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WAGENINGEN UNIVERSITY & RESEARCH

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This study examines how food traceability systems can enhance consumer acceptance of novel foods through enhanced supply chain transparency and reviews the integration of blockchain for improved traceability. Food traceability systems operate across physical, information, and governance layers and concern a wide variety of methodologies. An assessment framework was designed to identify and prioritise the most suitable approaches for different supply chain contexts. Developed and tested during expert workshops, it incorporated key criteria identified by experts to ensure it addressed real-world challenges in food traceability. Its relevance was demonstrated, particularly for novel foods such as plant-based meat replacers. The findings highlight the importance of a structured approach to traceability, showing how blockchain and traceability techniques can improve transparency while acknowledging challenges such as adoption barriers and regulatory inconsistencies.

Key words: Food traceability systems, consumer acceptance, novel foods, blockchain technology, traceability methods, traceability framework

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Contents

Preface

Our food system is undergoing a rapid transformation driven by innovations such as plant-based meat alternatives, lab-cultivated meats, and microalgae-derived proteins. While addressing many challenges in the food system, these innovations bring new layers of complexity that demand robust food traceability systems to ensure safety and transparency of future systems.

This report explores the intersection of emerging technologies and food traceability, with a particular focus on evaluating methodologies relevant to food traceability and the relevance of blockchain. We believe that the findings of this report will contribute to ongoing discussions and initiatives aimed at enhancing transparency and traceability in food systems, ultimately fostering innovations that support a more sustainable and resilient food system.

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Summary

S.1 Main research question: How to evaluate traceability methodologies and what is the relevance of blockchain to food traceability systems?

How can food traceability methodologies be evaluated and what is the relevance of blockchain to food traceability systems? As consumer acceptance of novel foods is not guaranteed due to concerns about safety, unfamiliarity and trust, traceability systems play a crucial role in increasing transparency, reliability, and real-time monitoring. Therefore, applying relevant and effective traceability methodologies is essential for ensuring robust food product tracking. Moreover, interest in blockchain as a key component of food traceability is increasing, highlighting the needs to assess its role in enhancing traceability systems.

S.2 Message: Food traceability and consumer acceptance of novel foods can be enhanced through traceability frameworks and blockchain integration

How can traceability systems address consumer acceptance challenges for novel foods and enhance the robustness of food traceability, through the creation of a framework for evaluating traceability methodologies and the integration of blockchain technology within the food supply chain?
Traceability systems play a crucial role in addressing consumer acceptance challenges for novel foods by providing transparency and building trust in the food supply chain. Establishing and applying a framework for evaluation of different traceability methodologies allows for the comparison of various approaches to ensure that they are efficient, accurate, and reliable. The integration of blockchain technology can further enhance the robustness of food traceability by providing an immutable, decentralised record of transactions, ensuring data integrity and making it easier for stakeholders to access and verify information in real time.

How does traceability contribute to overcoming consumer acceptance challenges in novel foods?
Traceability systems enhance consumer acceptance of novel foods by ensuring transparency, reliability, and real-time monitoring. Concerns about safety, unfamiliarity, and trust make acceptance uncertain, but traceability helps by documenting food origins, production, and safety measures.

What are the different layers that make up food traceability systems, and how does blockchain integrate into these layers to support a comprehensive strategy for consumer acceptance?
Food traceability systems consist of physical, information and governance layers. Blockchain, using data derived from the information layer, strengthens food traceability by providing decentralised, immutable record-keeping, enhancing trust and accountability across all layers and along the food supply chain.

What methods are used to generate traceability data for food traceability systems, and how do these methods contribute to robust tracking?
Methodologies used for food traceability include Internet of Things (IoT) technologies for data collection as well as analytical methods: laboratory-based analytical techniques that identify and quantify specific characteristics of food products. Selecting the appropriate method depends on supply chain needs and available resources, ensuring reliable and robust tracking.

What criteria can be used to evaluate and prioritise the most suitable food traceability methodologies for specific contexts in the food supply chain?
Criteria such as accuracy, robustness, costs, ease of use, fit for purpose, standardisation, timelessness, and data analysis can provide a framework for assessing and prioritising traceability methodologies based on their effectiveness in different contexts. Developed and tested in expert workshops, the framework was applied to novel foods like plant-based meat replacers and proved valuable in structuring the evaluation of various approaches. The framework could be adapted for other food categories.

What is the relevance of blockchain for robust food traceability systems in the context of consumer acceptance of novel foods?
Blockchain can enhance the information layer of traceability systems that is crucial in addressing consumer concerns about transparency, trust, and safety in novel foods.

S.3 Methodology: Literature review and expert workshops

The study employs a literature review to explore consumer acceptance of novel foods and the role of traceability. The framework for evaluating traceability methodologies was developed through expert workshops, where key criteria were identified and assessed, ensuring that the framework addressed real-world challenges in food traceability. The study also reviews blockchain integration within traceability systems, drawing on literature to examine its potential to enhance food traceability.

1 Enhancing traceability systems for novel food acceptance

1.1 From records to real-time: addressing the need for integrated approaches in the digital transformation of food traceability

Olsen and Borit (2013) define traceability as the ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications. Food traceability has evolved rapidly from records of origin and simple characteristics to the development of complete tracing systems using all kinds of sensors, machinery, and software to trace food and all its characteristics throughout the food supply chain.

Food traceability plays a crucial role in modern food safety systems for a variety of reasons. First, traceability provides essential documentation that enables efficient tracking of contamination sources during food emergencies through traceback investigations (Kennedy et al., 2020). This not only helps address accidental contamination but also counters intentional threats, such as bioterrorism, where non-state actors may use pathogens or toxins to harm a broader population (Knutsson et al., 2011). It is also critical for preventing the spread of livestock diseases to susceptible herds, which consequently endangers both animal and human health. Additionally, traceability frameworks are necessary to ensure the legality of food products, preventing the mixing of undocumented items with legitimate goods. Moreover, traceability plays a key role in reducing the growing instances of fraud and falsification of compliance with commercial standards required for certifications. By ensuring the authenticity of products, traceability helps prevent unfair competition in the marketplace. Beyond safety and legal reasons, consumers increasingly demand transparency and quick responses in food safety alerts (Kennedy et al., 2020; Dabbene et al., 2014).

Several methodologies can be used for food traceability, including analytical methods and Internet of Things (IoT) technologies. Analytical methods involve the use of laboratory tests and physical examinations to identify the chemical and microbiological properties of food products. These methods can provide detailed information about the origin, composition, and quality of food products, but may not be suitable for real-time monitoring or large-scale food production (Montet and Ray, 2021; Rejeb et al., 2020). On the other hand, IoT technologies are a network of interconnected physical objects, or ‘things’, that involve the use of sensors, RFID (Radio Frequency Identification) tags, and other smart devices to collect data and monitor food products throughout the supply chain. These technologies can provide real-time information about the location, temperature, and other conditions of food products, which can be used to improve food safety and reduce waste through early detection of spoilage and optimised supply chain management. However, the implementation of IoT technologies can be costly and requires significant infrastructure and technical expertise (Creydt and Fischer, 2019).

Blockchain technology has emerged as a promising tool for improving food traceability and transparency (van Hilten, et al., 2020, van Wassenaer, et al., 2021). By using a decentralised ledger system that records transactions and stores data securely and transparently, blockchain can help to track the movement of food products across the supply chain, from the farm to the table. Blockchain technology can provide a tamper-proof and immutable record of food production and distribution, making it easier to identify the source of contamination in case of a foodborne illness outbreak (Rejeb et al., 2020; Treiblmaier, 2018).

Identified research gaps include the need for a more comprehensive and integrated approaches to food traceability: current systems often rely on separate methodologies, each with limitations in terms of real-time monitoring or scalability. Therefore, a more unified approach leveraging the strengths of different technologies, while addressing their individual limitations and balancing safety concerns with consumer demand, is essential to develop robust and efficient traceability systems.

1.2 Food traceability must advance to ensure safety, transparency and sustainability

Food traceability is becoming increasingly critical as the world faces the dual challenge of expanding food production and shifting to more sustainable diets. To feed the global population by 2050, food production must increase by 70%. Simultaneously, there is a growing emphasis on adopting more sustainable diets, including plant-, insect-, and microalgae-based products (Valoppi et al., 2021). This demand for both increased production and dietary change has driven rapid growth in novel foods and advanced food production technologies, underscoring the necessity of effective traceability systems. As food systems become more complex and global trade expands, tracking the origin and processing of food products is increasingly challenging. Consumers are more interested in understanding where their food comes from and how it is produced, allowing them to make informed and safe dietary choices (Feng et al., 2020).

Beyond food safety, blockchain has the potential to revolutionise the food industry, as it can enhance consumer trust in the safety and quality of food products, while also improving efficiency and reducing costs for food producers and suppliers. Acting as an information conduit in food traceability systems, blockchain facilitates the seamless flow of data, enabling transparency and traceability across the supply chain. There is a growing interest in exploring the potential of blockchain technology to improve food traceability and address the growing concerns of consumers regarding food safety and origin (Creydt and Fischer, 2019). Utilising digital recording and tracing methods can contribute positively to the concept of sustainability, particularly regarding quality standards that depend on consumer trust, such as animal welfare, working conditions, and environmental requirements that cannot be measured through instrumental lab tests (Creydt and Fischer, 2019; Kim and Laskowski, 2017).

There is a need for robust food traceability systems that are highly advanced and seamlessly integrated into the global food supply chain to face these challenges. With the use of cutting-edge technologies such as IoT and blockchain to provide real-time, transparent, and tamper-proof tracking of food products from farm to table, consumers could have better access to detailed information about the origin, composition, and processing of their food. The implementation of these traceability systems could ensure food safety, prevent fraud, and enhance consumer trust. Additionally, these systems would support sustainable food production practices by promoting transparency and accountability in areas such as animal welfare, working conditions, and environmental impact. As a result, the global food supply chain would become more efficient, resilient, and capable of meeting the growing demand for both increased food production and sustainable diets.

1.3 Sub-questions and main research question: How to evaluate traceability methodologies and integration of blockchain technology in food supply chains?

The main research question of this research was: How can traceability systems address consumer acceptance challenges for novel foods and enhance the robustness of food traceability, through the creation of a framework for evaluating traceability methodologies and the integration of blockchain technology within the food supply chain?

The following sub-questions guide the research:

1. How does traceability contribute to overcoming consumer acceptance challenges in novel foods?
2. What are the different layers that make up food traceability systems, and how does blockchain integrate into these layers to support a comprehensive strategy for consumer acceptance?
3. What methods are used to generate traceability data for food traceability systems, and how do these methods contribute to robust tracking?
4. What criteria can be used to evaluate and prioritise the most suitable food traceability methodologies for specific contexts in the food supply chain?
5. What is the relevance of blockchain for robust food traceability systems in the context of consumer acceptance of novel foods?

1.4 Message: Food traceability and consumer acceptance of novel foods can be enhanced through traceability frameworks and blockchain integration

Traceability systems play a critical role in addressing consumer acceptance challenges for novel foods and strengthening food traceability by providing transparency, reliability, and real-time monitoring. As consumer acceptance of novel foods is not guaranteed due to concerns about safety, unfamiliarity, and trust, traceability helps build confidence by ensuring that food origins, production processes, and safety measures are clearly documented.

Effective traceability systems consist of three key layers—physical, information, and governance—each contributing to a comprehensive strategy for food transparency. Blockchain can enhance these systems by enabling immutable and decentralised record-keeping, improving trust and accountability across the supply chain.

Various methods generate traceability data, including IoT-based tracking for real-time monitoring and analytical techniques that verify food composition and authenticity, both of which contribute to robust tracking. The diverse range of food traceability methodologies highlights the need for a framework that identifies and prioritises the most suitable approach for each specific context, as the selection of an appropriate methodology is inherently linked to the unique needs and requirements of the food supply chain, along with the available resources and technical capabilities.

To support informed decision-making in the design of food traceability systems, a framework for evaluating and prioritising traceability methodologies was developed, allowing stakeholders to assess different approaches based on their suitability for specific supply chain contexts. The study’s framework was tested and demonstrated its relevance for evaluating traceability methods, particularly in the context of novel foods such as plant-based meat replacers and could be extended to other food categories and supply chains.

Blockchain’s integration within traceability systems further strengthens food traceability, but challenges remain, including adoption resistance, regulatory inconsistencies, and interoperability issues. While blockchain offers a promising solution, its effectiveness depends on its alignment with other traceability technologies and industry-wide acceptance.

2 Methodology: Literature review and expert workshops

The method used in Chapter 3, ‘Traceability advances consumer acceptance of novel foods and novel food technologies’, is a literature review that synthesises existing research from various sources, including studies from the years 2006 to 2022. The review aims to explore the challenges and opportunities surrounding consumer acceptance of novel foods and the role traceability systems can play in addressing these challenges. Drawing on 17 studies published in English, the review outlines the concept of food neophobia, examining factors that affect consumer willingness to try novel foods, and discusses how traceability can mitigate some of these concerns. The screening and selection of relevant literature were conducted by a single researcher.

In Chapter 4, ‘Food traceability systems enable a comprehensive approach to novel food acceptance through layered integration’, a literature review focusing on peer-reviewed academic sources was conducted to establish a comprehensive understanding of food traceability systems and the integration of blockchain technology into these systems. Key terms such as ‘food traceability’, ‘traceability methodology’, and ‘blockchain’ were used to identify 5 relevant studies published in English, dating from years 2017 to 2022.

The method used in Chapter 5, ‘Traceability information is generated through different methods for robust tracking,’ combines insights from existing literature with expert feedback to provide a comprehensive understanding of method used in food traceability systems. This section reviews the role of IoT technologies in data collection for real-time tracking of food products (Section 5.1), as well as the application of analytical methods for identifying food products through scientific techniques (Section 5.2). The literature includes 28 studies from various sources and from years 2006 to 2024. To ensure a thorough exploration of the subject, the snowballing technique was employed, allowing the references of selected articles to be examined to uncover additional pertinent works. In addition to the literature, experts in food analysis were consulted to provide valuable insights and feedback on the methods described in this section. Their expertise ensured the relevance and accuracy of the methods outlined, with a focus on the latest developments and practical applications in the field of food traceability.

The framework for the evaluation and prioritisation of food traceability methodologies that is detailed in Chapter 6, was developed based on the knowledge accumulated throughout the project, including insights gained from previous sections and through workshops. Two workshops were held to establish and refine the evaluation framework. The first workshop convened experts in food traceability to discuss and identify key criteria for evaluating traceability methods. These criteria formed the foundation of the framework. The second workshop, held towards the end of the project, focused on assessing the feasibility of various traceability methods and exploring how the framework could be applied to evaluate these methodologies in practice. The data collected from these workshops, including participant feedback, group discussions, and expert insights, were analysed to inform the study’s conclusions. This iterative process ensured that the proposed framework was robust, relevant, and well-suited for assessing different food traceability solutions in the context of real-world applications.

Blockchain technology has been further explored in Chapter 7 as a potential solution to enhance transparency and data integrity across the food supply chain. To assess blockchain’s role, we reviewed its integration with various methodologies that improve food traceability. The method used to explore these themes involved reviewing relevant literature from years 2018 to 2023, particularly studies that provide case examples and theoretical frameworks on blockchain’s integration with food traceability systems, consumer acceptance, and technological barriers. Key terms such as ‘blockchain technology’, ‘food traceability’, and ‘integration’ were used to identify 9 relevant studies.

3 Traceability advances consumer acceptance of novel foods and novel food technologies

3.1 Consumer acceptance of novel foods is not guaranteed

The need for increased food production alongside shifting dietary preferences is driving rapid growth in novel foods and innovative food production technologies. The European Commission (n.d.) defines them as 'newly developed, innovative food, food produced using new technologies and production processes, as well as food which is or has been traditionally eaten outside of the EU'. However, consumers do not easily accept these novel foods and novel food technologies, as shown in Figure 3.1 and Figure 3.2. The psychological attitude that affects the consumption and acceptance of food by consumers is referred to as *food neophobia*. It is a condition in which consumers feel doubtful toward and resistance against new foods (Siddiqui et al., 2022). According to Gresham et al. (2006), 80% of food innovation products fail. Therefore, food neophobia poses challenges for consumer acceptance of novel foods (Meiselman et al., 2010).

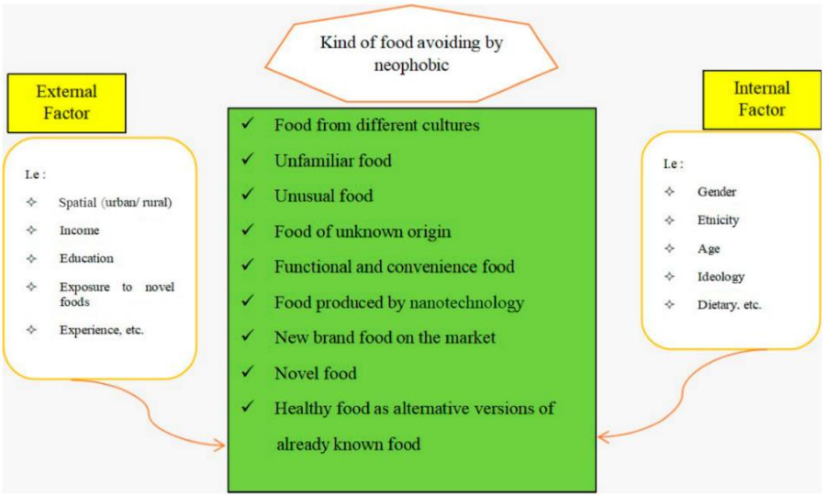

Figure 3.1 *The different types of food neophobia and the internal and external factors that influence them*
Source: Siddiqui et al. (2022).

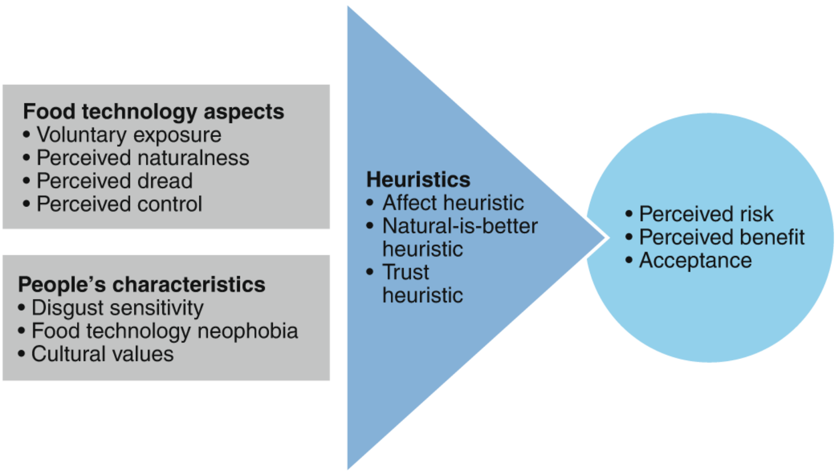

Figure 3.2 *Factors influencing the perception of novel food technologies*
Source: Siegrist and Hartmann (2020).

Consumer acceptance of novel foods has become an increasingly important topic in recent years, as advancements in food science and technology have led to the development of a wide range of new and innovative food products such as plant-based meat substitutes and alternative protein sources. While these novel foods have the potential to offer a variety of benefits, such as improved nutrition, enhanced flavour, and increased sustainability, their success in the marketplace ultimately depends on whether consumers are willing to try and accept them. Understanding the factors that influence consumer acceptance of novel foods is therefore critical for food producers, retailers, and policymakers looking to promote the development and adoption of new food products.

Some of the main reasons of food neophobia that need to be overcome include (Bryant and Barnett, 2018):

- *Lack of familiarity*
  Novel foods are often unfamiliar to consumers, and this can make them hesitant to try them. Consumers tend to prefer foods that they are familiar with and that are part of their cultural and social norms.
- *Perceived safety concerns*
  Consumers may have concerns about the safety of novel foods, particularly those that have been genetically modified or are made using new technologies. This can lead to a lack of trust in these products, and reluctance to consume them.
- *Taste and sensory qualities*
  The taste and sensory qualities of a food are important factors in determining whether consumers will accept it. Novel foods may have unusual flavours or textures that are unfamiliar to consumers, which can make them less appealing.
- *Labelling and communication*
  Clear and accurate labelling is important for helping consumers understand what they are eating and making informed choices. However, labelling for novel foods can be complex and require specific information that consumers may not be familiar with.
- *Cultural and social factors*
  Food preferences and behaviours are influenced by cultural and social norms, which can vary widely across different regions and demographics. This can make it difficult to introduce novel foods into certain markets or among specific groups of consumers.

3.2 Traceability as a key contributor to addressing consumer acceptance challenges in novel foods

Traceability and transparency, along with expectations of swift responses to food safety alerts, helps build trust and reduce fear, leading to higher sales and potentially greater profits for traceable foods. In the event of a foodborne illness or contamination, rapid responses and recalls save lives and minimise reputational damage (Kennedy et al., 2020). Alcorta et al. (2021) claim that through informative and clear labelling, a part of food neophobia can be alleviated. Schouteten et al. (2016) make a similar claim, that consumers demand clear information and regulation with concerns to safety and labelling, and product perception for consumers can be improved when clear and informative labelling is achieved (exact protein source, etc.).

The results of Siegrist et al. (2018) support that claim, as they found that consumer acceptance of insect-based burgers improved when information on the ingredients was provided, preferably in a non-technical manner that emphasises the final product instead of the production method. Additionally, high levels of processing, such as those required to improve texture, or the presence of preservatives can trigger food neophobia (Pasqualone, 2022). Bryant and Barnett (2018) claim that for novel foods that are perceived as unnatural or heavily processed product perception could be improved by specifying the exact protein source in the ingredients list and accompanying the food products with information explaining the environmental advantages of the innovation, as well as emphasising the specific qualities of the final product. Providing clear, clean, and informative information on novel foods is therefore a requirement to increase social acceptance which can be achieved by transparent food traceability.

Information and knowledge have been identified as key components for the acceptance of food trends in several studies. Information about food both in what consumers know about the product but also how accurate and correct the information is perceived (La Barbera et al., 2016). Therefore, in terms of information providence, consumers must be able to correctly interpret the information, comprehend it and trust it sufficiently so it can influence consumer acceptance of novel foods (Rupprecht et al., 2020).

By providing transparent and reliable information about the origin, processing, and safety of these products it could help consumers with accepting novel foods and novel food technologies. Several examples of how traceability could support this acceptance are:

- *Safety concerns*
  Traceability solutions can help address safety concerns by providing consumers with information about the source of the ingredients used in novel foods, as well as the processing methods and any safety testing that has been conducted. This can help build trust in the safety and quality of these products.
- *Labelling and communication*
  Clear and accurate labelling is important for helping consumers make informed choices about the foods they eat. It can help consumers with verifying the authenticity of food. Traceability solutions can enable accurate labelling by providing detailed information about the ingredients and processing methods used in novel foods, as well as any certifications or standards that have been met. Additionally, scientific labels which inform consumers about quality, nutrition, origin, and production conditions on food influences consumer decision making are valued by consumers (Olsen and Borit, 2013; Rupprecht et al., 2020).
- *Supply chain transparency*
  Traceability solutions can provide visibility into the entire supply chain for novel foods, from farm to table. This can help address concerns about sustainability, ethical sourcing, and fair labour practices, which are important factors for many consumers.
- *Consumer engagement*
  Traceability solutions can enable consumer engagement by providing interactive and personalised information about novel foods. For example, consumers could scan a QR code on a package of novel food to access information about the ingredients, nutritional value, and environmental impact of the product.
- *Trust*
  Trust is critical for food acceptability, and it has been demonstrated to affect risk and benefit perceptions of new food technologies (Bratanova et al., 2013). In terms of trust, information that the consumer receives regarding food is one of the criteria for affecting the consumer’s trust level. Trust is gained by a strong source for the information as well as enough information to evaluate a technology’s advantages and drawbacks (Siegrist and Hartmann, 2020). Trust allows consumers to choose based on their own desires to select sustainable, nutritious, authentic, and safe food items, by allowing them to make judgments based on unprovable facts (Siddiqui et al., 2022).

Traceability solutions offer significant potential in addressing many challenges related to consumer acceptance of novel foods. By providing transparent and reliable information about origin, processing, and safety, food traceability can help build trust, alleviate safety concerns, and enable informed decision-making.

However, it’s important to recognise that traceability alone cannot fully resolve all aspects of consumer acceptance. While traceability can effectively address issues such as safety concerns, labelling accuracy, and supply chain transparency, other factors influencing consumer acceptance remain beyond its scope. These include sensory experiences, cultural and social norms, deeply ingrained risk perceptions, and economic factors like price and accessibility. Addressing these multifaceted challenges requires a comprehensive approach that combines traceability with targeted education, marketing strategies, and consumer engagement initiatives. Ultimately, traceability serves as a valuable tool in promoting novel food acceptance, but it should be viewed as part of a broader strategy.

4 Food traceability systems enable a comprehensive approach to novel food acceptance through layered integration

A traceability system refers to the overall framework that integrates the physical, information, and governance layers, providing the infrastructure for tracking products through the supply chain. On the other hand, traceability methodologies are the specific approaches or methods used within that system to collect, record, and analyse supply chain data. These methodologies are inherently shaped by the structure and capabilities of the traceability system in place. As different traceability systems offer varying levels of detail, accuracy, and functionality, they influence the selection and application of traceability methodologies.

4.1 Three key layers of food traceability systems: physical, information, governance

Traceability systems play a crucial role in ensuring the visibility and integrity of supply chains, enabling the tracking of products and their components from origin to end use. These systems are structured into three key layers: the physical layer, the information layer, and the governance layer, each serving a distinct function in capturing and managing traceability data (see Figure 4.1).

The *physical layer* encompasses tangible elements such as products, packaging, and physical identifiers (e.g., barcodes, RFID tags) that are used to capture real-world data. In addition to these identifiers, traceable elements like origin and quality are captured through physical attributes at various stages: raw materials, harvest and logistics, importers and processors, end-product manufacturing, distribution, and at the consumer level (Creydt and Fischer, 2019; Galvez et al., 2018; Mirabelli and Solina; 2020).

The *information layer* involves the digital infrastructure and analytical methods that process and store the data collected from the physical layer. Technologies such as the IoT, cloud computing, blockchain, and analytical methods operate here to provide real-time monitoring and insights.

Finally, the *governance layer* sets the framework for the entire system by defining standards, norms, control systems, and regulations that ensure data accuracy, security, and compliance. This layer addresses issues such as data ownership, privacy, and interoperability, ensuring that the traceability system operates transparently and effectively across different stakeholders (TrustEat, n.d.).

Together, these layers create a robust traceability system that enhances supply chain efficiency, product authenticity, and consumer trust. Figure 4.1 illustrates the three layers and their respective components.

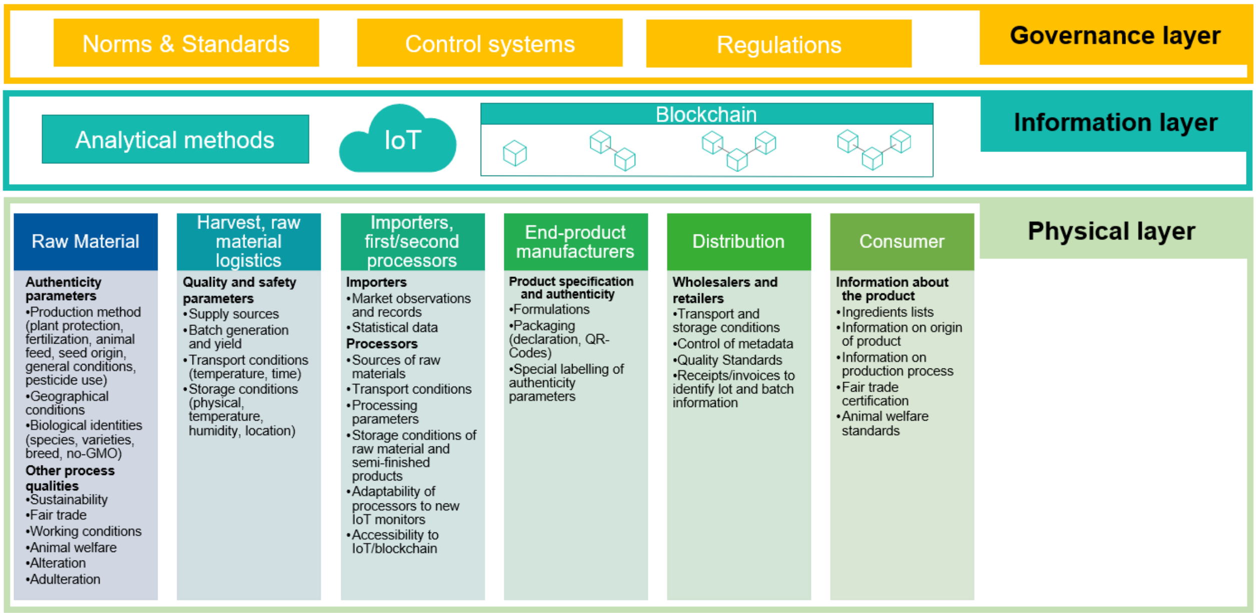

Figure 4.1 *The three layers of food traceability systems*

A comprehensive traceability system comprises elements that oversee the following (Galvez et al., 2018; GS1 Global Traceability Standard | GS1, 2017):

- The identification, labelling, and association of traceable items, individuals, and places.
- The automated capturing (via scanning or reading) of object-related movements or events.
- The recording and dissemination of traceability data, either within an organisation or among parties in a supply chain, to achieve visibility into past occurrences.

The capability to trace and identify specific products or animals is crucial for safeguarding businesses that uphold due diligence, while ensuring those who ignore safety regulations are held responsible. To assign blame accurately, companies must provide evidence that they adhered to all necessary due diligence processes. This emphasises the need for a reliable system that guarantees product quality and allows both regulators and companies to monitor food safety and quality over time and across regions (Munuhwa et al., 2022).

The transition from the physical layer to the digital layer and blockchain system is critical, and one of the major challenges is ensuring the quality of the input data from the physical world into the digital blockchain. However, it is important to acknowledge that falsifications are still possible, particularly during the initial stages of raw material production. For example, a food product declared as 'certified organic' may actually been produced using pesticides without being recorded on the blockchain. To address this issue, there are two potential options: (i) objective analytical methods can be used to verify the data, and (ii) regular audits of production sites can be conducted. Ideally, both approaches should be employed to maximise data input security. To this end, in addition to digital data profiles, analytical fingerprints – unique characteristics of the food product verifying authenticity - are recorded. It is crucial that such measures continue to be implemented in the digital age, to ensure the integrity of the traceability system (Creydt and Fischer, 2019).

4.2 Physical layer traceable elements supplying data to the information layer

Traceability of food products can be achieved through physical elements like barcodes, RFID tags, and QR codes or through physical markers such as chemical and biological markers. These markers provide essential data that can be captured and transferred to the information layer for further analysis and tracking.

Chemical and biological markers rely on analytical methods to gather information. This involves laboratory-based analytical techniques that identify and quantify specific characteristics of food products. Analytical methods used in food traceability include DNA-based methods, separation techniques, spectroscopy techniques, mass spectrometry techniques, and other techniques. These methods have been largely applied to verify the origin and quality of raw materials and finished products.

Elements or markers to be traced on the physical layer are the following:

- DNA/RNA: genetic markers that can confirm species identity and geographic origin.
- Proteins: protein biomarkers are linked to specific processing conditions, environmental factors or geographic regions.
- Lipids: fatty acid profiles that vary with diet, regional feed, or crop conditions.
- Carbohydrates: sugars and polysaccharides that can indicate plant of product origin based on cultivation practices and regional influences.
- Metabolites: small molecules reflecting environmental stress, growing conditions, and geographic influences.
- Stable isotope: isotopic ratios that provide information on environmental factors like climate, soil, and water sources.
- Trace elements: presence and concentrations of minerals or metals affected by local soil, water, and atmospheric conditions.
- Miscellaneous volatiles: volatile organic compounds such as aroma that can be unique to a geographic region due to local flora and environmental factors.
- Miscellaneous non-volatiles: non-volatile compounds like pesticides, polyphenols, and other residues that are influenced by regional agricultural practices.

4.3 A blockchain-based traceability system for enhanced traceability

Blockchain technology has emerged as a transformative tool for information exchange among multiple parties. As such, it can greatly enhance traceability system through the information layer. Its decentralised and immutable ledger system enables secure and transparent recording of transactions, making it ideal for tracking the journey of goods and data through complex supply chains. By providing a permanent and tamper-proof record of every step in a product’s lifecycle—from production and processing to distribution and retail—blockchain ensures that all stakeholders have access to accurate and reliable information. This level of traceability is particularly valuable in sectors such as agriculture, pharmaceuticals, and logistics, where product integrity and authenticity are critical. For example, blockchain can be used to verify the origin of food products, ensuring compliance with safety standards and reducing the risk of fraud (Ellahi et al., 2023). In the pharmaceutical industry, it can help combat counterfeit drugs by providing a verifiable history of each batch of medicine (Uddin, 2021).

Overall, blockchain’s ability to enhance transparency, accountability, and trust makes it a powerful tool for improving traceability. However, it is important to recognise that blockchain alone cannot achieve better traceability. Its application to food traceability is effective only when the essential components of a traceability system are already in place to generate the necessary information on traceable elements. Therefore, it is more accurate to describe this approach as a blockchain-based traceability system. The other components on the information layer of a traceability system are methods that generate traceability information. Broadly, they can be classified into IoT technologies and analytical methods, each with strengths and weaknesses of their own. Chapter 5 describes these methods in more detail.

5 Traceability information is generated through different methods for robust tracking

5.1 IoT technologies for data collection in food traceability systems allow for real-time tracking of food products

An approach to achieving food traceability is through IoT-based technologies. These technologies use internet-connected devices and sensors to collect real-time data on the location, condition, and movement of food products. Examples of IoT-based technologies used in food traceability include barcodes, radio frequency identification (RFID), QR codes and more recently develop technologies. These technologies can track the movement and storage conditions of finished products, ensuring that they remain safe and of high quality.

Barcodes
Barcodes are essential in food traceability systems as they provide a reliable and efficient way to track and monitor food products throughout the supply chain. They serve as unique identifiers for individual items or batches, and when scanned, their encoded information is recorded and linked to a centralised database (Fan et al., 2019). This allows stakeholders to access real-time information about the product's origin, production details, and movement. Barcodes enhance food safety by enabling swift identification of issues or contamination, leading to faster recalls and reduced consumer exposure. They streamline supply chain operations, improving inventory management and logistics. Barcodes also promote transparency by providing consumers with access to product information, empowering them to make informed choices (Fan et al., 2019; Galanakis, 2020).

Radio frequency identification (RFID)
RFID technology has revolutionised food traceability by enabling real-time and automated data capture, overcoming the limitations of traditional barcodes such as restricted visibility, environmental vulnerabilities, and human error. RFID tags can be read remotely and simultaneously, providing rapid and accurate identification of products throughout the supply chain. The unique identifier on each tag is linked to comprehensive data in a centralised database, offering enhanced visibility and granular insights. RFID tags are more resistant to physical damage and environmental challenges, ensuring reliable performance in harsh conditions (Fan et al., 2019; Montet and Ray, 2021). By automating data capture, RFID minimises the potential for human error and improves the accuracy of traceability records (Anir et al., 2008; Galanakis, 2020). While the initial setup cost and compatibility issues may be considerations, the benefits of RFID in food traceability are substantial. It enhances supply chain management, reduces errors, and promotes efficiency. With ongoing advancements and cost reductions, RFID technology is poised to play a crucial role in ensuring the safety, quality, and transparency of food products from farm to fork (Galanakis, 2020).

QR Codes
QR codes provide access to a wide range of information related to food traceability. By scanning a QR code, consumers can retrieve details about the product's origin, including the farm or producer information, processing methods, and certifications such as organic or fair-trade. They can also access information about the ingredients used, including allergen information, nutritional facts, and any potential additives or preservatives (Creydt and Fischer, 2019). QR codes can provide details on sustainability practices, such as environmental initiatives or ethical certifications. QR codes and barcodes differ in data capacity, data density, scanning speed, error correction, versatility, cost of use, and industry acceptance. QR codes offer greater data capacity, faster scanning, error correction, and greater versatility, while barcodes tend to be more cost-effective. Choosing between QR codes and barcodes depends on the specific needs and applications (Kim and Woo, 2016). A traceability system framework proposed by Tarjan et al. (2014) is based on the utilisation of both RFID and QR codes to ensure the effective traceability of food products. In this system, relevant

information about a specific product is embedded within both the RFID and QR codes, allowing for quick and easy access using a suitable reader.

More recently developed technologies

New technologies are being developed to produce authentication micro- and nano-barcodes, which hold promise for enhanced traceability and anti-counterfeiting in the food industry. These include extrinsic DNA tags (Scarano and Rao, 2014), fluorescent barcodes by fluorochromes (Montet and Ray, 2021), quantum dots (Nsibande and Forbes, 2016), and rare earth doped nanoparticles (Rong et al., 2020). Encapsulation and shaping by polymer particles (Wang et al., 2015), microfluidic generated particles (Lee et al., 2014), and random deposited particles (Montet and Ray, 2021) are also new technologies for creating or enhancing micro- and nano-barcodes.

To be effective, the micro-barcodes must meet several requirements, including affordability, long-term stability, compatibility with biological systems, and ease of detection and interpretation. Many emerging technologies utilise fluorescent dyes to encode information through the shape and optical properties of particles or objects. These characteristics, such as fluorescence spectrum or reflectance, create unique signatures that distinguish the objects to which they are attached. Despite the appeal of these precise and difficult-to-counterfeit micro-barcode production techniques, there are still areas that require additional advancements (Montet and Ray, 2021).

Other notable techniques include blockchain-based smart contracts. Smart contracts are digital agreements that automatically execute if-then conditions without human oversight, facilitating secure and reliable transactions (Creydt and Fischer, 2019; Li and Kassem, 2021). These data-driven technologies operate within the information layer, supporting the reliable transmission and exchange of data and information.

5.2 Analytical methods used in food traceability allow the identification of food products through scientific techniques

There are many analytical methods that can play important roles in food traceability by allowing for the identification and verification of food products and production methods through scientific means. For example, a collection of methods involves the use of biomarkers, which are biological indicators—such as DNA, stable isotopes, or chemical compounds—that can reveal the geographical origin or species composition of a food product.

Biological markers in foods play a crucial role in ensuring effective food traceability. These markers, also known as biomarkers, are specific biological substances or characteristics present in food products that can be used to authenticate their origin, monitor their quality, and track their movement throughout the supply chain. Depending on the focus and application different level of markers can be analysed.

DNA-based markers provide a unique genetic fingerprint for each organism, allowing for accurate species identification and verification of food authenticity. By analysing specific DNA sequences, such as simple sequence repeats (SSRs) and single-nucleotide polymorphism (SNP), species or even the individual genetic profile of a food item can be determined. This information can be compared with a reference database to confirm the origin and integrity of the product (Montet and Ray, 2021).

Another important class of biological markers is proteins. Proteomic analysis enables the identification and quantification of specific proteins present in food. These proteins can act as indicators of ingredients, processing methods, or even allergenic components (Afzaal et al., 2022). For instance, allergenic proteins like gluten in wheat or casein in milk can be detected using immunoassays or mass spectrometry-based techniques (Roncada et al., 2012; Yan et al., 2006). By analysing protein profiles, food traceability systems can ensure accurate labelling and prevent fraudulent practices (Afzaal et al., 2022; Montet and Ray, 2021).

Additionally, metabolites can serve as valuable biological markers. Metabolomics, the study of small molecules involved in metabolic processes, can provide insights into the biochemical composition and quality of food products (Montet and Ray, 2021). Analysis of metabolites, such as volatile compounds, sugars, or organic acids, can help identify specific production methods, detect adulteration, and assess the freshness or spoilage of food items (Castro-Puyana et al., 2017).

The detection of proteins and metabolites can be done with several technologies, such as chromatographic separation coupled to either light spectroscopy or mass spectrometry for detection. Methods can be very detailed with broad detection scope (non-targeted) or very specific, often with high sensitivity, in a targeted detection method. While non-targeted methods can provide a more complete 'profile' of composition, the data are complex and large. A targeted analysis on the other hand is more focused and more easily interpretable but is obviously limited to the investigated components.

Integrating the information gained from such techniques into traceability systems, along with technologies like barcoding, RFID (Radio Frequency Identification), or blockchain, can enhance transparency and enable accurate tracking of food products from farm to fork.

Analysing these biomarkers can help authenticate products and verify their claimed origins. Furthermore, various separation techniques can be used to identify components of food products. Other analytical approaches include spectroscopic techniques, which use light interaction to assess the chemical makeup of foods, and chromatographic methods, which separate food components to identify specific substances.

Separation techniques
Separation techniques play a crucial role in ensuring the traceability and safety of food products. Among the various analytical techniques used, liquid chromatography (LC) and gas chromatography (GC) are widely employed for the analysis of food samples. Through LC or GC, separated components are being detected either by (UV) light absorption or by mass-spectrometry. The latter provides substantially more insight in the molecular composition of the samples, with enhanced specificity, but also with higher data complexity.

Liquid chromatography techniques are commonly utilised for the analysis of various food components, including vitamins, amino acids, proteins, lipids such as triglycerides in fats and oils, chiral compounds, pigments, carbohydrates and organic acids, additives, pesticides, and mycotoxins. These analyses aid in assessing the nutritional value, authenticity, quality, and safety of food products. For example, LC methods can determine the presence and levels of pesticide residues in fruits and vegetables, ensuring compliance with regulatory standards. LC also allows for the detection and quantification of contaminants, such as mycotoxins produced by fungi in grains and cereals (Galanakis, 2020; Montet and Ray, 2021).

Gas chromatography techniques are extensively used for the analysis of food flavours, fragrances, volatile and semi-volatiles compounds, fatty acids, and contaminants such as residual solvents, pesticide residues, and veterinary drug residues. By employing GC, food manufacturers can verify the authenticity and quality of products, assess the presence of contaminants, and monitor compliance with regulatory guidelines (Montet and Ray, 2021).

Spectroscopy
Spectroscopy is the study of the interaction of light with matter. Generally, electromagnetic radiation is classified by wavelength into radio wave, microwave, infrared, visible light, ultraviolet, X-rays and gamma rays. Within food traceability, several spectroscopic techniques provide valuable insights into the composition, quality, and authenticity of food products. Fluorescence, vibrational and imaging spectroscopy are valuable techniques in food traceability. They provide insights into the composition, quality, and authenticity of food products.

Fluorescence spectroscopy arises from photons interacting with electrons orbiting atoms or molecules, generating electronic spectra (this occurs in the visible or UV-electromagnetic range). Fluorescence spectroscopy aids in quality assessment, shelf-life determination, and origin authentication (Galanakis, 2020; Montet and Ray, 2021). Researchers have highlighted the effectiveness of synchronous fluorescence (SyF) in detecting adulteration in olive oil. SyF utilises excitation-emission plots, which enhance the ability to differentiate between different fluorescence patterns (Poulli et al., 2007). Fluorescence spectroscopy offers significant advantages in assessing food quality and detecting adulteration, but it is often limited to specific cases where fluorescent compounds are present. While effective in these instances, it is not applicable to as broad a range of samples as other methods.

Vibrational spectroscopy is a collective term for analytical techniques that measure the vibrational energy levels of molecules to provide information their composition and interactions. Such methods play a critical role in food analysis because they provides detailed information about the molecular structure of samples and are widely applicable across various food types. Vibrational spectroscopy helps identify components, detect adulterants and contaminants, and assess food quality.

Infrared (IR) spectroscopy is a form of vibrational spectroscopy that offers many advantages, such as being non-destructive, fast, and capable of analysing samples without extensive preparation. Given its broader utility, IR spectroscopy is discussed in more detail to highlight its unique benefits and applications, especially in comparison to other spectroscopic techniques.

IR spectroscopy occurs when photons of lower energy are absorbed by a molecule, causing its covalent bonds to vibrate at characteristic frequencies. These patterns of vibrations are known as vibrational spectra. Near-infrared (NIR) spectra, on the other hand, arise from photons with intermediate energy. These photons are absorbed by the same covalent bonds but at fractional – such as half, third or quarter- of the fundamental infrared vibrations. These absorptions correspond to overtones and combinations of bonds such as CH, OH and NH.

In other words, covalent bonds possess distinctive characteristics such as length, strength, and direction, which are specific to each pair of atoms involved. Conceptually, covalent bonds can be likened to springs that connect atoms within a molecule. These bonds exhibit vibrational motion at unique frequencies determined by factors such as atomic masses and the ‘stiffness’ of the bond, showing anharmonic behaviour. They can absorb infrared photons if a vibration alters their dipole moment. These absorptions occur when photons of precisely the right frequency are encountered, leading to the excitation of the bond(s) to a higher vibrational state.

The frequency of these vibrations serves as a basis for qualitative analysis, providing information about the identity of the molecules involved. Meanwhile, the amplitude of the vibrations enables quantitative analysis, offering insights into the amount of substance present.

Infrared spectroscopy has numerous advantages in relation to other analytical techniques. These include the following arguments:
- It is a non-destructive method, where the composition or nature of the sample is not altered in any way. As a consequence, the same sample can be measured as many times as necessary. This enables reanalysis and verification in case of fraud detection.
- Measuring a spectrum takes only a few seconds, being an extremely fast technique. Thanks to this, a large number of samples can be measured in a short time.
- The error of a method is composed of the error of the analytical method plus the sampling error. The latter is usually 25 or 30 times larger than the former. Due to the aforementioned advantage, it is possible through NIR to drastically reduce the sampling error by measuring many samples in a short time.
- NIR spectra are highly reproducible.
- The technique is environmentally friendly since it does not use any reagents or chemical compounds.
- After the methods were validated, trained personnel are not required to analyse new samples.
- Sample preparation is very limited or absent. It is not necessary to isolate the analyte from the heterogeneous sample before analysis, the NIR technique can proceed with the sample as it is.
- Another especially important advantage is that online measurements, and even onsite, are possible with NIR. It is not necessary to take the sample to the laboratory, because there are portable devices that can perform measurements anywhere, and the results can be shared in real time.
- Spectral complexity and limited specificity can be solved with chemometrics techniques.

Regarding the drawbacks of NIR, they can be highlighted as follows:

- What is available is the technology, not the methodology. Before using the method routinely, it is necessary to develop and validate a model. To this end, representative samples of those to be measured in the routine must be collected. The number of samples is variable but should not be less than 150/200 samples. Models can only be used to predict samples that have similar characteristics in terms of variability, to those with which they were calibrated.
- It is necessary to measure all samples collected by a reference method. This procedure is expensive and time-consuming.
- For each problem, a specialised model must be calibrated and validated. It is not possible to use past models to solve new problems.
- NIR spectra do not show clear peaks but rather wide and overlapping bands, resulting from combination modes and overtones. Furthermore, these spectra are influenced by multiplicative and additive effects caused by measurement noise and light scattering. In addition, variables are interconnected, presenting collinearity. To solve all these problems, and to understand where the important information can be found in spectra, Chemometrics should be used. This discipline uses mathematical algorithms to perform multivariate regression and classification, and to design experiments.

According to Dayananda et al. (2023), researchers and industry experts can acquire knowledge about the chemical composition and quality of plant-based protein ingredients, non-destructively, by vibrational spectroscopy. Neves et al. (2018) developed a method to classify adulterants (wheat, soy protein, and whey) in plant-based protein powders and verify product authenticity using an FT-NIR analyser in diffuse reflectance mode, covering the range of 1,000 to 2,500 nm. To that end, the authors used a one-class partial least squares model to detect fraud, and partial least squares discriminant analysis to differentiate between adulterants. These authors have established a reliable classification between pure and adulterated proteins, obtaining 100% sensitivity and 100% specificity in the classification of pure and adulterated plant-based foods. Regarding the classification of adulterants, they obtained sensitivities of 92.85% (soy), 96.43% (whey), and 96% (wheat), with corresponding specificities of 98.88%, 98.88%, and 97.73% respectively).

Raman spectroscopy is a type of vibrational spectroscopy employed in food traceability to analyse the molecular composition and quality of food products. By illuminating a sample with monochromatic laser light, the technique detects inelastic scattering that results in energy shifts corresponding to specific molecular vibrations. This generates characteristic spectral fingerprints that can identify the chemical composition and authenticity of food items. Its non-destructive nature and minimal sample preparation make Raman spectroscopy a promising and innovative approach for detecting chemicals in food, offering a non-destructive, rapid, specific, ultrasensitive, and high-throughput screening capability. In comparison to other spectroscopy techniques, Raman spectroscopy facilitates the simultaneous detection of multiple analytes, thanks to its superior spectral resolution and narrower bandwidths (Petersen et al., 2021).

Fluorescence and vibrational spectroscopy techniques offer rapid analysis, non-destructive testing, and contribute to regulatory compliance. However, limitations include spectral complexity, limited specificity, and the need for specialised equipment. Overall, these spectroscopic methods enhance transparency, ensure safety, and maintain food integrity in the supply chain (Galanakis, 2020).

Hyperspectral imaging is emerging as a powerful tool for online and real-time food monitoring. Its ability to capture spatial and spectral information across a wide range of wavelengths holds promise for future applications. In a publication by Dhanapal and Erkinbaev (2024), a hyperspectral imaging (which measures spectra in a defined space) system was coupled to a portable system to determine the quality of meat analogue products. The measurement system uses diffuse reflectance scans in the range 400 to 1,000 nm (204 variables, 512*204 (spatial and spectral resolution)). The authors conclude that VNIR-HSI combined with chemometrics is effective for determining the quality of these foods. The PLSR models demonstrated strong prediction accuracies for redness (R2P = 0.95, RMSEP = 0.27), yellowness (R2P = 0.94, RMSEP = 0.45), moisture (R2P = 0.92, RMSEP = 0.74), and hardness (R2P = 0.81, RMSEP = 0.88).

Nuclear magnetic resonance (NMR) spectroscopy is a powerful method for analysing food products composed of various molecules, such as sugars, amino acids, and fatty acids. By generating comprehensive metabolic fingerprints, NMR can effectively authenticate food and identify adulteration across a range of items, including olive oil, honey, fish, spirits, wine, coffee, saffron, and vinegar. This non-destructive technique provides high accuracy and rapid detection, relying on the energy absorption of atomic nuclei (notably ^{1}H, ^{13}C, ^{19}F, and ^{31}P) in a magnetic field. The surrounding atoms influence these energy levels, yielding detailed insights into the molecular structure and chemical properties of food samples. NMR fingerprinting examines the entire sample, allowing for simple quantification of major compounds. Its advantages include minimal sample preparation, low solvent usage, and quick analysis times, although the equipment can be expensive, and interpreting the data may be complex (Galanakis, 2020).

Mass spectrometry

Mass spectrometers (MS) function by ionising analyte molecules, converting them into a charged state. These ions, along with any fragment ions generated during the ionisation process, are then analysed based on their mass-to-charge ratio (m/z) (Pitt, 2009).

One application of MS in food traceability is stable isotope analysis, which relies on isotope ratio mass spectrometry to determine the ratios of stable isotopes present in a sample. Stable isotopes are non-radioactive isotopes of elements that occur naturally in different proportions. Their ratios can be very due to environmental conditions and biological processes. The most used stable isotopes in agricultural applications are carbon-13 (^{13}C), nitrogen-15 (^{15}N), hydrogen-2 (^{2}H or deuterium), oxygen-18 (^{18}O), and sulfur-34 (^{34}S) (Chung et al., 2017).

Isotope ratio mass spectrometry is particularly effective for food authentication and geographical determination. However, the application of isotope analysis is limited to relatively pure components, as mixtures can result in averaged isotope ratios which are difficult to interpret or could only be used in specific conditions. Therefore, it is important to note that stable isotope analysis should be used in conjunction with other traceability methods and should be interpreted within the broader context of supply chain management. (Zhao and Zhao, 2020).

The combination of mass spectrometry with chromatographic techniques has long been favoured due to MS's high sensitivity and specificity, which surpasses that of other chromatographic detectors (Pitt, 2009).

Gas chromatography-mass spectrometry (GC-MS) is an analytical technique used to identify and characterise the chemical compounds in a sample by determining their molecular weight, elemental composition, and molecular structure. This method combines two distinct instruments: gas chromatography and mass spectrometry. In the first stage, gas chromatography separates the individual components of a sample based on their volatility and interaction with the column's stationary phase. As the sample is vaporised and carried by an inert gas, its constituents are separated and detected, allowing for quantification.

Following separation, the mass spectrometry component analyses the ions generated from the sample. It measures the mass-to-charge ratio (m/z) of these ions, providing detailed information about their molecular weight and structure. This dual approach enables GC-MS to effectively identify unknown compounds, quantify known substances, and provide insights into the complex mixture of compounds present in various samples, including environmental, food, and biological matrices (Singha and Deka, 2023). Affordable and dependable GC-MS systems have become common in many clinical biochemistry labs and are essential in fields where analysing complex mixtures and achieving clear identification are crucial (Pitt, 2009).

Liquid chromatography-mass spectrometry (LC-MS) is highly effective for detecting a broad spectrum of food metabolites, offering both specificity and sensitivity. Unlike gas chromatography, LC-MS doesn't typically require a derivatisation step, making sample preparation simpler and faster. One drawback of LC-MS in metabolomics is the lack of widely available, transferable libraries for metabolite identification, a feature where GC-MS excels (Galanakis, 2020). LC-MS is suitable for analysing various biological molecules, and when combined with stable isotope internal standards, it enables the creation of highly sensitive and accurate assays. Its fast scanning speed allows for the detection of multiple compounds in a single run. However, method optimisation is often needed to mitigate ion suppression (Pitt, 2009).

Non-chromatographic mass spectrometry methods like Matrix-Assisted Laser Desorption/Ionisation Time-of-Flight (MALDI-TOF-MS), Proton Transfer Reaction Mass Spectrometry (PTR-MS), and Direct Analysis in Real-Time (DART-MS) are commonly used to verify food authenticity. A newer method, Proton Transfer Reaction Time-of-Flight Mass Spectrometry (PTR-TOF-MS), has also proven useful in food authentication. MALDI-TOF-MS allows for rapid screening without the need for chromatography or analyte derivatisation. DART-MS, when paired with TOF-MS, is another effective tool for verifying food origins. These techniques have been used to check the authenticity of various products like spices, juices, olive oil, honey, and beer (Galanakis, 2020).

There are several elemental techniques to analyse the elemental profile of food, with common methods including Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) which measure the concentration of elements by ionising the sample with a plasma source and detecting mass-to-charge ratios or emitted photons, or Optical Emission Spectrometry (ICP-OES) which detects light emitted by elements as they return to their ground state after excitation in an argon plasma. For example, ICP-AES was used to analyse the elemental makeup of tea, successfully distinguishing teas from Africa (Kenya) and Asia (China, Japan, Sri Lanka, and India). Similarly, ICP-AES helped differentiate potatoes grown in Idaho from those in other regions, and ICP-OES was used to classify wines from Italy and Slovenia based on elemental data. These methods are highly effective in determining the geographic origin of different food products. In these studies, many elements were analysed but using ICP-MS/AES requires digesting the samples first. Some elements, like mercury, need extra preparation. Since preparing and analysing multiple samples takes time, this method may not be ideal for quick screening (Galanakis, 2020).

Various factors affect food and additive safety, such as microbial contamination, pesticide residues, and other substances, but one often overlooked issue is elemental contaminants, commonly referred to as metals. Several methods have historically been used for metal screening, including Flame Atomic Absorption Spectroscopy (FAAS), which measures light absorbed by metals in a flame, and its more sensitive variant, Graphite Furnace Atomic Absorption Spectroscopy (GFAAS). Another technique is Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). The most advanced method, Inductively Coupled Plasma Mass Spectrometry (ICP-MS), measures metal concentrations based on their mass-to-charge ratio following ionisation. Due to its high sensitivity, ICP-MS is now the preferred instrument for analysing trace metals, especially since many metals become toxic at very low concentrations (Kroukamp et al., 2024).

Microbial fingerprinting

The demand for a precise and efficient analytical method to verify the authenticity of food has become increasingly important, particularly due to rising concerns and incidents of fraud. Within this context, microbial communities in the environment are recognised as valuable indicators reflecting the state and conditions of food. Microbial fingerprinting involves the characterisation and comparison of microbial communities present in food samples. It aims to identify unique microbial patterns or signatures that can be used for traceability purposes (Galanakis, 2020). PCR-DGGE, also known as polymerase chain reaction-denaturing gradient gel electrophoresis, is a highly effective method for unravelling the intricacies and dynamics of the microbial environment in foods (Montet and Ray, 2021).

Temperature monitoring

Temperature monitoring is a crucial aspect of food traceability, ensuring the safety and quality of food products throughout the entire supply chain. By closely monitoring and controlling temperatures at various stages, including production, processing, transportation, and storage, potential risks associated with temperature deviations can be mitigated.

Maintaining appropriate temperatures is vital because certain foodborne pathogens can multiply rapidly in the temperature danger zone (between 4 °C and 60 °C). By frequent or constant monitoring temperatures, potential microbial growth can be prevented, reducing the risk of foodborne illnesses (Rolfe and Daryaei, 2020).

Temperature monitoring involves the use of reliable and accurate measurement devices such as thermometers, data loggers, or wireless monitoring systems. These devices provide real-time temperature readings, enabling timely intervention if temperatures deviate from the desired range (Aung and Chang, 2023).

Different types of food require specific temperature control measures. For example, perishable goods like meat, dairy products, and seafood must be stored and transported at low temperatures to preserve their freshness and prevent spoilage. On the other hand, cooked food or hot-held items need to be maintained at appropriate temperatures to prevent bacterial growth (Odeyemi et al., 2020).

Temperature monitoring data should be accurately recorded and stored for future reference and analysis. This data helps establish an audit trail, enabling the traceability of food products and facilitating investigations in the event of temperature-related incidents or recalls. Those data records could be directly transferred to the blockchain (Creydt and Fischer, 2019).

Immunological techniques

Immunoassays are a subset of immunological techniques that are commonly used in food safety diagnostics and research. These biochemical tests rely on the reaction between an antigen and an antibody to measure the presence or concentration of specific substances and detect specific proteins or other molecules, offering a powerful method for food traceability and quality control. They have gained widespread use in verifying the identity and authenticity of various food types and components due to their speed, sensitivity, high specificity, and cost-effectiveness. Enzyme-Linked Immunosorbent Assay (ELISA), the most common immunoassay, is extensively used to authenticate dairy, meat, and fish products, as well as to detect undeclared food irradiation processes and genetically modified organisms (GMOs) (Galanakis, 2020).

6 A framework for the evaluation and prioritisation of food traceability methods

6.1 Development of a framework for evaluation of food traceability methods

A more traditional approach to evaluation of analytical methods of food traceability is assessing each method individually, as presented in Table 6.1 and Table 6.2.

Table 6.1 *Strengths and weaknesses of current authentication IoT technologies*

Technology	Strengths	Weaknesses	Sources
Barcodes	Affordable Easy to use Well-established technology and with quality standards Trustworthy and accurate	Optical line-of-sight scanning Limited visibility Resource-demanding Vulnerable to environmental damage Susceptible to human mistakes Restricted storage capacity	(Costa et al., 2013; Galanakis, 2020)
RFID technology	Ability to simultaneously read multiple tags Reduces processing time for consumers Minimise human mistakes and inaccuracies Provides the highest level of security of the available identification methods	Highly expensive Complex, challenging to operate Data overlap can occur Data Privacy and security concerns A reader is needed to collect data	(Anir et al., 2008; Fan et al., 2019; Galanakis, 2020; Nasir et al., 2011; Zuo et al., 2022)
QR codes	Easy and affordable implementation Accessibility and versatility Real-time updates	User dependence Limited storage capacity Vulnerable to environmental damage	(Creydt and Fischer, 2019; Y. G. Kim and Woo, 2016; Tarjan et al., 2014)
Micro-barcodes	Significant amount of information stored in very small space Difficult to counterfeit due to their microscopic size and complex encoding	More expensive implementation than traditional barcodes Requires adequate resources and expertise	(Wang et al., 2015)

Table 6.2 *Strengths and weaknesses of current authentication analytical technologies*

Technology	Strengths	Weaknesses	Sources
Methods for analysis of biological markers: DNA, Protein or Metabolites	Enhanced authentication Highly detailed detection Accurate species identification Allergen detection Sensitivity Quality monitoring	Technical complexity Invasive and low speed analysis Sample preparation process Sample storage and stability Reference databases Cost implications	(Afzaal et al., 2022; Danezis et al., 2016; El Sheikha, 2019a; Montet and Ray, 2021)
Chromatographic Techniques	Compound specificity Widespread application High resolution capability Multi-detector compatibility Automated analysis Multi-analyte detection	Complex sample preparation Expensive equipment Non-targeted analysis challenges Multi-step process Analyte stability concerns	(Cortés-Herrera et al., 2018; Messaoudi, 2024; Núñez and Lucci, 2020)
Spectroscopy	Rapid analysis Wide applicability High reproducibility Detailed molecular insights Non-destructive	Complex testing data Sample variability and interferences Skilled personnel needed Limited application range Limited specificity Expensive equipment	(Dayananda et al., 2023; Dhanapal and Erkinbaev, 2024; Galanakis, 2020; Neves et al., 2018; Petersen et al., 2021)
Isotope analysis	Accurate origin and authenticity confirmation High sensitivity Destructive Long-term stability	Not easily applicable to mixtures. Lack of standard materials for the biological matrix (the chemical matrix is the most used). Reference gas is used for single-point calibration, which cannot ensure the accuracy of the data. Isotope data are incomparable between laboratories. The isotope reference materials are expensive H isotope ratio is easily affected by the environment.	(Danezis et al., 2016; Drivelos and Georgiou, 2012; Zhao and Zhao, 2020)
Microbial fingerprint	Very sensitive (study of a complex mixture of species) A large number of samples can be analysed simultaneously Rapid, reproducible, and reliable Estimating the qualitative and semi-quantitative diversity	Difficult to compare a large number of gels Optimisation of procedure for new genes One band can represent more than one species The maximum length of 500 bp PCR biases Difficult to compare results between laboratories and gels	(El Sheikha, 2019b; Galanakis, 2020)
Temperature monitoring	Food safety assurance Real-time monitoring	Reliance on human intervention (except sensors) Limited sampling Equipment limitations (calibration, battery life) Lack of appropriate data storage and analysis Cost of the monitoring systems Lack of standardisation and environmental conditions	(Aung and Chang, 2023; Creydt and Fischer, 2019; Galanakis, 2020)
Immunological techniques	High specificity and sensitivity Rapid results Versatility Ease of use	Potential for cross-reactivity Limited quantitative capability Sample preparation can be extensive	(Posthuma-Trumpie, et al., 2009)

However, evaluating methods in isolation overlooks a key aspect: how well each method aligns with various traceability systems, as their effectiveness often depends on specific criteria that can vary with different products, contexts, and resource availability. Placing these methods within the broader context of food traceability systems allows for a more realistic assessment of their suitability, adaptability, and overall performance in meeting diverse traceability demands. The strengths and weaknesses as presented in Table 6.1 and Table 6.2 have been informative for the first selection of methods for traceability system. These findings are validated with relevant experts in the project team to assess their relevance to specific contexts (such as the food products and purpose of traceability).

Table 6.3 outlines the criteria identified during a first workshop as relevant for evaluating different food analysis methods. These criteria can be applied to various methods with respect to specific food products, enabling an assessment of each method's suitability. The criteria were defined broadly but also differentiated by traceability layer, allowing for insight into their diverse applications across the traceability system.

Table 6.3 *Proposed framework to evaluate current authentication analytical technologies based on several criteria*

Criteria	**Explanation**	**Layer of traceability**		
		Governance	**Digital/information**	**Physical**
Accuracy	Sensitivity, specificity, selectivity		Accurate data points	Sampling is precise and representative
Robustness	Reproducibility (the test producing the same outcome following the same protocols); the test indicates the right category (yes/no) even though the quantity may vary; reliability	Specified protocols to ensure reproducibility and reliability across different contexts	Data is consistently processed, stored and transferred without corruption	Reproducibility
Costs	Resource requirements, investment needed, labour	Compliance with regulatory requirements, costs to meet standards	Software development, maintenance, infrastructure, technology	Sampling, lab testing, materials
Ease of use	Sampling requirements, equipment needed	Regulations linked to method	User-friendly interface, clear reporting	Simplicity of testing procedure
Fit for purpose	Allergen, authenticity (fraud); targeted vs non-targeted; applicability; maturity		Aligns with objectives	Possession of appropriate samples
Standardisation	Sensitivity to preparation/extraction methods, sampling environment, testing environment, analysists	Set protocols and procedures	Must allow for comparability of information across systems	Consistent sampling techniques and handling methods
Timelessness	Speed: rapid test; portability: on site use (sampling on site, or sent back to laboratory)	Time-sensitive products requirements	Rapid data processing	Speed of test
Data analysis	Ease of interpretation of results	Requirements for data analysis transparency	Software for complex computations, statistical analysis	Interpretation of results on-site

The criteria descriptions were applied to analytical methods but can also be applied to IoT technologies:
- Accuracy assesses the precision of the collected data.
- Robustness ensures reliability across varying conditions.
- Costs evaluate the financial feasibility of implementation.
- Ease of use considers the user-friendliness of the technology.
- Fit for purpose determines whether the method meets specific requirements.
- Standardisation ensures compatibility with existing regulations.
- Timelessness focuses on the ongoing relevance of the data over time.
- Data analysis evaluates the ability to interpret and effectively utilise the collected data.

When applied to IoT technologies, these criteria highlight both strengths and challenges. For instance, IoT systems can have an enhanced accuracy and timeliness by providing real-time data but may struggle with robustness due to potential vulnerabilities in connectivity and data integrity. Additionally, while IoT solutions can lower costs through automation, they may require significant initial investment in infrastructure. Overall, aligning these criteria with IoT capabilities helps to develop efficient and reliable food traceability systems that meet contemporary safety and quality standards.

6.2 Demonstration of the application of the framework to an analytical method of traceability

Applying this framework to an analytical method for food traceability offers valuable insights into the relevance of the chosen method in fulfilling different traceability objectives: identifying specific compounds in a food product, detecting adulteration, verifying authenticity, ensuring quality, and supporting compliance with regulatory standards throughout the supply chain.

In a subsequent workshop, participants—comprising researchers and technicians with expertise in food analysis—examined the various criteria and their relevance to food traceability. The criteria were revisited and discussed to improve their effectiveness, with particular emphasis placed on the importance of the 'fit for purpose' and 'accuracy' criteria within the context of food analysis studies. However, in the realm of food traceability, the emphasis on accuracy diminished. While accuracy is important, the focus should be on identifying the right compounds rather than achieving precise quantification. In many instances of food traceability, the primary requirement is a binary confirmation—either a yes or no—rather than exact numerical values. Therefore, from a traceability standpoint, accuracy becomes less critical as long as the employed method is robust and standardised. Conversely, the 'fit for purpose' criterion retains its importance, as it encompasses all essential factors needed to effectively achieve specific traceability objectives. Figure 6.1 illustrates the importance assigned to the various criteria of the framework in food analytical methods within the context of food traceability. The 5-point scale ranges from 0 (not important at all) to 5 (very important).

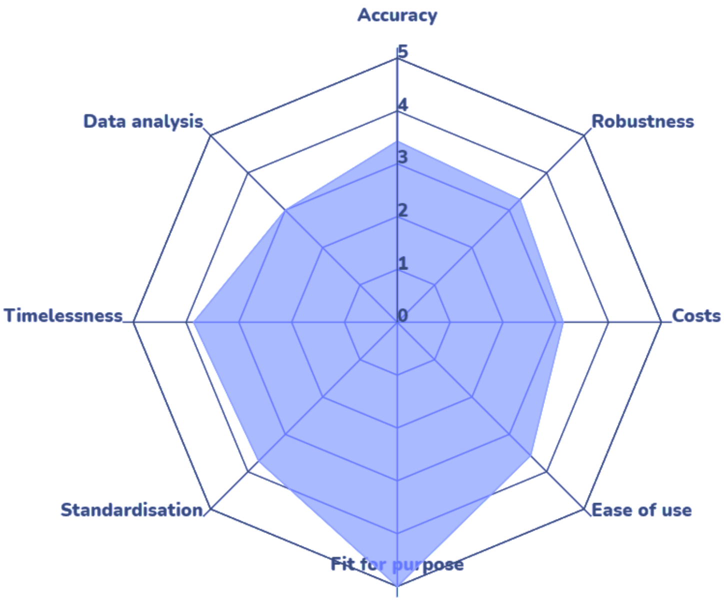

Figure 6.1 *Spider diagram of the importance of each criterion in food analytical methods*

Given the assumption that the strengths and weaknesses of these methods can vary by product, the framework was tested by mapping a methodology to a specific product. It was applied to the analytical method of liquid chromatography–mass spectrometry (LC-MS), in the context of detecting adulteration in plant-based meat alternatives. The workshop participants selected this method for testing the framework based on it being the one most familiar to the group collectively, enabling more informed and thorough responses to the criteria evaluating the method. Zooming in on the application of the framework to LC-MS, scores ranging from 0 to 5 were gathered on the perceived performance of the method against the established criteria (see Figure 6.2), followed by qualitative reflections for each criterion (see Table 6.4). A score of 0 represented the lowest possible rating for the associated criteria, while 5 indicated the highest.

Workshop participants noted LC-MS's strengths in accuracy and its suitability for detailed analyses; however, they also identified challenges such as high costs, complex data analysis, lack of standardisation, and limited ease of use and timeliness due to its reliance on expertise and slow processing times. While LC-MS is currently in a developmental phase for food traceability, it is regarded as sufficiently accurate and fit for purpose when applied to plant-based meat. Nonetheless, improvements are needed in areas such as ease of use, cost, timeliness, and data analysis, with potential advancements anticipated through further development and standardisation.

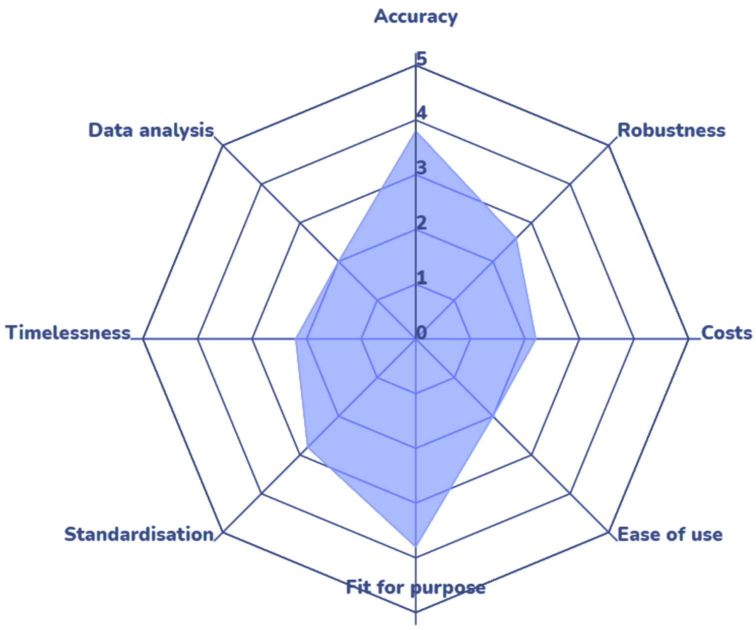

Figure 6.2 *Spider diagram of the perceived importance of each criterion in food analytical methods*

Table 6.4 *Assessment of LC-MS based on the framework criteria*

Accuracy (score 3.8)	**Robustness (score 2.6)**	**Costs (score 2.2)**	**Ease of use (score 2)**
The accuracy of LC-MS in detecting adulteration in plant-based meat alternatives is generally considered satisfactory. The method demonstrates high specificity in detecting multiple components and offers sufficient sensitivity. However, it was noted that for food traceability investigations requiring only binary (yes/no) outcomes, the level of accuracy provided by LC-MS may exceed requirements.	The robustness of the LC-MS method is significantly influenced by sample preparation procedures. Optimising extraction techniques and understanding their relationship to food processing effects are crucial for ensuring the method's effectiveness.	Currently, LC-MS is perceived as a relatively expensive method, particularly considering the volume of data generated. This is attributed to its ongoing development phase. However, when applied in a multiplex approach with increased standardisation, the cost-benefit ratio improves. Opinions on future costs vary, with some experts anticipating a decrease due to process streamlining, while others expect costs to remain comparatively high.	The method requires specialised expertise or training for consistent reproducibility. The sample preparation phase, in particular, is currently labour-intensive and time-consuming, lacking automation. This aspect significantly impacts the overall ease of use of the LC-MS method in this application.
Fit for purpose (score: 3.8)	**Standardisation (score: 2.8)**	**Timelessness (score: 2.2)**	**Data analysis (score: 2)**
LC-MS demonstrates high suitability for specific analytical needs in food authenticity. The method can be tailored for particular purposes, offering versatility in addressing various authenticity questions, including analysing modifications in proteins and peptides, detecting the absence of animal proteins, and confirming the presence and quantity of primary protein content.	The standardisation of LC-MS in this application faces several challenges, including a lack of established reference standards and difficulties in standardising pre-treatment procedures. Participants believe that standardisation is achievable but depends upon the accumulation of sufficient knowledge and effective communication and harmonisation among stakeholders. The process of standardisation is ongoing and requires collaborative efforts within the industry.	Current LC-MS applications in this field are characterised by relatively slow processing times, although there is potential for optimisation. The method is not suitable for field applications, limiting its use to laboratory settings. Additionally, untargeted analysis procedures are time-intensive, while targeted analysis approaches tend to be faster.	The data analysis phase of LC-MS presents notable challenges, as current processes are complex and time-consuming. Targeted analysis is generally more manageable than untargeted analysis, which requires specialised expertise. However, there is potential for improvement through process optimisation, increased targeting of analyses, standardisation of procedures, and future automation of data processing.

During the workshop, it was observed that the framework effectively structured participants' reflections on the strengths and weaknesses of various analytical methods. By providing a clear set of criteria, the framework facilitated organised discussions, allowing participants to systematically evaluate each method's performance. This structured approach enabled attendees to identify specific areas for improvement and potential applications of the analytical techniques in food traceability. Overall, the framework proved to be a valuable tool for guiding thoughtful evaluation in food analysis.

Participants highlighted the importance of harmonising standardisation across reports, methods, and reference standards to ensure consistency in food analysis and traceability. They emphasised the necessity of having a clear question or target for analysis, such as detecting adulteration, to effectively evaluate a method's appropriateness using the framework. Another key point discussed was that evaluations are conducted at a specific point in time, and it is essential to recognise that performance can improve with further development. Consequently, the developmental stage of an analytical method significantly influences its scores across various criteria in the framework.

Methods may be assessed differently in the contexts of food analysis and food traceability, with varying criteria gaining importance in each context. This underscores the need for flexible and context-specific evaluation framework. Additionally, the presence of an expert in the evaluated method is vital for accurate assessment. The participants also noted that training and expertise are crucial for successfully adopting new methods. Furthermore, there is potential for integrating multiple methods to address different aspects of food traceability effectively.

The evaluation framework provides valuable advantages in assessing food traceability methods, offering a structured approach to identify their strengths and weaknesses. However, despite these insights into their suitability for various contexts, several key challenges and limitations remain within current traceability methods. Many existing techniques struggle with a lack of standardisation, leading to inconsistencies in data reporting and analysis. Additionally, the complexity and cost of certain analytical methods may hinder widespread adoption, particularly among smaller producers. There is also a reliance on manual processes, which can introduce human error and reduce the efficiency of data collection and sharing. Addressing these issues will require time and further investment in their development.

7 Blockchain as a relevant solution for the improvement of food traceability systems

The challenges associated with traceability methodologies underscore the need for more robust and transparent systems that can enhance traceability throughout the supply chain. In this context, blockchain technology emerges as a promising solution to some of these challenges, offering a decentralised and immutable ledger that acts as a conduit of information, improving data integrity, facilitating real-time tracking, and enhancing collaboration among stakeholders. As demonstrated in Figure 7.1, by leveraging blockchain, the food industry has the potential to address some of the current limitations in traceability methods, allowing for improved transparency and accountability.

When combined with other technologies, it can provide transparency and assurance, addressing concerns about safety, origin, and quality of various food chain stakeholders. However, despite these benefits, blockchain also faces its own challenges that must be resolved to fully unlock its potential in enhancing food traceability and consumer trust.

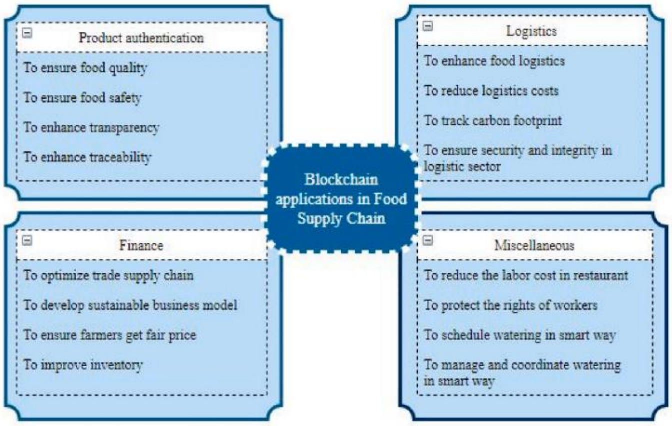

Figure 7.1 *Blockchain as a traceability solution to enhance consumer acceptance of novel foods and technologies*
Source: Pandey et al. (2022).

7.1 Combining blockchain with other food traceability methodologies

One must note that blockchain functions as an information linkage within food traceability systems but cannot operate as a standalone solution (see Figure 7.2). Blockchain primarily contributes by enhancing information security and data reliability, ensuring that traceability records are trustworthy and immutable. However, its effectiveness is highly dependent on the quality and integrity of data received from other elements within the traceability system. This dependency highlights the need for a critical assessment of information generated by analytical methods and Internet of Things devices when integrating blockchain into food traceability. Through a secure information exchange, blockchain also facilitates improvements in other areas, such as labour costs, logistics efficiency, environmental benefits, food safety, and authenticity, ultimately supporting a more transparent and accountable food supply chain.

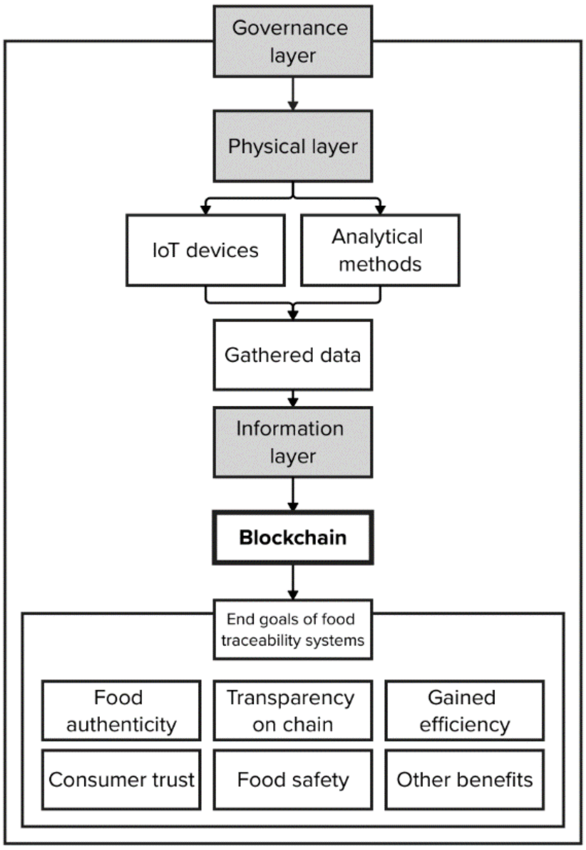

Figure 7.2 *Blockchain as an information conduit in food traceability systems*

Blockchain offers opportunities for synergies with other emerging Industry 4.0 and Web 3.0 technologies. Combining these innovations allows to digitising food supply chains, leading to comprehensive supply chain optimisation. Industry 4.0 technologies allow for digital systems to interact with physical objects, making data and services available for diverse uses. These include innovative mechanisms such as artificial intelligence, GPS, big data analytics, RFID, cloud computing, and IoT. Meanwhile, Web 3.0 technologies further amplify these capabilities, fostering more seamless integration and access to information across multiple platforms and applications. Examples of Web 3.0 include decentralised ledger systems, machine learning, and edge computing (Ellahi et al., 2023).

One of the technologies blockchain can be used together with is *Near-Field Communication* (NFC). NFC creates a magnetic field that powers an integrated circuit with a sensor module, enabling seamless data transmission. This allows for the detection of numerous environmental factors, including temperature, soil moisture content and pH levels. Through the technology, a farmer can provide a distinct number to every item of product, establishing a system of tracking to follow the produce’s path from farm to table. By incorporating blockchain, essential information such as the product’s origin, cultivation location and handling procedures may be safely documented by incorporating blockchain. Any smartphone with NFC support may act as a reader, highlighting the benefits of NFC integrated to blockchain for improved food traceability and increased consumer trust (Ellahi et al., 2023).

Big data analytics is another key innovation driving food safety, especially when paired with blockchain. This technology enables the tracking of food product flow, identification of waste, and strengthening of safety protocols by collecting vast volumes of data through devices such as sensors, GPS devices or RFID tags. For example, devices can optimise farming techniques like fertilisation and irrigation, or can be worn by livestock and help identify illnesses early through tracking of their behaviour and health. Additionally, synchronised digital labelling linked to cloud-based data, along with real-time monitoring during transport and storage, boosts efficiency and transparency across the supply chain, encouraging risk-reducing investments for all stakeholders involved (Ellahi et al., 2023). Hence, big data plays a crucial role in data acquisition and pre-processing in the food production chain. However, challenges might arise in pre-processing due to the sheer volume of data generated throughout food production. Moreover, these data originate from multiple sources, making it difficult to trace their origins and ensure timely updates (Zhou et al., 2022). These challenges inherent to big data can hinder seamless integration with blockchain, for examples as differences in data formats and processing requirements between big data platforms and blockchain networks may create compatibility issues, reducing the efficiency and scalability of such systems.

Numerous IoT source as sensors and drones provide massive amounts of agricultural data, and *cloud computing* provides a versatile platform to utilise them. In a blockchain system, central cloud servers allow supply chain extension and simplifies communication across the food production cycle. Consumers can easily access information on the sourcing of the products through a smartphone interface that is linked to the cloud server and verified via blockchain (Ellahi et al., 2023). It is important to note that technologies reliant on cloud computing can lead to high bandwidth usage, increased latency, and challenges related to security and privacy. Solutions such as Edge Artificial Intelligence (AI) can help address these challenges, as proposed by Dedeoglu et al. (2023).

Artificial intelligence improves the food supply chain through controlling pests, assisting healthy crop development, provide accurate weather predictions during production, monitoring soil conditions and allowing other significant advancements to agriculture such as data processing and analysing for food safety assessment. When combined with blockchain, a mutually beneficial relationship emerges: blockchain supplies reliable data for AI's deep learning processes and guarantees a safe, decentralised system, while AI generates valuable insights for the food supply-chain, including the identification of security concerns (Ellahi et al., 2023). However, AI models require large volumes of labelled data, meaning human experts are needed to annotate datasets to train the models effectively. Additionally, due to the complexity of AI models and their data demands, significant computing resources are needed (Zhou et al., 2022). Given these limitations, it is important to consider that AI depends on continuous data updates and flexible processing for model training and improvement. This can pose challenges for integration with blockchain, as its immutable ledger structure makes modifications difficult.

Global Positioning Systems (GPS) provide a real-time tracking of food goods, allowing for the tracking of every step in the supply chain and notification of the appropriate authorities of any deviations from the defined cold chain conditions. This tracking process is made easier by logging GPS data on the blockchain. Moreover, blockchain-based smart contracts efficiently streamline the transfer of ownership as products move through the supply chain while also monitoring any irregularities that may arise during distribution (Ellahi et al., 2023).

Blockchain can also be integrated with *analytical methods* to enhance traceability and data security. For example, blockchain technology can store data from chemical analyses in a tamper-proof, chronological order. DNA samples from animals can provide critical information, such as breed, country of origin, and exposure to toxins or unregulated medications. By attaching a digital copy of a DNA sample to each individual product, traceability is brought to the item level rather than just the batch level, enabling precise tracking throughout the supply chain. These data can be cross-referenced with blockchain records to verify the animal's authenticity and lifecycle (Galvez et al., 2018).

7.2 Challenges remain in the adoption of blockchain

As demonstrated, blockchain has the potential to complement existing technologies that enhance food traceability and address consumer demands for safety, labelling, supply chain transparency, consumer engagement, trust, and communication. However, there are additional challenges in the implementation of blockchain.

One key issue is the inconsistent and conflicting regulations from national authorities, where standards for allergens, trace elements, and pesticides vary widely. The global nature of food sourcing adds another layer of complexity, as time zone differences can delay response times (Galvez et al., 2018). Beyond regulatory concerns, blockchain must also meet the security, scalability, and stability requirements necessary for IoT-based traceability in the global food supply chain. System performance remains a concern, as maintaining stability and security in blockchain-based IoT applications requires solutions that optimise energy consumption, latency, and storage capacity. Interoperability and standardisation are also crucial, as different ledger types (e.g., public and private) must be compatible to enable seamless collaboration and data protection. However, design limitations can restrict consensus algorithms, transaction capacity, and data accessibility. Advancements in blockchain technology will be essential in addressing these constraints and enhancing security and integrity in IoT platforms (Feng et al., 2020).

Small and medium-sised enterprises (SMEs) face additional hurdles, as limited resources and technical constraints make current blockchain solutions difficult to implement. While affordable software options do exist, they often lack interoperability, making it difficult for different systems to communicate effectively. This lack of integration leads to isolated data systems, which can result in duplicated, incomplete, or missing information. Consequently, organisations struggle to share and process critical data. Addressing these technical and regulatory challenges is essential for blockchain to fully realise its potential in advancing food traceability (Galvez et al., 2018).

In addition to previously mentioned challenges, blockchain faces further hurdles that need to be addressed to enhance food traceability. Certain aspects of acceptance of new foods remain beyond the full reach of current technological solutions, including taste and sensory experience, cultural and social acceptance, perception of risk, and issues related to price and accessibility. Progress must be made in understanding the factors influencing the acceptability of food traceability methods, including blockchain technology, to gain consumer trust.

According to Castellini et al. (2022), research indicates that individual factors significantly impact the acceptance of new food traceability technologies. Notably, acceptance is positively impacted by how much people value their health and the environment. Additionally, personal traits related to food and food involvement, play a role. At the macro level, trust in institutions and stakeholders—such as government, the media, farmers, the food industry, and scientists—enhances the positive evaluation of new food traceability technologies. Lastly, the type of food being traced, and the socio-economic context of the product's marketing are factors significantly influencing acceptance of food traceability technologies. These factors were not examined as antecedents for blockchain acceptance by consumers in the assessed studies. Addressing these research gaps in future studies is essential for gaining a deeper understanding of the barriers and facilitators of consumer trust in traceability technology.

To address innovation resistance in blockchain technology, it is essential to consider all social actors involved, not just end consumers. Resistance to blockchain adoption can vary across sectors due to institutional norms and socio-cultural dynamics. Thompson and Rust (2023) discuss the seafood industry, where wholesalers may be cautious about adopting blockchain due to concerns over its compatibility with traditional practices and its potential to disrupt existing trade dynamics, such as information asymmetries regarding trade, price, and provenance. While other supply chain actors, like fishers and restaurateurs, may value the increased transparency that blockchain offers, they might also be hesitant due to concerns about their relationships with wholesalers. Fishers and aqua culturists generally find blockchain technology to align with their existing operations. The adoption of a permissionless blockchain could allow for broader access to trade data and facilitate sharing among authorised users, addressing concerns about product sourcing and potential misrepresentation. Such an approach could promote greater transparency and equity within the supply chain, enabling various actors to work more directly and collaboratively while preserving their own interests.

8 Discussion

The findings of this study highlight the complexity of consumer acceptance of novel foods. The results indicate that while technological advancements in food production offer promising solutions for food security and environmental concerns, consumer perceptions remain a significant barrier to widespread adoption. These findings align with previous studies suggesting that familiarity, trust in food producers, and perceived naturalness play critical roles in shaping consumer attitudes towards novel foods.

Examining various food traceability methods clarified the available tools and facilitated the development of a framework to assess their suitability in different resource contexts.

The framework was tested during a workshop focused on analytical methods, where it effectively structured participants' reflections on the strengths and weaknesses of each method through organised discussions. This systematic approach allowed attendees to evaluate each method's performance, identify specific areas for improvement, and explore potential applications in food traceability. Overall, the framework proved to be a valuable tool for guiding thoughtful evaluations in food analysis. Testing the framework also revealed that evaluations must consider factors such as the ongoing development of different technologies, which can influence their overall scores and performance. For example, some methods may exhibit weaknesses due to a lack of automation but have the potential for improvement. A noted limitation of the study was the lack of resources to apply the framework in-depth to IoT technologies, indicating a need for further testing in this area.

The framework proves its relevance through its successful application to plant-based meat replacers and its adaptability to other novel foods and supply chains. With the growing demand for traceability systems driven by consumer and regulatory pressures, the rapid advancement of IoT technologies offers new opportunities to improve supply chain transparency. Future research could extend the framework's application to a wider variety of food categories and supply chain configurations, assessing the suitability and effectiveness of both analytical and IoT technologies. By providing decision support, the framework enables stakeholders to identify traceability solutions tailored to their needs and the evolving dynamics of food production and distribution.

Blockchain presents a promising solution to enhance food traceability by providing a decentralised, tamper-proof ledger that improves data integrity, real-time tracking, and stakeholder collaboration. However, its effectiveness relies on integration with other technologies, as blockchain alone does not generate or verify data. Combining blockchain with Industry 4.0 and Web 3.0 innovations—such as IoT, AI, NFC, GPS, and big data analytics—can improve supply chain transparency, food safety, and logistical efficiency. Despite these advantages, blockchain adoption faces challenges, including regulatory inconsistencies, technical limitations, and concerns over scalability and interoperability. Additionally, consumer acceptance of blockchain-driven traceability depends on trust in institutions, perceived benefits, and socio-economic factors. Addressing these barriers requires further research and collaboration across the supply chain to ensure blockchain's full potential in improving food traceability and consumer confidence.

9 Conclusion

This study explored how food traceability systems can enhance consumer acceptance of novel foods and improve food traceability through a structured evaluation framework and with the integration of blockchain to food traceability methods.

Traceability systems, composed of physical, information, and governance layers, ensure transparency and safety in the food supply chain. While traceability can reduce food neophobia by providing reliable product information, it cannot fully address factors like taste, cultural preferences, or affordability. A broader approach, incorporating education and consumer engagement, is needed to complement traceability efforts.

Effective traceability requires integrating multiple methods. Analytical techniques verify product authenticity, IoT technologies monitor supply chains, and audits ensure data accuracy. Blockchain can enhance transparency but faces challenges, including regulatory inconsistencies and industry resistance. Its adoption depends on interoperability with existing technologies, which 5G advancements may help facilitate.

To guide implementation, this study developed a framework for evaluating traceability methodologies based on key criteria. A multidisciplinary approach is essential for ensuring that traceability not only strengthens food safety and transparency but also addresses consumer acceptance challenges in the evolving food industry.

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The mission of Wageningen University & Research is “To explore the potential of nature to improve the quality of life”. Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,700 employees (7,000 fte), 2,500 PhD and EngD candidates, 13,100 students and over 150,000 participants to WUR’s Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.