been extended to the fuzzy environment, nor it has been combined with the FARE method. Therefore, this is another research gap that this study covers.

Methodology

To solve the MCDM problem in this study, a novel hybrid model is defined which combines the FFARE method to obtain the criteria weights and the FADAM method to rank the alternatives. The model application steps are provided below.

Step 1: Identify alternatives and criteria for their evaluation.

Table 1 Evaluation scale

Evaluation	Abbreviation	Fuzzy values for criteria/alternatives
"None"	"N"	(1, 1, 2)
"Very low"	"VL"	(1, 2, 3)
"Low"	"L"	(2, 3, 4)
"Fairly low"	"FL"	(3, 4, 5)
"Medium"	"M"	(4, 5, 6)
"Fairly high"	"FH"	(5, 6, 7)
"High"	"H"	(6, 7, 8)
"Very high"	"VH"	(7, 8, 9)
"Extremely high"	"EH"	(8, 9, 10)

Step 2: Define the evaluation scale (Table 1). A nine-point scale, also known as Saaty's scale, which was originally developed for the AHP, and subsequently ANP, method was used. The main advantage of this scale is its granularity, i.e., the scale offers a wide range of options (nine levels) to express preferences and importance (Javed and Du 2023). Five main levels and four intermediate levels allow decision-makers to provide more accurate and detailed assessments of the relative significance of criteria and alternatives.

Step 3: Apply the FFARE method to obtain the criteria weights (adapted from Roy et al. 2020):

Step 3.1: Form the matrix:

$$\widetilde{A} = \left[\widetilde{a}_{ij}\right]_{n\times n}, \tag{1}$$

where $\widetilde{a}_{ij} = \left(l^{a_{ij}}, m^{a_{ij}}, u^{a_{ij}}\right)$ indicates dominance of criterion i over criterion j obtained by transforming DMs' linguistic evaluations into fuzzy values using the scale given in Table 1. Items $l^{a_{ij}}$, $m^{a_{ij}}$ and $u^{a_{ij}}$ are lower, middle, and upper values of the fuzzy value $\widetilde{a}_{ij}$, and n is the total number of criteria.

Step 3.2: Obtain the value of $\widetilde{I}$ as

$$\widetilde{I} = \widetilde{H}(n-1), \tag{2}$$

where $\widetilde{H}$ is the highest value of the scale proposed in Table 1.

Step 3.3: Obtain the values of $\widetilde{I}_j$ as

$$\widetilde{I}_j = \sum_{i=1}^{n} \widetilde{a}_{ij}, \forall j = 1, \ldots, n, j \neq i, \tag{3}$$

Step 3.4: Obtain the weights $\widetilde{w}_j$ as

$$\widetilde{w}_j = \widetilde{I}_j^r / \widetilde{I}_H, \forall j = 1, \ldots, n, \tag{4}$$

where $\widetilde{I}_H$ is obtained as

$$\widetilde{I}_H = \left(\underset{j}{min} l^{\widetilde{I}_j^r}, \underset{j}{mean} m^{\widetilde{I}_j^r}, \underset{j}{max} u^{\widetilde{I}_j^r}\right), \tag{5}$$

and $\widetilde{I}_j^r$ is obtained as:

$$\widetilde{I}_j^r = \widetilde{I}_j + \widetilde{I}, \forall j = 1, \ldots, n, \tag{6}$$

Step 4: Apply the fuzzy extension of ADAM method (Krstić et al. 2023b) to rank the alternatives. The method is based on the establishment of the complex polyhedra volumes to rank the alternatives. Therefore, the method relies on geometric and trigonometric operations to calculate volumes of pyramids from which the pyramids are composed. Detailed steps of the method application are as follows.

Step 4.1: Define the matrix.

$$\widetilde{E} = \left[\widetilde{e}_{ij}\right]_{m \times n}, \tag{7}$$

where $\widetilde{e}_{ij} = (l^e, m^e, u^e)$ are the evaluations of the alternatives i in relation to criteria j, m is the total number of alternatives.

Step 4.2: Define the matrix.

$$\widetilde{F} = \left[\widetilde{f}_{ij}\right]_{m \times n}, \tag{8}$$

where $\widetilde{f}_{ij} = \left(l^f, m^f, u^f\right)$ indicate the normalized evaluations $\widetilde{e}_{ij}$ obtained as:

$$\begin{aligned} l^f &= \frac{l^e}{\max u^e} \\ m^f &= \frac{m^e}{\max u^e} \\ u^f &= \frac{u^e}{\max u^e} \end{aligned} \tag{9}$$

Step 4.3: Define the matrix.

$$\widetilde{S} = \left[\widetilde{s}_{ij}\right]_{m \times n}, \tag{10}$$

where $\widetilde{s}_{ij} = (l^s, m^s, u^s)$ indicate the sorted evaluations $\widetilde{f}_{ij}$ in descending order.

Step 4.4: Find the fuzzy coordinates $\left(\widetilde{x}_{ij}, \widetilde{y}_{ij}, \widetilde{z}_{ij}\right)$ of the fuzzy reference $\widetilde{R}_{ij}$ and fuzzy weighted reference $\widetilde{P}_{ij}$ points:

$$\widetilde{x}_{ij} = \left(l^{x_{ij}}, m^{x_{ij}}, u^{x_{ij}}\right) = \left(l^{s_{ij}} \times \sin\alpha_j, m^{s_{ij}} \times \sin\alpha_j, u^{s_{ij}} \times \sin\alpha_j\right), \forall j = 1, \ldots, n; \forall i = 1, \ldots, m, \tag{11}$$

$$\widetilde{y}_{ij} = \left(l^{y_{ij}}, m^{y_{ij}}, u^{y_{ij}}\right) = \left(l^{s_{ij}} \times \cos\alpha_j, m^{s_{ij}} \times \cos\alpha_j, u^{s_{ij}} \times \cos\alpha_j\right), \forall j = 1, \ldots, n; \forall i = 1, \ldots, m, \tag{12}$$

$$\widetilde{z}_{ij} = \left(l^{z_{ij}}, m^{z_{ij}}, u^{z_{ij}}\right) = \begin{cases} (0,0,0), for \widetilde{R}_{ij} \\ \left(l^{w_j}, m^{w_j}, u^{w_j}\right), for \widetilde{P}_{ij} \end{cases}, \forall j = 1, \ldots, n; \forall i = 1, \ldots, m \tag{13}$$

where α_j is obtained as:

$$\alpha_j = \left(j - 1\right)\frac{90^\circ}{n - 1}, \forall j = 1, \ldots, n, \tag{14}$$

The fuzzy coordinates are used to form the complex polyhedra for each alternative. The polyhedra are composed of pyramids. Since the fuzzy values are used for the coordinates, for each pair of criteria 81 (3^4) different pyramids are obtained as the combinations of all possible reference and weighted reference points.

Step 4.5: Obtain the fuzzy values of complex polyhedra volumes as:

$$\widetilde{V}_i^C = \oplus_{k=1}^{n-1} \widetilde{V}_k, \forall i = 1, \ldots, m, \tag{15}$$

where $\widetilde{V}_k$ are the fuzzy volumes of the pyramids determined by each pair of two consecutive criteria, obtained as:

$$\widetilde{V}_k = \frac{1}{3} \widetilde{B}_k \otimes \widetilde{h}_k, \forall k = 1, \ldots, n-1, \tag{16}$$

where $\widetilde{B}_k$ are the fuzzy values of the base areas of each pyramid, obtained as:

$$\tilde{B}_k = \tilde{c}_k \otimes \tilde{a}_k \oplus \frac{\tilde{a}_k \otimes \left(\tilde{b}_k \Theta \tilde{c}_k\right)}{2}, \tag{17}$$

where $\widetilde{a}_k = \left(l^{a_k}, m^{a_k}, u^{a_k}\right)$ are the fuzzy values of the Euclidian distances in which:

$$\begin{aligned}
l^{a_k} &= \min\left(\sqrt{\left(u^{x_{j+1}} - l^{x_j}\right)^2 + \left(u^{y_{j+1}} - l^{y_j}\right)^2}, \sqrt{\left(l^{x_{j+1}} - u^{x_j}\right)^2 + \left(l^{y_{j+1}} - u^{y_j}\right)^2}\right) \\
m^{a_k} &= \sqrt{\left(m^{x_{j+1}} - m^{x_j}\right)^2 + \left(m^{y_{j+1}} - m^{y_j}\right)^2} \\
u^{a_k} &= \max\left(\sqrt{\left(u^{x_{j+1}} - l^{x_j}\right)^2 + \left(u^{y_{j+1}} - l^{y_j}\right)^2}, \sqrt{\left(l^{x_{j+1}} - u^{x_j}\right)^2 + \left(l^{y_{j+1}} - u^{y_j}\right)^2}\right)
\end{aligned} \tag{18}$$

$\widetilde{\mathrm{b}}_{\mathrm{k}} = \left(l^{b_k}, m^{b_k}, u^{b_k}\right)$ and $\widetilde{\mathrm{c}}_{\mathrm{k}} = (l^{c_k}, m^{c_k}, u^{c_k})$ are equal to:

$$\widetilde{\mathrm{b}}_{\mathrm{k}} = \widetilde{z}_j, \tag{19}$$

$$\widetilde{\mathrm{c}}_{\mathrm{k}} = \widetilde{\mathrm{z}}_{\mathrm{j+1}}, \tag{20}$$

Following Eqs. (16)–(18), Eq. (15) can be expressed as $\widetilde{B}_k = \left(l^{B_k}, m^{B_k}, u^{B_k}\right)$ in which:

$$\begin{aligned}
l^{B_k} &= l^{c_k} \times l^{a_k} + \frac{l^{a_k} \times \left(l^{b_k} - u^{c_k}\right)}{2} \\
m^{B_k} &= m^{c_k} \times m^{a_k} + \frac{m^{a_k} \times \left(m^{b_k} - m^{c_k}\right)}{2} \\
u^{B_k} &= u^{c_k} \times u^{a_k} + \frac{u^{a_k} \times \left(u^{b_k} - l^{c_k}\right)}{2}
\end{aligned} \tag{21}$$

$$\widetilde{h}_k = \frac{2\sqrt{\widetilde{s}_k\left(\widetilde{s}_k - \widetilde{a}_k\right)\left(\widetilde{s}_k - \widetilde{d}_k\right)\left(\widetilde{s}_k - \widetilde{e}_k\right)}}{\widetilde{a}_k} \tag{22}$$

where $\widetilde{h}_k$ are the fuzzy values of the pyramid heights and $\widetilde{s}_k$ are the fuzzy values of semi-circumferences of the triangles defined by the reference points of two consecutive criteria and the coordinate origin.

$$\widetilde{s}_k = \frac{\widetilde{a}_k \oplus \widetilde{d}_k \oplus \widetilde{e}_k}{2}, \tag{23}$$

where $\widetilde{d}_k$ can be expressed as $\widetilde{d}_k = \left(l^{d_k}, m^{d_k}, u^{d_k}\right)$ in which:

$$\begin{aligned} l^{d_k} &= \sqrt{\left(l^{x_j}\right)^2 + \left(l^{y_j}\right)^2} \\ m^{d_k} &= \sqrt{\left(m^{x_j}\right)^2 + \left(m^{y_j}\right)^2} \\ u^{d_k} &= \sqrt{\left(u^{x_j}\right)^2 + \left(u^{y_j}\right)^2} \end{aligned} \tag{24}$$

and $\widetilde{e}_k$ can be expressed as $\widetilde{e}_k = (l^{e_k}, m^{e_k}, u^{e_k})$ in which

$$\begin{aligned} l^{e_k} &= \sqrt{\left(l^{x_{j+1}}\right)^2 + \left(l^{y_{j+1}}\right)^2} \\ m^{e_k} &= \sqrt{\left(m^{x_{j+1}}\right)^2 + \left(m^{y_{j+1}}\right)^2} \\ u^{e_k} &= \sqrt{\left(u^{x_{j+1}}\right)^2 + \left(u^{y_{j+1}}\right)^2} \end{aligned} \tag{25}$$

Following Eqs. (22) and (23), Eq. (21) can be expressed as $\widetilde{s}_k = (l^{s_k}, m^{s_k}, u^{s_k})$ in which:

$$\begin{aligned} l^{s_k} &= \frac{l^{a_k} + l^{d_k} + l^{e_k}}{2} \\ m^{s_k} &= \frac{m^{a_k} + m^{d_k} + m^{e_k}}{2} \\ u^{s_k} &= \frac{u^{a_k} + u^{d_k} + u^{e_k}}{2} \end{aligned} \tag{26}$$

and Eq. (22) can be expressed as $\widetilde{h}_k = \left(l^{h_k}, m^{h_k}, u^{h_k}\right)$ in which:

$$\begin{aligned} l^{h_k} &= \frac{2\sqrt{l^{s_k}\left|l^{s_k} - u^{a_k}\right|\left|l^{s_k} - u^{d_k}\right|\left|l^{s_k} - u^{e_k}\right|}}{u^{a_k}} \\ m^{h_k} &= \frac{2\sqrt{m^{s_k}\left|m^{s_k} - m^{a_k}\right|\left|m^{s_k} - m^{d_k}\right|\left|m^{s_k} - m^{e_k}\right|}}{m^{a_k}} \\ u^{h_k} &= \frac{2\sqrt{u^{s_k}\left|u^{s_k} - l^{a_k}\right|\left|u^{s_k} - l^{d_k}\right|\left|u^{s_k} - l^{e_k}\right|}}{l^{a_k}} \end{aligned} \tag{27}$$

According to the transformed Eqs. (19) and (25), Eq. (14) can be expressed as $\widetilde{V}_k = \left(l^{V_k}, m^{V_k}, u^{V_k}\right)$ in which:

$$\begin{aligned} l^{V_k} &= \frac{l^{B_k} \times l^{h_k}}{3} \\ m^{V_k} &= \frac{m^{B_k} \times ml^{h_k}}{3} \\ u^{V_k} &= \frac{u^{B_k} \times u^{h_k}}{3} \end{aligned} \tag{28}$$

and Eq. (13) as $\widetilde{V}_i^C = \left(l^{V_i^C}, m^{V_i^C}, u^{V_i^C}\right)$ in which:

$$
\begin{aligned}
l^{V_i^C} &= \sum_{k=1}^{n-1} l^{V_k} \\
m^{V_i^C} &= \sum_{k=1}^{n-1} m^{V_k} \\
u^{V_i^C} &= \sum_{k=1}^{n-1} u^{V_k}
\end{aligned}
\tag{29}
$$

Step 5: Rank the alternatives by the crisp values (adapted from Rahmani et al. 2016)

$$
Crisp\left(\widetilde{V}_i^C\right) = \left(4 \times m^{V_i^C} + u^{V_i^C} - 2l^{V_i^C}\right)/3\left(u^{V_i^C} - 2l^{V_i^C}\right), \tag{30}
$$

Problem description

E-traceability drivers in the agri-food supply chain refer to a wide range of factors that encourage companies to adopt electronic systems to track and monitor products throughout the supply chain. Overall, e-traceability drivers are diverse and multifaceted. The combination of consumer demand, regulatory requirements, certifications and standards, brand reputation and technological advancements drives the adoption of electronic systems to track and monitor products throughout the supply chain, ultimately benefiting consumers and producers.

E-traceability drivers

Globalization (D1)

With the increasing globalization of the food supply chain, it has become more difficult to track the origin and movement of food products (Liu and Gao 2016). By providing real-time tracking and monitoring of products, e-traceability can help companies address the challenges of global trade and meet the demands of consumers, regulators and investors for greater transparency and accountability in the agri-food supply chain (Liu and Gao 2020).

Supply chain efficiency (D2)

E-traceability can help to improve supply chain efficiency by providing real-time data on the location and status of products, which can reduce waste and improve inventory management (Liu and Gao 2020). E-traceability can also help companies to identify and manage risks in their supply chains, such as potential contamination or product recalls (Srivastava and Dashora 2021). Companies that implement e-traceability systems in their supply chains may gain a competitive advantage over those that do not, as they can offer greater transparency and reliability to their customers.

Sustainability (D3)

E-traceability can help companies track the environmental and social impact of their products throughout the supply chain, which is becoming increasingly important for consumers who are concerned about sustainability (Rana et al. 2021). In the agri-food supply chain, e-traceability can help address some of the major sustainability challenges faced by the industry, such as reducing greenhouse gas emissions, protecting biodiversity and promoting fair labor practices (Feng, et al. 2020). E-traceability can also help to reduce food waste by identifying areas of the supply chain where products are being lost or damaged, implementing corrective actions to prevent further waste.

Food safety (D4)

Governments around the world are implementing stricter food safety regulations, which require detailed traceability records to be kept throughout the supply chain. Food fraud is a growing problem, with criminal organizations exploiting weaknesses in the supply chain to sell counterfeit or adulterated food products. E-traceability can help to prevent food fraud and increase safety by providing a complete record of the product's journey from farm to fork (Liu and Gao 2016).

Food quality (D5)

E-traceability can help to ensure the quality and freshness of food products by tracking the time and temperature conditions throughout the supply chain and can also help to improve animal welfare by tracking the movement and conditions of livestock throughout the supply chain, ensuring that they are treated humanely and ethically. All this ultimately leads to the improvement of the quality of agri-food products (Violino et al. 2020).

Technology development (D6)

As new technologies emerge and existing technologies become more sophisticated, companies are able to track and monitor products more accurately and efficiently, improving the transparency, sustainability and security of the supply chain (McGrath et al. 2021). Technology development has also led to the emergence of new e-traceability solutions, such as digital twins and virtual sensors (Dyck et al. 2022). These technologies use digital models and simulations to track and monitor products in real time, providing a level of visibility and transparency that was previously impossible. In addition, the use of blockchain technology in e-traceability systems can provide an even greater level of security and transparency in the supply chain, as all transactions are recorded in a tamper-proof, decentralized ledger (Zhang et al. 2022).

Improved data collection and analysis (D7)

E-traceability systems can collect large amounts of data on product movement, which can be analyzed to identify trends and opportunities for process improvements throughout the supply chain. The development of data analytics and machine learning technologies has made it possible for companies to analyze large amounts of data generated by e-traceability systems, identifying patterns and trends that can help improve efficiency and reduce waste (Zhang et al. 2021).

Brand reputation and competitive advantage (D8)

As consumers become more informed and concerned about issues such as food safety, sustainability and ethical sourcing, companies are under increasing pressure to provide transparent and verifiable information about their products. E-traceability can help companies meet these demands by providing a clear and verifiable record of product origins, quality and sustainability practices. Companies that can demonstrate transparency and accountability in their supply chains through e-traceability are likely to enjoy a better reputation with consumers, build consumer trust, strengthen brand loyalty and differentiate their products from those of competitors, thus increasing sales and creating a competitive advantage (Rahman et al. 2021).

Market participants' demand (D9)

Consumers are increasingly interested in knowing where their food comes from and how it was produced (Kayikci et al. 2022). Accordingly, many large retailers and food manufacturers are now requiring their suppliers to implement traceability systems to meet their own supply chain transparency goals (Collart and Canales 2022). This demand is driving the need for e-traceability.

Regulations and certifications (D10)

Governments and industry organizations have proposed various regulations and certifications aimed at improving the transparency, traceability and safety of the supply chain (Venkatesh et al. 2020). Regulations and certifications can also incentivize companies to adopt e-traceability systems by creating a more level playing field for businesses. Requiring all companies to implement e-traceability systems, regulations and certifications can reduce the risk of free-riding and encourage companies to invest in the necessary infrastructure and technologies to ensure compliance (Manshoven and Opstal 2022).

Criteria for prioritization of e-traceability drivers

The drivers that have been described can be assessed and prioritized using several criteria. These criteria were established according to the literature review and experts' opinions. The composition of the expert pool and the way in which they were selected are presented in more detail in the following section.

Regulatory requirements (C1)

Drivers that are required by law or regulation, such as food safety regulations, should be given a high priority (Liu et al. 2019).

Business impact (C2)

Drivers that have a significant impact on the business, such as improving supply chain efficiency or enhancing brand reputation, should be given a high priority (Duan et al. 2020).

Potential for innovation (C3)

Drivers that have the potential to spur innovation and lead to new opportunities, such as blockchain technology, should be given a high priority (de Villiers et al. 2021).

Impact on food waste reduction (C4)

Drivers that have a positive impact on food waste reduction, such as e-traceability systems that can identify areas of waste in the supply chain, should be given a higher priority (Visconti et al. 2020).

Data security and privacy (C5)

Drivers that prioritize data security and privacy, such as e-traceability systems that protect sensitive information from unauthorized access, should be given a higher priority (Xue and Wang 2022). The aim is to reduce the risks associated with each driver (Hao et al. 2020).

Resilience (C6)

Drivers that prioritize resilience in the face of unforeseen events or disruptions, such as e-traceability systems that allow for rapid response to food safety incidents or supply chain disruptions, should be given a higher priority (Kumar and Kumar Singh 2022).

Transparency (C7)

Drivers that prioritize transparency throughout the supply chain, such as e-traceability systems that allow consumers to access detailed information about the origin and movement of their agri-food products, should be given a higher priority (Feng et al. 2020).

Health and safety (C8)

Drivers that prioritize the health and safety of consumers and workers, such as e-traceability systems that ensure the safety and quality of agri-food products, should be given a higher priority (Yuan et al. 2020).

Adaptability (C9)

Drivers that prioritize adaptability and flexibility, such as e-traceability systems that can be easily modified or updated to meet changing needs and requirements, should be given a higher priority (Gorbunova and Kornienko 2022).

Standardization (C10)

Drivers that prioritize standardization and consistency, such as e-traceability systems that adhere to industry standards and best practices, should be given a higher priority (Nurgazina et al. 2021).

Results

The problem defined in Sect. "Problem description" is solved using the methodology proposed in Sect. "Methodology." The following presents the obtained results based on which the prioritization of e-traceability drivers has been done. The stability and validity of the obtained results are confirmed by conducting the sensitivity analysis and comparing the results with the results obtained by other relevant MCDM methods for the same inputs.

Prioritization of e-traceability drivers

E-traceability drivers and criteria for their prioritization were evaluated by the members of the focus group established for this purpose. A total of 27 experts with various backgrounds, experience and expertise from the sector of supply chain management and agri-food were surveyed (Table 2). The members of the focus group were chosen based on their knowledge and experience in the field, which lends credibility to the evaluation

Table 2 Pool of experts

Sector	Number of experts	Experience (Years)
Supply chain management	4	< 5
	4	5–15
	7	> 15
Agri-food	2	< 5
	6	5–15
	4	> 15

Table 3 Criteria comparison

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	–	–	–	–	"VL"	–	–	–	–	"L"
C2	H	–	"FH"	"L"	"VH"	"VL"	"FL"	"M"	"FL"	"EH"
C3	"VL"	–	–	–	"L"	–	–	–	–	"FL"
C4	"M"	–	"FL"	–	"FH"	–	"VL"	"L"	"VL"	"H"
C5	–	–	–	–	–	–	–	–	–	"VL"
C6	"FH"	–	"M"	"VL"	"H"	–	"L"	"FL"	"L"	"VH"
C7	"FL"	–	"L"	–	"M"	–	–	"VL"	–	"FH"
C8	"L"	–	"VL"	–	"FL"	–	–	–	–	"M"
C9	"FL"	–	"L"	–	"M"	–	"N"	"VL"	–	"FH"
C10	–	–	–	–	–	–	–	–	–	–

process. The inclusion of experts from various backgrounds and experiences ensured a comprehensive evaluation. This diversity allowed for different viewpoints, leading to a well-rounded understanding of the topic.

The experts' evaluations of the criteria and alternatives were statistically merged using a probability distribution, with the most frequent assessments representing the entire focus group, and subsequently transformed into triangular fuzzy values to create a fuzzy criteria evaluation matrix (1) based on pairwise comparisons from Table 3.

Using Eqs. (2) and (3), the potential criteria impact and total impact (importance) of criteria were obtained. Afterwards, the final fuzzy weights of criteria were obtained using Eqs. (4)–(6). Aforementioned values are presented in Table 4.

Statistically merged evaluations of the alternatives (e-traceability drivers) by the criteria (Table 5) were transformed into triangular fuzzy numbers, thus forming a fuzzy decision matrix (7). Using Eqs. (8)–(9) a normalized fuzzy decision matrix is formed, while using Eq. (10) a sorted fuzzy decision matrix is formed, based on which coordinates of the fuzzy reference and fuzzy weighted reference points were obtained by applying Eqs. (11)–(14).

Afterwards, the fuzzy values representing the fuzzy volumes of the complex polyhedra were calculated using Eqs. (15)–(29). They were afterwards defuzzified, applying Eq. (30) and used for ranking the alternatives (Table 6).

Ranking was carried out according to the decreasing crisp values and as it can be seen from the results the best ranked e-traceability driver is D2 (Supply chain efficiency), D6 (Technology development) and D3 (Sustainability).

Table 4 Potential impact, total impact and fuzzy weights of criteria

	$\widetilde{I}$	$\widetilde{I}_j$	$\widetilde{w}_j$
C1	(4.4, 6.8, 9.8)	(76.4, 87.8, 99.8)	(0.520, 0.870, 1.356)
C2	(39.0, 48.0, 57.0)	(111.0, 129.0, 147.0)	(0.755, 1.277, 1.998)
C3	(7.3, 10.8, 14.8)	(79.3, 91.8, 104.8)	(0.540, 0.909, 1.424)
C4	(22.6, 29.8, 37.5)	(94.6, 110.8, 127.5)	(0.643, 1.098, 1.733)
C5	(2.5, 3.9, 5.8)	(74.5, 84.9, 95.8)	(0.507, 0.841, 1.303)
C6	(30.3, 38.5, 47.0)	(102.3, 119.5, 137.0)	(0.696, 1.183, 1.862)
C7	(16.3, 22.1, 27.8)	(88.3, 103.1, 117.8)	(0.601, 1.021, 1.602)
C8	(11.3, 15.8, 21.1)	(83.3, 96.8, 111.1)	(0.567, 0.958, 1.51)
C9	(16.8, 22.1, 28.8)	(88.8, 103.1, 118.8)	(0.604, 1.021, 1.615)
C10	(1.6, 2, 2.9)	(73.6, 83, 92.9)	(0.5, 0.822, 1.263)

Table 5 Evaluations of e-traceability drivers

	D1	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**	**D9**	**D10**
C1	"VH"	"EH"	"L"	"N"	"N"	"M"	"VL"	"FL"	"H"	"VL"
C2	"N"	"EH"	"H"	"VH"	"N"	"FH"	"L"	"VL"	"L"	"VL"
C3	"N"	"EH"	"EH"	"H"	"L"	"FH"	"VL"	"N"	"VL"	"L"
C4	"N"	"EH"	"VH"	"N"	"N"	"VH"	"L"	"VL"	"VL"	"N"
C5	"N"	"H"	"FH"	"VL"	"N"	"VH"	"FL"	"VH"	"EH"	"L"
C6	"N"	"FH"	"H"	"EH"	"VH"	"L"	"VL"	"M"	"M"	"VH"
C7	"VL"	"VH"	"M"	"FL"	"FL"	"EH"	"FH"	"L"	"N"	"L"
C8	"N"	"M"	"H"	"VH"	"VH"	"M"	"FH"	"N"	"VL"	"EH"
C9	"N"	"VH"	"VL"	"M"	"FL"	"H"	"EH"	"FH"	"VL"	"FH"
C10	"N"	"M"	"VL"	"VL"	"VL"	"M"	"L"	"FH"	"H"	"VH"

Table 6 Ranking of e-traceability drivers

	D1	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**	**D9**	**D10**
Crisp($\widetilde{V}_i^C$)	0.324	0.368	0.354	0.344	0.340	0.354	0.343	0.339	0.341	0.344
Rank	10	1	3	4	8	2	6	9	7	5

Sensitivity analysis

Sensitivity analysis in the context of Multi-Criteria Decision-Making (MCDM) involves assessing how changes in the relative weights of criteria used in the decision-making process affect the final outcomes and rankings of alternatives. It allows decision-makers to understand the extent to which changes in the criteria weights affect the rankings of alternatives. By testing the sensitivity of the results to variations in criteria weights, decision-makers can evaluate the robustness of their decisions. A robust decision remains consistent even when the weights of criteria are changed. In addition, MCDM methods often involve subjective judgments to assign criteria weights. Sensitivity analysis provides a way to explore the impact of different weightings, allowing decision-makers to understand the range of possible outcomes. Finally, sensitivity analysis aids in understanding the trade-offs between criteria. By observing how changes in weights affect

Table 7 Sensitivity analysis

Scenario	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
"Sc.0"	10	1	3	4	8	2	6	9	7	5
"Sc.1"	10	1	3	4	8	2	6	9	7	5
"Sc.2"	10	1	3	4	8	2	6	9	7	5
"Sc.3"	10	1	3	4	8	2	6	9	7	5
"Sc.4"	10	1	3	4	8	2	6	9	7	5
"Sc.5"	10	1	3	4	8	2	6	9	7	5
"Sc.6"	10	1	3	4	8	2	6	9	7	5
"Sc.7"	10	1	3	4	8	2	6	9	7	5
"Sc.8"	10	1	3	4	9	2	6	8	7	5
"Sc.9"	10	1	2	4	9	3	6	8	7	5
"Sc.10"	10	1	2	4	9	3	5	8	7	6
"Sc.11"	10	1	2	4	9	3	5	8	7	6
"Sc.12"	10	1	2	4	9	3	5	8	7	6
"Sc.13"	10	1	3	4	8	2	6	9	7	5
"Sc.14"	10	1	2	4	8	3	6	9	7	5
"Sc.15"	10	1	2	4	8	3	6	9	7	5
"Sc.16"	10	1	2	4	8	3	6	9	7	5
"Sc.17"	10	1	2	6	8	3	5	9	7	4
"Sc.18"	10	1	2	6	8	3	4	9	7	5

the rankings, decision-makers can grasp the compromises that might need to be made among conflicting criteria.

To analyze the sensitivity of the solution obtained in this study, 18 scenarios ("Sc.1–18") were established. In the first six scenarios, the weight assigned to the most critical criterion (C2) was reduced by 15%, 30%, 45%, 60%, 75% and 90%, respectively. In the following six scenarios, the same was done with the second most important criterion (C6) and in the last six scenarios, the same was done with the third most important criterion (C4). The obtained rankings were compared with the results obtained in the basic scenario (Sc.0) (Table 7).

It can be seen from Table 7 that alternative D2 is the best-ranked, while alternatives D6 and D3 are interchangeably ranked as the second and third best, in all 18 scenarios. From the comparative overview of the obtained rankings, presented in Fig. 1, it can be concluded that there are no significant changes in the obtained rankings. Therefore, it can be concluded that the ranking obtained in the basic scenario is stable enough.

Validation of results

The validation was carried out by comparing the results obtained using the fuzzy ADAM method to the results obtained using several other MCDM methods, such as fuzzy TOPSIS, fuzzy VIKOR, fuzzy COBRA, fuzzy AHP, fuzzy CODAS and fuzzy SWARA. The aim of this validation process was to assess the effectiveness and reliability of the proposed method. The validation was conducted on the same dataset, and the comparative view of the obtained rankings is presented in Fig. 2.

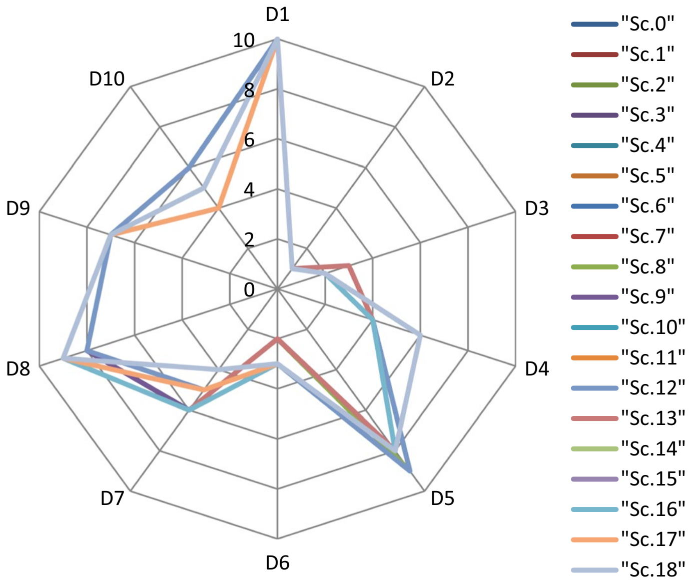

Fig. 1 Sensitivity analysis

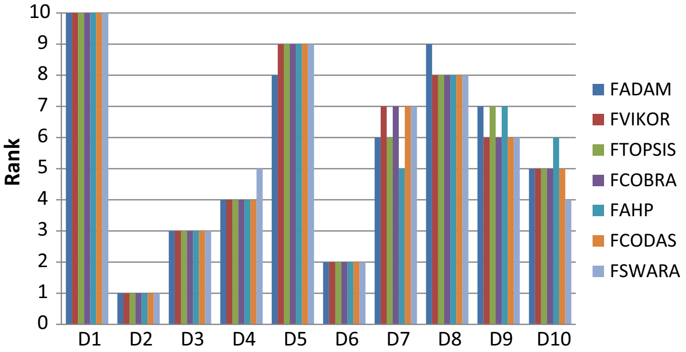

Fig. 2 Comparison of the rankings obtained by various MCDM methods

Subsequently, the Spearman correlation coefficient (SCC) was employed to gauge the intensity and direction of the relationship between the rankings obtained. A high Spearman correlation coefficient indicates that the MCDM method is consistent with the benchmark rankings, which provides evidence for the validity of the MCDM method. SCC values for the comparison of rankings obtained using the fuzzy ADAM method with the rankings obtained by other MCDM methods are presented in Table 8. The fuzzy ADAM method achieved an average value of 0.976, which indicates that there is a significant statistical correlation of the results with the results obtained with other MCDM methods. Therefore, it is confirmed that the proposed method is consistent and reliable, which highlights its potential for use in decision-making applications in various fields.

Table 8 SCC values for comparing the results obtained by fuzzy ADAM method to other MCDM methods

	FVIKOR	FTOPSIS	FCOBRA	FAHP	FCODAS	FSWARA
FADAM	0.97576	0.98788	0.97576	0.97576	0.97576	0.9634

Discussion

The study makes significant contributions to the field of agri-food, logistics, supply chains and multi-criteria decision-making by addressing a pressing research problem and providing novel insights. In this section, the key contributions of the study, highlighting its innovative approaches, methodologies and findings are discussed. It is emphasized how the study fills existing research gaps and advances the current state of knowledge in the field. In addition, a critical discussion of the limitations and potential challenges encountered during the research process is provided. By acknowledging these limitations, the aim is to provide a transparent evaluation of the study's scope and boundaries. Lastly, the broader implications of the findings, discussing their potential impact on theory, practice, and policy are provided.

Contributions

One of the main contributions of the study lies in its comprehensive analysis and definition of a broad set of e-traceability drivers in agri-food supply chains. Unlike some previous studies dealing with drivers (e.g., Davari et al. 2023; Liu and Gao 2020, 2016; Zhang et al. 2021; Srivastava and Dashora 2021, etc.) and enablers, issues and challenges (e.g., Arora et al. 2023; Della Corte et al. 2021), this study establishes a holistic framework that encompasses the key elements necessary for successful implementation of e-traceability systems within the agri-food sector by examining various factors and considerations. These drivers encompass supply chain efficiency, technology development, sustainability, food safety, regulations and certifications, data collection and analysis and so forth. The contribution lies in providing a systematic and detailed understanding of the multifaceted drivers that shape e-traceability, thereby offering valuable insights for policymakers, industry stakeholders and researchers to effectively navigate the complexities and leverage the potential of electronic traceability to enhance transparency, safety and sustainability in the agri-food sector.

Previous studies have investigated some of the criteria for evaluating certain e-traceability drivers (e.g., Liu et al. 2019; Duan et al. 2020; de Villiers et al. 2021; Patidar et al. 2021; Yadav et al. 2022), but this study proposes a comprehensive and systematic overview of a broad set of criteria that can be utilized to evaluate and prioritize e-traceability drivers, which is another notable contribution of this study. By considering these criteria, the study offers a structured approach to assess the relative importance and potential impact of different drivers. This framework equips policymakers, industry practitioners and researchers with a robust tool to make informed decisions regarding the selection and implementation of e-traceability drivers in the agri-food sector. By integrating multiple dimensions and providing a systematic evaluation process, the contribution significantly enhances the understanding and application of e-traceability.

One of the main contributions of the study lies in the development of a novel hybrid MCDM model that merges the FARE and ADAM methods within a fuzzy environment. The FARE method has already been extended to the fuzzy environment (Roy et al. 2020), but this is the first study using the fuzzy extension of the conventional ADAM method (Krstić et al. 2023b). This innovative approach addresses the inherent uncertainty and imprecision associated with decision-making processes in complex systems, such as agri-food supply chains. By integrating the strengths of both FARE and ADAM, the hybrid model offers a more robust and reliable framework to evaluate and prioritize various factors and alternatives related to e-traceability in the agri-food sector. This contribution not only enhances the scientific understanding of decision-making methodologies but also provides practical guidance to policymakers, industry stakeholders and researchers in effectively navigating the complexities of e-traceability implementation and improving overall decision-making processes for sustainable and efficient agri-food supply chains.

Limitations

While the study considers a comprehensive range of e-traceability drivers, it should be noted that the list provided is not exhaustive. Additional drivers that hold significant importance in promoting the widespread adoption of e-traceability strategies within agri-food supply chains may exist. Similarly, the defined set of criteria is subject to potential expansion. However, any inclusion of additional criteria would require careful consideration of the problem's dimensions and the feasibility of adequately evaluating alternatives across a large number of criteria. It is important to acknowledge that such an expansion could considerably heighten the complexity of the problem at hand. Therefore, striking a balance between inclusivity and manageability becomes crucial when contemplating the integration of supplementary drivers or criteria into the framework.

Another issue is the selection of experts. While including experts from various backgrounds and experiences can enhance the comprehensiveness of the evaluation, the generalizability of the results might still be limited. The focus group's diversity may not fully capture the range of perspectives and expertise present across the entire population relevant to the evaluation. The insights obtained from a diverse focus group may not fully reflect the opinions and priorities of stakeholders outside the group, potentially affecting the generalizability of the results. Accordingly, another notable limitation of the study is the lack of separate consideration for the perspectives of different stakeholders in addressing the problem. By not explicitly incorporating the viewpoints of various stakeholders, there is a possibility that the final ranking of alternatives might undergo certain modifications if strict measures were in place to ensure comprehensive representation. Furthermore, the failure to account for individual perspectives from different interest groups hinders the ability to assign priority to specific stakeholders, which could be valuable in certain contexts or scenarios. Incorporating the diverse views of interest groups would enhance the comprehensiveness and fairness of the decision-making process, allowing for a more nuanced understanding of the complex dynamics at play within the agri-food supply chains. Future research should aim to address this limitation by incorporating the voices of different stakeholders and exploring their implications on the prioritization and decision-making processes.

The MCDM model employed in this study presents a limitation regarding the dimensions of the problem at hand. While the theoretical framework itself possesses the capability to address and resolve problems of any scale, practical implementation of the model poses challenges, particularly in scenarios involving large dimensions. The inherent complexity of such problems necessitates substantial resources, predominantly in terms of time, to obtain meaningful and relevant results. The increased dimensionality introduces computational and logistical burdens, which may impede the efficiency and feasibility of applying the MCDM model to real-world contexts. As a result, careful consideration must be given to striking a balance between problem dimensionality and the available resources to ensure that the MCDM model is applied effectively and efficiently. Future research should explore innovative approaches, such as optimization techniques or parallel computing, to mitigate the limitations associated with large-dimensional problems, thereby enhancing the practical applicability and scalability of the MCDM model.

Implications

There are two main aspects of theoretical and practical (managerial) implications of the problem defined and solved in this study. The first one concerns the problem itself, while the other one concerns the developed methodology.

The evaluation and ranking of e-traceability drivers can have several theoretical implications. They can improve understanding of the underlying mechanisms and dynamics that shape the performance, sustainability and legitimacy of the supply chains. In light of the network theory, e-traceability can be seen as a tool that facilitates coordination and communication among the various actors in the supply chain. Network theory suggests that effective coordination and communication can lead to improved performance of the network as a whole (Hearnshaw and Wilson 2013). Therefore, evaluation and ranking of e-traceability drivers can help identify the key drivers that contribute to the coordination and communication among the actors in the supply chain and ultimately improve the performance of the network. Resource dependence theory suggests that organizations depend on each other for resources that they cannot produce themselves (Casciaro and Piskorski 2005). In the context of agri-food supply chains, e-traceability can be seen as a resource that is needed by all the actors in the supply chain to ensure the safety and quality of the products. Evaluation and ranking of e-traceability drivers can help identify the key resources that are needed by the actors in the supply chain and how these resources can be managed to ensure their availability and quality. Further, institutional theory suggests that organizations are influenced by the norms, values and beliefs of their institutional environment (David et al. 2019). In the context of agri-food supply chains, e-traceability can be seen as a norm that is expected by consumers and regulators to ensure the safety and quality of the products. The evaluation and ranking of e-traceability drivers can help identify the key norms and values that are associated with e-traceability and how these norms and values can be aligned with the institutional environment to ensure their legitimacy and acceptance. Finally, stakeholder theory posits that organizations have a responsibility to prioritize the interests of all stakeholders, including customers, suppliers, employees and society as a whole (Dmytriyev et al. 2021). In the context of agri-food supply chains, e-traceability can be seen as a tool that helps organizations to fulfill their responsibility toward the stakeholders by ensuring the safety and quality of the products. Evaluation and ranking of e-traceability drivers can help identify the key stakeholders in the agri-food supply chains, and how their interests can be aligned with the e-traceability drivers to ensure their satisfaction and support.

Evaluation and ranking of e-traceability drivers can have several practical (managerial) implications. By identifying the key drivers and employing them to boost e-traceability, several positive effects can be generated for companies and practitioners dealing with agri-food supply chains. E-traceability can improve transparency and accountability in agri-food supply chains by providing accurate and timely information on the origin, quality and safety of the products (Heft-Neal et al. 2016). This can help build trust among the stakeholders and improve the reputation of the supply chain. E-traceability can help identify and manage risks in the supply chain, such as food safety hazards, product recalls and supply chain disruptions (Corallo et al. 2020). This can help reduce the impact of such risks on the supply chain and improve its resilience. E-traceability can improve the efficiency and productivity of the supply chain by reducing the time and resources required for tracing and tracking products (Manavalan and Jayakrishna 2019). This can help reduce costs and improve the overall performance of the supply chain. E-traceability can facilitate collaboration and coordination among the stakeholders in the supply chain, such as farmers, processors, distributors and retailers (Dmytriyev et al. 2021). This can help improve communication, reduce conflicts and enhance the overall effectiveness of the supply chain. E-traceability can help ensure compliance with regulations and standards related to food safety, quality and environmental sustainability (World Health Organization 2020). This can help reduce the risk of legal and reputational consequences and improve the competitiveness of the supply chain.

The development of a new multi-criteria decision-making (MCDM) model can have several practical implications for managers and decision-makers. The new MCDM model can provide managers with a more structured and systematic approach to decision-making. It can help to organize and evaluate complex decision problems involving multiple criteria, leading to more informed and effective decisions. By developing a new MCDM model, this study introduces innovative techniques and frameworks that allow managers to better assess and rank the available alternatives. This can lead to more reliable and accurate evaluations, aiding in the selection of the most suitable options. MCDM models often involve considering the perspectives and preferences of various stakeholders involved in a decision. The new MCDM model developed in this study can provide mechanisms for incorporating stakeholder input and facilitate participatory decision-making processes. This can enhance stakeholder engagement, leading to increased acceptance and satisfaction with the decision outcomes. Decision-making in real-world scenarios is often accompanied by uncertainty and risk. The new MCDM model is developed in the fuzzy environment to explicitly address the uncertainty and ambiguity of the decision-makers' evaluations. This can assist managers in making more reliable decisions based on various decision-makers' opinions. Certain decision problems involve a high degree of complexity, such as resource allocation, project portfolio management or strategic planning. The new MCDM model can offer tailored techniques or algorithms to handle such complex problems efficiently. This can save managers' time and effort in decision analysis, enabling them to focus on more critical aspects of the decision-making process. Different organizations may have unique decision-making requirements, constraints or preferences. Developed MCDM model allows for customization and adaptation to specific organizational contexts. Managers can tailor the method to suit their organization's specific needs, industry characteristics or decision-making culture, resulting in more contextually relevant and actionable decision support.

The development of a new multi-criteria decision-making (MCDM) method has several theoretical implications. MCDM methods are rooted in decision theory, which aims to understand and improve the decision-making process. By developing the new MCDM method, this study contributes to the theoretical advancements in decision theory by proposing a novel approach to handle complex decision problems involving multiple criteria. MCDM methods are designed to help decision-makers make more informed and rational choices when faced with complex decisions. The new MCDM method improves decision quality by offering a more robust and effective framework to evaluate and compare alternatives based on multiple criteria. Many decision problems in various domains, such as business, engineering, environmental planning and healthcare, involve multiple conflicting criteria and uncertainties. The new MCDM method can provide a theoretical basis to address these complexities, allowing decision-makers to make more comprehensive and realistic decisions in practical scenarios. MCDM methods often aim to bridge the gap between theoretical models and real-world decision-making situations. By developing the new MCDM method, this study contributes to the theoretical foundation of decision-making while also ensuring its practical relevance by incorporating insights and considerations from real-world applications. Overall, the theoretical implications of developing a new MCDM method lie in advancing decision theory, improving decision quality, addressing complexity and bridging theory and practice. These implications contribute to the overall development and evolution of the field of decision-making, benefiting both researchers and practitioners alike.

Conclusion

Focusing on the prioritization of e-traceability drivers within agri-food supply chains, the study identified three key drivers as the most important ones: supply chain efficiency, technology development and sustainability. Through a rigorous analysis and evaluation process, these drivers emerged as critical factors that significantly impact the successful implementation and adoption of e-traceability strategies in the agri-food sector. The prioritization of supply chain efficiency underscores the importance of streamlining operations, enhancing transparency and optimizing resource utilization to improve overall performance. The emphasis on technology development highlights the need for continuous innovation and integration of advanced technologies to enable effective traceability systems. Additionally, the inclusion of sustainability as a top driver reflects the growing recognition of environmental and social responsibilities within the agri-food industry, emphasizing the significance of sustainable practices and their integration into e-traceability initiatives. By identifying and prioritizing these drivers, the study provides valuable insights for policymakers, industry practitioners and researchers to develop strategies and frameworks that promote efficient, technologically advanced and sustainable e-traceability systems.

The prioritization of e-traceability drivers within agri-food supply chains was carried out based on the evaluations of 27 experts. The selection of experts from the sectors of supply chain management and agri-food provided evaluations that are more relevant and applicable to this particular industry. However, the generalization of these findings could also be extended to other sectors or industries by considering their unique characteristics and requirements. Different industries may have specific drivers, priorities and criteria that need to be taken into account, which should be fully represented in the focus group.

Future research efforts could address the main limitations of this study, as well as some other aspects. Additional drivers and criteria for their evaluation could be included. Evaluation could also be done by involving representatives of multiple stakeholders. Furthermore, the developed MCDM, or some of its parts, could also be used to develop other MCDM models, but also to solve other problems in this or any other area.

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Author contributions
GPA and MK conceptualized the original research idea, designed the methodology, collected the data, and wrote the original draft of the manuscript. PPM conducted the investigation, performed the formal analysis, supervised the entire research activity planning and execution and wrote the original draft. ST dealt with the visualization of the manuscript and wrote the original draft. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed for the current study are available on reasonable request to the corresponding author.

Declarations

Competing interests
The authors declare that they have no competing interests.

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