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Requirements for a food traceability system in a fruit supply chain

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ABSTRACT

Food traceability systems play a critical role in enabling traceability within fruit supply chains. To develop, implement, and evaluate food traceability systems, a set of system requirements is required. However, requirements published to date mainly comprise more general principles and functional requirements, without including non-functional requirements. Existing requirements also do not reflect the need for adaptability of such systems nor expressly consider data quality. Therefore, this paper develops requirements for a food traceability system in a fruit supply chain, comprising functional requirements and non-functional requirements, that consider data quality as well as adaptability. The set of requirements presented in this paper integrates inputs from stakeholder interviews within a representative fruit supply chain (i.e. the deciduous fruit industry of the Western Cape, South Africa), relevant literature, as well as standards on traceability, data quality, and software and information systems quality. The paper shows that the system requirements address the essential functional requirements of a food traceability system, while also defining non-functional requirements that address adaptability and data quality. In further research and in industry, the system requirements can be used in the development and evaluation of food traceability systems in fruit supply chains.

1. Introduction

Food traceability is particularly important in food supply chains due to the following drivers: legislation and certification, safety and quality, customer satisfaction, sustainability, and value and efficiency (Islam & Cullen, 2021). Tran et al. (2024) report that consumers are prepared to pay on average 32 % more for food products with traceability information. Moreover, consumer concerns over the safety and quality of food are further increased by the outbreak of foodborne illnesses such as salmonella (Aung & Chang, 2014).

Various definitions of traceability have been presented (Bosona & Gebresenbet, 2013; Olsen & Borit, 2013). Islam and Cullen (2021) reviewed traceability definitions and proposed the following definition for food traceability: “*Food traceability is an ability to access specific information about a food product that has been captured and integrated with the product's recorded identification throughout the supply chain.*“. This definition aims to capture all relevant aspects of traceability in food supply chains and will be used in this paper.

Food traceability systems (FTSs) are information systems that enable food traceability (Duan et al., 2017). Some of the challenges faced by FTSs include linking of food chain records, inaccuracy and errors in records, and delays in acquiring essential data (Pizzuti et al., 2014). Furthermore, poor design and execution of FTSs lead to rework, high contamination levels, customer complaints, and recalls (Mgonja et al., 2013). An important concept in FTSs is that of a traceable resource unit (TRU), which is a resource that needs to be traced as the resource moves between food business operators (FBOs) (Kim et al., 1995).

To develop, implement, and evaluate FTSs that efficiently and effectively enable traceability, a set of system requirements is required. A set of FTS requirements will also provide a basis for comparing different FTSs. Despite an abundance of literature on food traceability, limited research on FTS system requirements is found in the literature. Where the requirements are addressed, they are not the central focus of the paper, most do not distinguish between functional and performance requirements, and none expressly address data quality (Feng et al. (2013); Kafetzopoulos et al. (2024); Lin et al. (2019); Salampasis et al. (2012)).

This paper addresses the above research gap by presenting a set of functional requirements (FRs) and non-functional requirements (NFRs) that consider data quality and adaptability. These requirements can be used in the development and evaluation of FTSs. The paper uses an FTS in a fruit supply chain as context. The set of requirements integrates

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inputs from stakeholder interviews within a representative fruit supply chain (i.e. the deciduous fruit industry of the Western Cape, South Africa), relevant literature, as well as standards on traceability, data quality, and software and information systems quality. The focus here on fruit supply chains, as a subset of food systems, is relevant because of their economic significance, and their considerable system complexity related to the diversity, time-variability and interconnectedness of their elements (outlined in Section 3.1). Consequently, enabling traceability in fruit supply chains proves to be challenging.

The paper is structured as follows: Section 2 describes the method applied in carrying out this study and Section 3 describes the FTS context. In Section 4, a needs analysis is presented, followed by the system requirements for an FTS presented in Section 5. A discussion is presented in Section 0 and the conclusions of the study are presented in Section 7.

2. Methods

The research method used to develop system requirements for an FTS in a fruit supply chain is illustrated in Fig. 1. The method was informed by the systems engineering approach (SEBoK Editorial Board, 2023). A systems engineering approach is appropriate because the development of system requirements, which can guide system design and evaluation, is a central focus in systems engineering. As shown in Fig. 1, the system requirements are derived from literature, stakeholder interviews, and standards.

The methodology used to carry out the stakeholder interviews was informed by the "Seven Steps to Conducting, Analysing, and Reporting Semi-Structured Interview Data (7S CARS-SID) for Pharmacy Services Research" proposed by Adeoye-Olatunde and Olenik (2021). Semi-structured interviews were selected for their flexibility, allowing for exploratory, open-ended, and deep discussions that could lead to novel insights that may contribute towards requirements for FTSs.

Stakeholders from the fruit supply chain of the deciduous fruit industry of the Western Cape, South Africa, were interviewed. This industry is a major fruit exporter and is, therefore, a representative context for this research. Due to confidentiality considerations, the stakeholders cannot be identified, but it can be stated that they include a manager of an organisation that represents the deciduous fruit industry, a manager at a certification body, managers at three packhouses, and managers at two exporters. The sample size is relatively small due to limited access to stakeholders and the limited time available for conducting the interviews. However, the selected sample is representative of the industry at large as it encompasses stakeholders with the required expertise from diverse organisations.

During each interview, the stakeholders were asked to describe the operations of their organisation, as well as how traceability and challenges related to traceability are currently handled. The stakeholder responses were captured into Microsoft Word documents. Subsequently, a process of coding (Adeoye-Olatunde & Olenik, 2021) was employed, i.e. identifying and labelling topics, similarities and differences in the interview data. Lastly, a thematic analysis (Adeoye-Olatunde & Olenik, 2021) was employed, i.e. combing the codes to summarise the findings coherently.

To enhance the generality of the work presented here and to include the wider aspects of the FTS context, relevant literature and standards were consulted to supplement interviews.

The FTS context, as presented in Section 3, was formulated using the responses of the stakeholders, literature, and standards. The next step in the research method was to conduct a needs analysis, presented in Section 4, informed by the FTS context. Here too, to ensure completeness, relevant literature and standards were considered to identify any additional stakeholder needs. Moreover, to ensure that data quality is considered when defining the system requirements for an FTS in a fruit supply chain, a relevant standard on data quality, namely ISO/IEC 25012 (2008), was consulted to define a set of data quality requirements, presented in Section 4.3.

The research method then proceeded by deriving system requirements for an FTS (presented in Section 5) from the stakeholder needs, data quality requirements, literature, and standards. The system requirements comprise FRs and NFRs.

3. Food traceability system context

The FTS context is presented as informed by relevant literature, standards, and interviews with relevant stakeholders within the South African deciduous fruit industry. The information presented in this section that does not include literature citations is informed by the stakeholder interviews. As previously indicated, the identity of the respective stakeholders cannot be disclosed due to confidentiality constraints. The complexity of fruit supply chains, the traceability audit process, and resource considerations are discussed in Sections 3.1, 3.2, and 3.3, respectively. Subsequently, stakeholders of an FTS are outlined in Section 3.4.

3.1. Fruit supply chain diversity and interconnectedness

The diversity and interconnectedness of the elements of fruit supply chains result in significant system complexity. This section focuses on this complexity.

Fruit supply chains deliver fruit to a variety of target markets, and traceability regulations requirements differ globally (Zhang & Bhatt, 2014). Phytosanitary requirements aim to minimise the economic and ecological damage caused by phytosanitary pests (Heather & Hallman, 2008). There is no commonly adopted standard for the recording and transmission of traceability information by FBOs (Islam et al., 2021). Consequently, traceability is handled differently by FBOs within the same fruit supply chain (Morreale et al., 2011). This complicates external traceability, as traceability information must be integrated across heterogeneous data formats and FBO information management systems.

Fruit supply chains are characterised by alternating diverging and

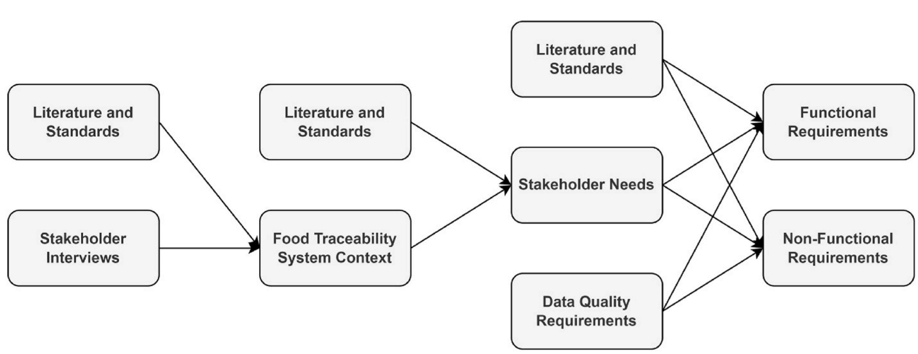

Fig. 1. Research Method (© University of Stellenbosch, used with permission).

converging processes (Trienekens et al., 2014), with various transformations of TRUs being performed, such as splitting and joining. An example is when several cartons are packed onto a pallet. Consequently, TRUs may comprise other TRUs and packaging, all of which must be traceable (Trienekens et al., 2014). Different FBOs may use different identification technologies and identifiers to identify TRUs, which may include barcodes and radio frequency identification (RFID) (Mehannaoui et al., 2023), while TRU identifiers may be numeric or alphanumeric (Olsen & Borit, 2018).

Typical FBOs in a fruit supply chain include farms, packhouses and exporters, as illustrated in Fig. 2. Moreover, there may be FBOs that do not directly handle fruit, such as marketers, but still contribute to the overall functioning of the fruit supply chain. The main processes in a fruit supply chain are the handling, conditioned storing, packing, transportation, and trading of fruit (Van der Vorst et al., 2005). Fruit moves in bulk bins from farms to packhouses, where the bins may be stored before being sorted and packed into cartons according to the requirements of various target markets. Cartons are subsequently packed into pallets, which are then loaded into shipping containers. Following this, an exporter transports the shipping containers from the packhouse to the relevant target markets.

Each FBO has an information management system that manages its internal traceability information. Several diverse third-party systems are typically used by FBOs to manage their internal traceability information and these systems may change over time. Some FBOs may use paper-based systems or general-purpose software (like Excel), while other FBOs use advanced systems that integrate traceability with production and logistics processes (Morreale et al., 2011). Therefore, an FTS may encounter considerable interoperability challenges and data integration issues, due to heterogeneous data sources (Bougdira et al., 2020).

3.2. Traceability audit process and data integration

Traceability audits rely on integrating information across a supply chain. Traceability audits can be investigative in nature or evaluative in nature. Two types of investigative traceability audits are *forward traceability* and *backward traceability* audits. Evaluative audits are used by FBOs to test whether their FTSs are meeting their requirements.

A forward traceability audit tracks a TRU through subsequent stages of the fruit supply chain (Islam & Cullen, 2021). These audits can be conducted to determine the location of all TRUs from a defective batch (Scholten et al., 2016). A backward traceability audit traces a TRU through prior stages of the fruit supply chain (Islam & Cullen, 2021), such as to determine the cause of an interception (detection of a phytosanitary pest) or a quality issue (Scholten et al., 2016). A backward traceability audit is used to determine what corrective action should be taken to prevent further interceptions from occurring.

The primary output of the traceability audit process is a traceability audit report. These reports typically have to comply with the specific information and formatting requirements of various target markets and food safety standards (e.g. BRCGS (2018)). Furthermore, the type of traceability audit, i.e. forward or backward, may influence the information requirements of the report.

A barrier to data integration is that information management systems of FBOs often act as *data silos,* i.e. segregated groups of data stored in multiple enterprise applications (Patel, 2019), with no or limited integration between the information management systems of FBOs. Consequently, there is a lack of end-to-end FTSs (Scholten et al., 2016). The result is that, during traceability audits, traceability information from different FBOs must be manually integrated and compiled into a traceability audit report, making it time-consuming and labour-intensive.

Another barrier to information integration in supply chains is that FBOs in the same fruit supply chain may be competitors with conflicting interests. FBOs may, therefore, be concerned that their confidential business information will be exposed to their competitors, rather than focusing on the benefits that sharing traceability information could have for all stakeholders in a fruit supply chain (Scholten et al., 2016).

3.3. Costs and resource considerations

The development and implementation of FTSs are expensive and complicated (Bosona & Gebresenbet, 2013). The initial cost is seen as the primary deterrent against the development and implementation of FTSs (Bosona & Gebresenbet, 2013; Islam et al., 2021), while the benefits of FTSs are difficult to quantify (Islam et al., 2021). Furthermore, beyond financial costs, the development and implementation of FTSs require other resources such as time, personnel, and technological infrastructure. Consequently, due to resource constraints, small- and medium-sized FBOs may be unable to implement improved FTSs (Zhang & Bhatt, 2014).

3.4. Stakeholder identification

The stakeholders of an FTS form an important part of the system's context. The stakeholders of an FTS are illustrated in the system context

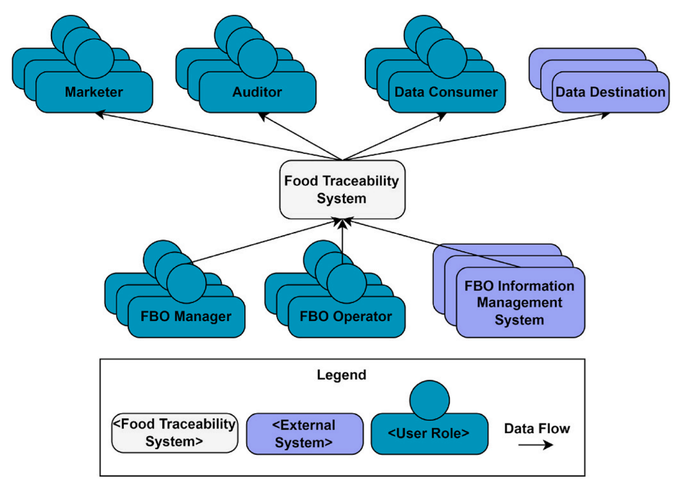

Fig. 3. Food Traceability System Context Diagram (© University of Stellenbosch, used with permission).

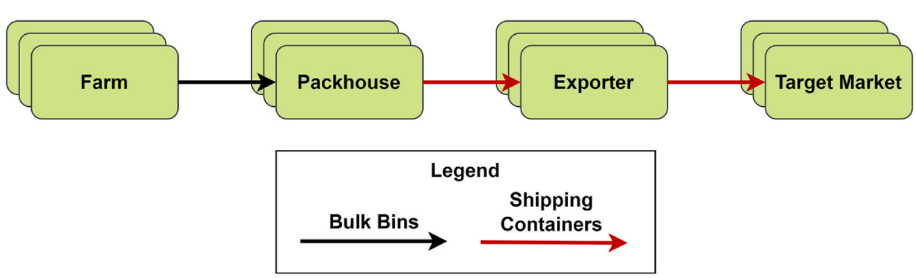

Fig. 2. Representative Fruit Supply Chain (© University of Stellenbosch, used with permission).

diagram in Fig. 3, which has been drawn using the C4 model (Brown, 2023). The FTS is represented as a black box in the system context diagram.

Islam and Cullen (2021) identified the following categories of stakeholders for FTSs.

- public, international standardisation, and non-governmental certification bodies
- business partners and stakeholders
- consumers and the community
- food business operators
- the scientific community

These stakeholders each have their own needs concerning traceability information and, consequently, FTSs (Islam & Cullen, 2021). The abovementioned stakeholders include primary users of an FTS, i.e. users who engage directly with the FTS to accomplish its primary objectives (ISO/IEC 25010, 2023). Fig. 3, therefore shows data flows to marketers, auditors, and other data consumers, as primary users. Fig. 3 also shows users that act as data sources, i.e. FBO managers and operators. The data source and data destination systems are not stakeholders of an FTS in the normal sense, but the FTS system requirements must still account for them. Therefore, Fig. 3 shows that traceability information flows from the FBO information management systems to the FTS. Data outputs from the FTS, i.e. the traceability information, flows from the FTS to external systems (hereafter referred to as data destinations).

Certification bodies are not explicitly indicated as stakeholders in Fig. 3, but certification bodies can act as auditors, data consumers and/or data destinations. Moreover, similarly to FBOs, certification bodies can act as data sources through their information management systems, and managers and operators. Stakeholders that do not directly interact with the FTS, such as consumers and the scientific community are traditionally not shown in context diagrams, but their needs are captured indirectly through the primary users and data destinations. Secondary users, such as system maintainers, configurators, and administrators, support the operation of the FTS (ISO/IEC 25010, 2023). Although the needs of these secondary users should also be considered, the secondary users are traditionally not shown in context diagrams.

4. Needs analysis

The stakeholder needs, as derived from the system context, are presented in Section 4.1. To cross-reference with the system requirements, the needs are labelled N1, N2, etc. Literature has reported principles of food traceability that also reflect the stakeholder needs. These principles are outlined in Section 4.2 and labelled P1, P2, etc. for cross-referencing. Since data quality is central to an FTS, data quality requirements (labelled DQR1, DQR2, etc.) are presented in Section 4.3.

4.1. Stakeholder needs

Different stakeholders may have a diverse set of potentially conflicting needs (Morreale et al., 2011). The stakeholder needs presented in this section are informed by the system context, presented in Section 3, as well as the stakeholder needs identified in the literature and standards.

The need for *end-to-end traceability* (N1) is central to FTSs throughout fruit supply chains, including both forward and backward traceability. The integrated information can be used for monitoring and reporting.

An FTS should aid *monitoring* (N2) by providing traceability information about the current status of TRUs and their compliance with the requirements of the target market (Morreale et al., 2011). Monitoring typically entails detecting deviations between the actual state and the planned state of the TRUs. Deviations may include delays in processes or processes being performed incorrectly. If deviations are detected, alerts should be generated (Morreale et al., 2011). Monitoring could prevent interceptions and/or quality issues, and the associated financial and reputational damage.

An FTS should generate *TRU market compliance reports* (N3). These reports would indicate whether TRUs are compliant with the requirements of target markets. These TRU market compliance reports could be used by marketers when allocating TRUs to different target markets.

The value of data is widely recognised in the era of artificial intelligence (AI). To extract value from the data in an FTS, the FTS should provide *access to aggregated traceability information* (N4) so that the data can be analysed at FBO and supply-chain levels, providing valuable insights that can inform improved decision-making. For example, pest records can be aggregated across several orchards (and even farms) and provided to farmers to warn them of a pest outbreak so that they can adapt the spraying of pesticides accordingly.

Storing traceability information (N5) is required to comply with regulatory and/or certification requirements. For example, the BRCGS (2018) global food safety standard requires that traceability information is stored, at a minimum, for a period of the shelf life of the food product plus twelve months.

Despite the need to integrate data, multi-stakeholder data privacy and confidentiality concerns require that FBOs can *secure traceability information* (N6), either in their own information management systems or within the FTS. An FTS must allow an FBO to decide whether to give an FTS user or organisation access to their traceability information. An FTS must also ensure the immutability of traceability information and prevent tampering with this information.

The need for a *flexible FTS* (N7) is evident from the diversity and interconnectedness described in Section 3.1. An FTS must interoperate with diverse information management systems of FBOs, accommodate changes to these systems, and accommodate the different identification technologies and identifiers used by FBOs. Further, an FTS must serve the requirements of diverse target markets and food safety standards, as well as changes in these requirements.

Ever-present resource constraints require a *cost-effective and scalable FTS* (N8). The initial and operational costs of the FTS must allow it to be implemented at large FBOs with abundant resources and at small- and medium-sized FBOs with limited resources (Zhang & Bhatt, 2014). The value of the FTS must justify the initial and operational cost, for example by providing automated traceability audits, thereby reducing the time and effort associated with performing traceability audits.

4.2. Principles of food traceability

The following principles of food traceability, as reported in the literature, also reflect the stakeholder needs:

P1: Identification of TRUs – defining the size or granularity of TRUs and ensuring that TRUs are uniquely identified (Islam & Cullen, 2021).

P2: Data Recording – choosing the types of traceability information to be recorded and the mediums used to record the traceability information (Islam & Cullen, 2021).

P3: Data Integration – integrating traceability information within FBOs (enabling *internal traceability*) and between FBOs (enabling *external traceability*) (Islam & Cullen, 2021; Moe, 1998).

P4: Data Accessibility – providing users with relevant traceability information (Islam & Cullen, 2021; Šenk et al., 2013).

Applying the above principles involves making choices for a specific instance of an FTS in its specific context. If an FTS should serve multiple instances to justify its development cost, the FTS should adhere to the four principles and be customisable to a specific context.

4.3. Data quality requirements

The data managed by an FTS is, in some respects, a stakeholder in the FTS and, therefore, this section considers the data quality requirements that may lead to system requirements for an FTS. Poor quality data exchanged between FBOs would negatively affect FTS processes such as trace-back investigations or recall activities (GS1, 2017). The data quality requirements presented here are informed by the ISO/IEC 25012 (2008) data quality model, which comprises fifteen data quality characteristics. This data quality model considers data quality from two perspectives: *Inherent data quality* relates to the quality of the data itself, while *system dependent data quality* relates to the extent to which data quality is achieved and maintained within an FTS. Some data quality characteristics are relevant from both perspectives. The data quality requirements are summarised in Table 1, along with their respective data quality perspective(s). Note that the descriptions should be taken in a specific context of use.

5. System requirements

SEBoK Editorial Board (2023) defines a requirement as "a *statement that identifies a product or processes operational, functional, or design characteristic or constraint, which is unambiguous, testable, or measurable and necessary for product or process acceptability*".

In this section, the system requirements for an FTS in a fruit supply chain are presented. The system requirements were derived from the stakeholder needs (N cross-references) and principles of food traceability (P cross-references) presented in Sections 4.1 and 4.2, as well as the data quality requirements presented in Section 4.3 (DQR cross-references). Furthermore, relevant literature and traceability standards, in particular ISO 22005 (2007) and GS1 (2017), were consulted.

Table 1
Data quality requirements (adapted from ISO/IEC 25012, 2008).

ID	Requirement Description	Data Quality Perspective[a]
DQR1	Accuracy – the data attributes correctly represent the true value of the intended attributes of a concept.	I
DQR2	Completeness – the subject data associated with an entity has values for all expected attributes and related entity instances.	I
DQR3	Consistency – the data attributes are free from contradiction and are coherent with other data.	I
DQR4	Credibility – the data attributes are regarded as true and believable by users.	I
DQR5	Currentness – the data attributes are of the right age.	I
DQR6	Accessibility – the data can be accessed, particularly by people with disabilities.	I & SD
DQR7	Compliance – the data attributes adhere to standards, conventions or regulations in force and similar rules relating to data quality.	I & SD
DQR8	Confidentiality – the data attributes ensure that it is only accessible and interpretable by authorised users.	I & SD
DQR9	Efficiency – the data attributes can be processed with the expected levels of performance by using the appropriate amounts and types of resources.	I & SD
DQR10	Precision – the data attributes are exact or provide discrimination.	I & SD
DQR11	Traceability (hereafter referred to as Data Traceability) – the data attributes provide an audit trail of access to the data and of any changes made to the data.	I & SD
DQR12	Understandability – the data attributes enable it to be read and interpreted by users, and are expressed in appropriate languages, symbols and units.	I & SD
DQR13	Availability – the data attributes enable it to be retrieved by authorised users and/or applications.	SD
DQR14	Portability – the data attributes enable it to be installed, replaced or moved from one system to another preserving the existing quality.	SD
DQR15	Recoverability – the data attributes enable it to maintain and preserve a specified level of operations and quality, even in the event of failure.	SD

[a] I = inherent; SD = system dependent.

For generality, the system requirements were formulated for a generic fruit supply chain rather than specific to the context of any particular fruit supply chain. Moreover, the system requirements were formulated to be independent of the implementation technology. The system requirements are classified into FRs (Section 5.1) and NFRs (Section 5.2).

5.1. Functional requirements

The FRs are separated into primary FRs (Section 5.1.1) and derived FRs (Section 5.1.2). The primary FRs address the flow of information across the system boundary (illustrated in Fig. 3). A derived requirement is defined as a "*requirement that is not explicitly stated in customer requirements, but is inferred from contextual requirements (such as applicable standards, laws, policies, common practices, and management decisions) or from requirements needed to specify a product or service component*" (ISO/IEC/IEEE 24765, 2017).

5.1.1. Primary functional requirements

The primary FRs, cross-referenced with the related stakeholder needs, food traceability principles, and data quality requirements, are presented in Table 2 and are discussed below in further detail.

FR1 and FR2 capture the core purpose of an FTS, i.e. to provide traceability information to stakeholders (N1, N3), such as auditors and marketers, and to data destinations (N4), such as machine learning analyses. FR1 and FR2, therefore, implement the data accessibility principle (P4). While FR1 and FR2 are reactive, FR3 is pro-active. Although an FTS will be useful without it, FR3 will add considerable value to stakeholders by preventing interceptions and/or quality concerns.

FR4 and FR5 are also core functions of an FTS and essential to implement principles P2 and P3. An FTS must be able to ingest traceability information both autonomously through interfacing with FBO information systems and through manual interactions, thereby accommodating a range of digital maturities amongst FBOs. For example, a farm with low digital maturity may employ paper records for traceability information while a packhouse with high digital maturity will

Table 2
Primary functional requirements for a food traceability system in a fruit supply chain.

ID	Requirement Description	Needs Analysis Cross-References
FR1	Generate reports a) on forward and backward traceability audits according to the requirements of target markets and food safety standards, i.e. traceability audit reports. b) on the compliance of TRUs with the requirements of target markets, i.e. TRU market compliance reports.	P4, N1, N3
FR2	Provide traceability information to data destinations and data consumers.	P4, N1, N4
FR3	Generate alerts a) when deviations between the actual state and the planned state of TRUs in the fruit supply chain are detected, and b) when data quality issues are detected.	N2
FR4	Autonomously ingest traceability information from the information management systems of FBOs a) pre-emptively, or b) when required by other FTS functions	P3, N1
FR5	Ingest traceability information from digital interfaces used by FBOs to manually capture traceability information by a) entering data on user interfaces provided by the FTS, b) uploading files such as spreadsheets, and c) providing interfaces whereby domain experts can correct data quality issues.	P2, P3, N1

employ digital systems for traceability information. For the farm, FR5a and FR5b are required, while for the packhouse, FR4 is required.

Pre-emptive ingestion indicates ingestion before the traceability information is required, while on-demand ingestion indicates ingestion when the information is required. Both pre-emptive and on-demand ingestion should be provided by an FTS because the option used will be influenced by the level of trust in the persistence of the relevant FBO information management system. This level of trust can differ from one FBO to another and, for a given FBO, can change over time. For example, consider two packhouses: one packhouse has a low level of trust in the persistence of its information management system, while the other packhouse has a high level of trust in the persistence of its information management system. Therefore, for the first packhouse, FR4a will be required, while for the second packhouse, FR4b will be required.

FR5c complements FR3b and, as for FR3, an FTS will be useful without FR5c, but it will add considerable value to the stakeholders.

5.1.2. *Derived functional requirements*

The derived FRs, which are addressed in this section, are high-level functions that an FTS should perform to be able to perform the primary FRs, which are addressed in Section 5.1.1. The derived FRs, with the related stakeholder needs and data quality requirements, are presented in Table 3 and discussed below in further detail.

FR6 and FR7 are required if an FTS performs FR3 and FR5c. Therefore, FR6 and FR7 will enable value-adding functionality, even though an FTS will be useful without these derived functions. It should be noted that an FTS cannot autonomously ensure inherent data quality, but an FTS can perform some data quality checks to help ensure that data meets the following inherent data quality requirements: accuracy (DQR1), completeness (DQR2), consistency (DQR3), credibility (DQR4), currentness (DQR5), compliance (DQR7), and precision (DQR10). For example, when the FTS ingests traceability information, it may detect missing values and values that fall outside the ranges specified in the requirements of a corresponding target market, using AI models contained within the FTS.

FR8 directly addresses P1 by recording the unique identifiers associated with a TRU as it passes through the different FBOs. Each TRU must have a unique identifier in an FBO because it is otherwise impossible to distinguish between different TRUs (Islam & Cullen, 2021). In this study, it is assumed that FBOs are responsible for assigning unique identifiers to the TRUs that they create. Further, FBOs must maintain the relationship between the TRUs when one or more TRUs are “consumed” in a process that “creates” one or more new TRUs. At the end of a supply chain, a TRU will have undergone multiple transformations, potentially with multiple unique identifiers. Consequently, an FTS is required to maintain a record of the unique identifiers assigned to TRUs by the relevant FBOs. FR8 is also essential to accomplish FR9.

Data integration (FR9) is another core functionality of an FTS, implementing P3 and accomplishing the “end-to-end” aspect of N1. Because an FTS typically captures processes in an FBO where the incoming and outgoing TRUs are not the same, an FTS must integrate internal traceability information within FBOs that link the relevant traceability information to the unique identifier(s) of relevant TRUs. Furthermore, an FTS must integrate traceability information between FBOs to enable external traceability for end-to-end traceability (N1).

Transformation of incoming and outgoing data (FR10) is required for several purposes. Firstly, to address the stakeholder need for a flexible FTS (N7), an FTS must transform incoming data from the internal schema of FBO information management systems to the standardised schema of the FTS. For example, one FBO may refer to a temperature using the name “Temp”, while another FBO uses “T”. In this case, the FTS must transform the variable names from “Temp” and “T” to the variable name in the schema of the FTS, such as “temperature”.

Secondly, an FTS must transform outgoing data into the format required by different target markets and food safety standards for traceability audit reports. For example, a target market may require all temperature values to be reported in Fahrenheit, while the temperature values are stored in Celsius in the schema of the FTS. In this case, the FTS must transform the temperature values from Celsius to Fahrenheit when generating the traceability audit report.

Finally, to enable the data quality requirement of compliance (DQR7), an FTS must transform data such that it conforms to relevant standards, conventions or regulations concerning data quality.

An FTS must store traceability information (FR11) at least for periods determined by relevant legal, regulatory and/or certification requirements, thereby addressing N5. An FTS should accommodate multiple data storage strategies to accommodate the different levels to which FBOs want to maintain custody of their traceability information (N7). Storage strategies can be separated into warehousing and federation (or virtual integration) (Doan et al., 2012). The choice between the data storage strategies and implementation architectures is affected by data privacy considerations, the level of trust in the persistence of the relevant FBO information management system, and data-access latency considerations. For example, when traceability information is ingested pre-emptively due to a low-level of trust in the relevant FBO information management system, the data must be stored within the FTS’s data warehouse. On the other hand, when traceability information will be ingested on-demand from an FBO with a high level of trust, a federation approach is used where the data is only stored for the long term in the relevant FBO information management system.

Storing also implies that an FTS would be required to maintain backups of traceability information so that traceability information can be recovered in the event of failures, thereby enabling the data quality requirement of recoverability (DQR15). When traceability information is to be ingested on-demand, and consequently stored within the relevant FBO information management system, the responsibility of maintaining backups of the relevant traceability information should be placed on the relevant FBO information management system and not the FTS.

Security is more typically related to NFRs, but here some functional aspects are included in FR12, specifically that an FTS must provide role-based information access (N6, DQR8, DQR11, DQR13), log changes to the data (DQR11), and ensure immutability of traceability information,

Table 3
Derived functional requirements for a food traceability system in a fruit supply chain.

ID	Requirement Description	Needs Analysis Cross-References
FR6	Monitor the state of TRUs in the fruit supply chain to detect deviations between the actual state and the planned state of the TRUs.	N2
FR7	Perform data quality checks using a) rule-based tests, b) schema-based tests, and c) AI-based tests.	N3, DQR1, DQR2, DQR3, DQR4, DQR5, DQR7, DQR10
FR8	Maintain the relationship between TRUs and their unique identifiers.	P1, N1
FR9	Integrate diverse traceability information a) within FBOs, and b) between FBOs.	P3, N1
FR10	Transform a) data ingested from diverse FBOs, and b) information provided to diverse users.	P3, N7, DQR7
FR11	Store traceability information using a combination of a) data warehousing, and b) data federation.	N5, N7, DQR15
FR12	Secure data access by a) only providing access to data that the particular user is authorised to access, b) logging changes to the data, and c) implementing measures that ensure immutability of the traceability information provided to users.	N6, DQR4, DQR8, DQR11, DQR13

for example through digital signatures (DQR4). Role-based access includes providing logs of accesses and changes to traceability information, thereby enabling the data quality requirement of data traceability (DQR11).

5.2. Non-functional requirements

NFRs, also known as performance attributes, describe how or how well a system must perform its functions (ISO/IEC/IEEE 24765, 2017). NFRs, therefore, complement FRs in describing the required quality of a system. ISO/IEC/IEEE 24765 (2017) defines quality as "*the degree to which the system satisfies the stated and implied needs of its various stakeholders, and thus provides value*".

The NFRs in this section were informed by the ISO/IEC 25010 (2023) "Systems and software Quality Requirements and Evaluation (SQuaRE) — Product quality model" to ensure that all important factors of quality are taken into account. SQuaRE comprises nine quality characteristics: functional suitability, performance efficiency, compatibility, interaction capability, reliability, security, maintainability, flexibility, and safety. Each quality characteristic is further divided into a set of quality sub-characteristics. Potentially all quality characteristics and sub-characteristics of SQuaRE are relevant to an FTS, but here priority is given to the NFRs related to the stakeholder needs and the data quality requirements (Section 4). Three quality characteristics of the ISO/IEC 25010 (2023) product quality model that have not been included as part of the NFRs, namely functional suitability, security, and safety, deserve further discussion.

Functional suitability is defined as the "*capability of a product to provide functions that meet stated and implied needs of intended users when it is used under specified conditions*" (ISO/IEC 25010, 2023). Therefore, functional suitability is not included as an NFR because it is addressed by the FRs (presented in Section 5.1).

Security is defined as the "*capability of a product to protect information and data so that persons or other products have the degree of data access appropriate to their types and levels of authorisation, and to defend against attack patterns by malicious actors*" (ISO/IEC 25010, 2023). Some aspects of security are addressed in FR12, but there are numerous aspects that can be expressed as NFRs. The NFR aspects are not unique to FTSs and are, therefore, not considered further here.

Lastly, safety is defined as the "*capability of a product under defined conditions to avoid a state in which human life, health, property or the environment is endangered*" (ISO/IEC 25010, 2023). From a functional perspective, an FTS is inherently aimed at supporting safety in fruit supply chains. From an NFR perspective, the safety quality attributes for an FTS are similar to all software systems and are, therefore, not considered here.

The NFRs, with the related stakeholder needs and data quality requirements, are presented in Table 4. Quality-in-use for primary users is greatly impacted by the following NFRs: performance efficiency, compatibility, interaction capability, reliability, and flexibility (ISO/IEC 25010, 2023). For secondary users who are involved in the maintenance of the FTS, quality-in-use is greatly impacted by the following NFRs: performance efficiency, compatibility, reliability, maintainability, and flexibility (ISO/IEC 25010, 2023).

Performance efficiency (NFR1) is defined as the "*capability of a product to perform its functions within specified time and throughput parameters and be efficient in the use of resources under specified conditions*" (ISO/IEC 25010, 2023). The sub-characteristics of performance efficiency are time behaviour, resource utilisation, and capacity. N8 and DQR9 require an FTS that efficiently uses resources such as computational resources and data storage. Time behaviour is important, in particular, because an FTS is required to complete traceability audits within the period specified by legal, regulatory and/or certification requirements. For example, BRCGS (2018) requires that a traceability audit be completed within 4 h. Another example of NFR1 is the maximum allowed latency for user interactions, i.e. the maximum time duration between a user selecting a function on the user interface and the FTS providing the required response. This NFR could require an FTS implementation to use data warehousing if an FBO's information system is too slow to use data federation, even if the FBO can be trusted to maintain the data for the long term.

Compatibility (NFR2) is defined as the "*capability of a product to exchange information with other products, and/or perform its required functions while sharing the same common environment and resources*" (ISO/IEC 25010, 2023). The sub-characteristics of compatibility are co-existence and interoperability. NFR2, therefore, directly addresses N7 to be interoperable with the diverse information management systems of FBOs, various data destinations, and diverse identification technologies and identifiers used by FBOs. For example, an FTS may be required to interoperate with the fruit quality system and packing material system of a particular packhouse to obtain relevant traceability information.

Interaction capability (NFR3) is defined as the "*capability of a product to be interacted with by specified users to exchange information between a user and a system via the user interface to complete the intended task*" (ISO/IEC 25010, 2023). The sub-characteristics of interaction capability are appropriateness recognisability, learnability, operability, user error protection, user engagement, inclusivity, user assistance, and self-descriptiveness. NFR3, therefore, contributes to meeting the accessibility requirements of DQR6 and the understandability requirements of DQR12. Examples of this NFR include the languages for user interfaces and the maximum acceptable training time for new users.

Reliability (NFR4) is defined as the "*capability of a product to perform specified functions under specified conditions for a specified period of time without interruptions and failures*" (ISO/IEC 25010, 2023). The sub-characteristics of reliability are faultlessness, availability, fault tolerance, and recoverability, which directly address DQR13. Typical NFRs for reliability are the required percentage of up-time and the acceptable levels of degradation of FTS operations in the presence of network interruptions.

Maintainability (NFR5) is defined as the "*capability of a product to be modified by the intended maintainers with effectiveness and efficiency*" (ISO/IEC 25010, 2023). The sub-characteristics of maintainability are modularity, reusability, analysability, modifiability, and testability. To address the stakeholder need for a flexible FTS (N7), an FTS is required to be easily modifiable to accommodate changes to the information management systems of FBOs, and the TRU identification technologies and identifiers used by FBOs. Furthermore, an FTS is required to be easily modifiable to accommodate the diverse information and formatting requirements of target markets and food safety standards for traceability audit reports. For example, when the requirements of existing target markets and food safety standards change or new target markets and food safety standards with their own sets of requirements are introduced, an FTS is required to be easily modifiable to accommodate these changes.

NFR5 also contributes to compliance (DQR7) by ensuring that an FTS can easily be modified to accommodate different requirements related to standards, conventions or regulations concerning data quality. Lastly, to enable the data quality requirement of precision (DQR10), an FTS is required to be easily modifiable to accommodate different precision requirements for traceability information.

Table 4
Non-functional requirements for a food traceability system in a fruit supply chain.

ID	Non-Functional Requirement	Needs Analysis Cross-References
NFR1	Performance Efficiency	N8, DQR9
NFR2	Compatibility	N7
NFR3	Interaction Capability	DQR6, DQR12
NFR4	Reliability	DQR13
NFR5	Maintainability	N7, DQR7, DQR10
NFR6	Flexibility	N8, DQR14

Flexibility (NFR6) is defined as the "*capability of a product to be adapted to changes in its requirements, contexts of use, or system environment*" (ISO/IEC 25010, 2023). The sub-characteristics of flexibility are adaptability, scalability, installability, and replaceability. To address the stakeholder need for a cost-effective and scalable FTS (N8), an FTS is required to be scalable. An example of this NFR is a requirement that the FTS can be implemented at FBOs with varying sizes, resources, and implementation technologies. NFR6, thereby, also contributes to portability (DQR14).

6. Discussion

The system requirements presented in Section 5 can be evaluated against three sets of general criteria: firstly the principles of food traceability proposed by Islam and Cullen (2021), secondly the requirements for traceability systems presented in the GS1 (2017) global traceability standard, and, finally, characteristics for FTSs proposed by McEntire et al. (2010). Section 5 shows explicitly where the principles of food traceability proposed by Islam and Cullen (2021) are reflected in the system requirements and, therefore, this section focuses on the other sets of criteria.

The requirements for traceability systems presented in the GS1 (2017) global traceability standard are categorised as follows: identification requirements, automatic data capture and identification (AIDC) requirements, data recording requirements, and data sharing requirements. In each category, there are several requirements, but a comparison between the system requirements presented in this paper and each of the requirements proposed under each category in the GS1 (2017) global traceability standard is beyond the scope of this paper. Therefore, the requirements presented in this paper are only compared against the categories of requirements proposed by the GS1 (2017) global traceability standard.

The identification requirements are primarily concerned with the unique identification of TRUs, which is addressed by FR8, while the data recording requirements are primarily concerned with the recording of traceability information, which is addressed by FR4 and FR5. The data-sharing requirements are primarily concerned with the sharing of traceability information between FBOs, which is addressed by FR9.

The AIDC requirements are primarily concerned with the use of open standards for TRUs that require automatic identification. Although this aspect is not directly addressed by the system requirements presented in this paper, NFR5 accommodates this aspect by requiring the FTS to be able to be modified to new requirements which may include a requirement for the FTS to use open standards for TRUs that require automatic identification.

Lastly, to evaluate the system requirements in this paper, the following characteristics of FTSs proposed by McEntire et al. (2010) can be considered.

- Breadth – the amount of information the traceability system records.
- Depth – how far upstream or downstream in the supply chain the system tracks.
- Precision – the degree of assurance with which the system can pinpoint a particular product's movement or characteristics.
- Access – the speed with which track-and-trace information can be communicated to supply chain members and the speed with which requested information can be disseminated to public health officials during food-related emergencies.

The system requirements presented in this paper address the characteristic of breadth with FR4 and FR5. Furthermore, the system requirements address the characteristic of depth with FR9 which makes provision for the integration of traceability information between FBOs, thereby enabling external traceability.

Precision, on the other hand, is not directly addressed by the system requirements. Rather, the precision of the FTS will be determined by the level of granularity employed by the FBOs in the fruit supply chain. However, through FR8, the system requirements make provision for various levels of granularity that may be employed by FBOs. Lastly, the system requirements address the characteristic of access with NFR1, which specifies that FTSs should be able to complete traceability audits within a specified period.

The requirements do not explicitly specify the amount of information the FTS records, how far upstream or downstream the FTS enables traceability, the level of granularity of TRUs, nor the speed with which traceability information should be provided. These target values would be specific to the context of a particular fruit supply chain.

Based on this discussion, it can be concluded that the system requirements presented in this paper address the essential FRs of an FTS. Furthermore, as previously indicated, existing requirements lack in defining NFRs for FTSs and considering data quality when defining requirements for FTSs. The system requirements presented in this paper address these shortcomings and the resulting set of requirements not only informs what functions an FTS should perform, but also includes measures of the quality of functions. Therefore, the system requirements can be useful in the development and evaluation of FTSs in fruit supply chains.

The system requirements for an FTS in a fruit supply chain presented in this paper lack target values. Target values for FRs and NFRs are context dependent and, therefore, the lack of target values is inevitable for a generic set of system requirements that are relevant to various fruit supply chain contexts. However, the FRs and NFRs presented here provide a framework for formulating target values in a particular context and, when comparing different FTSs, comparing the targets achieved. Target values may be specified according to relevant food safety standards, industry standards, target market requirements, and FBO requirements.

The generality of the FRs and NFRs presented here could be explored in future research. This paper focuses on the system requirements for an FTS in a fruit supply chain, but at a high level, many of the FRs and NFRs are independent of the food product being traced. The system requirements could, therefore, inform the development and evaluation of FTSs in other food supply chains.

7. Conclusion

This paper presents a set of system requirements, expressed as FRs and NFRs, for an FTS in a fruit supply chain. The system requirements can be used in the development and evaluation of FTSs. The presented set of requirements integrates inputs from stakeholder interviews within a representative fruit supply chain, literature, and standards. The requirements were developed by first considering the context of an FTS, noting inter alia the diversity and interconnectedness of the context. From the context, the stakeholder needs, principles of food traceability, and data quality requirements were formulated, which led to the system requirements for an FTS in a fruit supply chain, comprising FRs and NFRs. The requirements were evaluated against principles of food traceability, the requirements for traceability systems, and the characteristics of FTSs reported in the literature.

This paper, therefore, addresses a gap in the research literature by providing a set of system requirements for FTSs aimed at fruit supply chains and by expressly addressing requirements related to data quality and adaptability. The system requirements presented in this paper present a starting point for the industry to formulate target values for the development or evaluation of FTSs aimed at fruit supply chains.

Future work should consider specifying target values for the system requirements and adapting the system requirements to other types of food supply chains. Formulating metrics that can be used to evaluate compliance with FRs and NFRs should also be investigated. Additionally, future work should consider the development of an FTS in a fruit supply chain that satisfies the system requirements presented in this paper. Such an FTS should then be implemented within a case study of a representative fruit supply chain. The FTS implemented within the context of the case study, should then be verified and evaluated against the system requirements presented in this paper.

CRediT authorship contribution statement

Azhar Cader: Writing – original draft, Validation, Methodology, Investigation. **Anton H. Basson:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Karel Kruger:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Nicole C. Taylor:** Writing – review & editing, Supervision.

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Data availability

The data that has been used is confidential.

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