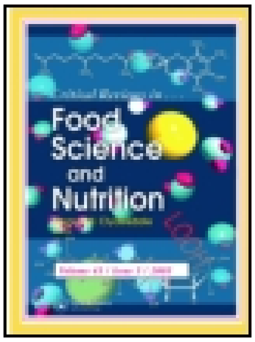

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REVIEW

Traceability in food processing: problems, methods, and performance evaluations—a review

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ABSTRACT
Processed food has become an indispensable part of the human food chain. It provides rich nutrition for human health and satisfies various other requirements for food consumption. However, establishing traceability systems for processed food faces a different set of challenges compared to primary agro-food, because of the variety of raw materials, batch mixing, and resource transformation. In this paper, progress in the traceability of processed food is reviewed. Based on an analysis of the food supply chain and processing stage, the problem of traceability in food processing results from the transformations that the resources go through. Methods to implement traceability in food processing, including physical separation in different lots, defining and associating batches, isotope analysis and DNA tracking, statistical data models, internal traceability system development, artificial intelligence (AI), and blockchain-based approaches are summarized. Traceability is evaluated based on recall effects, TRUs (traceable resource units), and comprehensive granularity. Different methods have different advantages and disadvantages. The combined application of different methods should consider the specific application scenarios in food processing to improve granularity. On the other hand, novel technologies, including batch mixing optimization with AI, quality forecasting with big data, and credible traceability with blockchain, are presented in the context of improving traceability performance in food processing.

KEYWORDS
Artificial intelligence (AI); batch mixing; food processing; resource transformation; traceability

1. Introduction

Attention focused on food safety after several shocking events occurred in the 1990s, including the bovine spongiform encephalopathy outbreak in the United Kingdom (Wales, Harvey, and Warde 2006), the contamination of chicken feed with dioxin in Belgium (Bernard et al. 2002), and the melamine contamination in China (Wu and Chen 2018). Traceability is the ability to track the source of a food product at any point in production, i.e., knowing a food production chain history. For processed food, traceability includes harvest, transport, storage, processing to distribution, and sales (Regattieri, Gamberi, and Manzini 2007; Olsen and Aschan 2010). Traceability systems enable food manufacturers to identify sources of safety or quality-control issues, gauge the extent of potential food safety problems, decrease the production of unsafe or poor-quality foods, and curtail bad public relations, liability, and recalls (Olsen and Borit 2018). Investments in traceability systems are worthwhile due to improved food safety and quality and reduced risks (Corallo et al. 2020).

Recent research into traceability systems has focused on operating mechanisms, consumer perceptions (Kim and Woo 2016; Rodriguez-Salvador and Dopico 2020), traceability modeling (Van der Spiegel et al. 2013; Zhao, Wang, and Yang 2020), system development (Feng et al. 2013; Thakur et al. 2020), and traceable technology (Li et al. 2010; Pierini et al. 2016). Traceability systems have been implemented throughout the world due to interest in the safety and quality of food and due to regulatory, social, and economic issues (Bosona and Gebresenbet 2013). Supervision systems have been initiated by some government agencies, including the EU Rapid Alert System for Food and Feed (RASFF) (Pádua et al. 2019), the Food Modernization and Safety Act (USA), and the National Agriculture and Food Traceability System (Canada) (Badia-Melis, Mishra, and Ruiz 2015). For supply chain management (SCM), traceability systems, and applications for different agro-food or food quality requirements have been investigated, including traceability systems for vegetables (Mainetti et al. 2013; Qian et al. 2020), fruits (Porto, Arcidiacono, and Cascone 2011; Reyes et al. 2012), aquaculture (Marchante et al. 2014) and pork (Chen et al. 2020).

From field to table, food supply chains consist of farming, handling, logistics, storage, and sales. Processing is the main body of a food supply chain (FSC). Processed foods are very common in contemporary society (Silva and Sanjuán 2019). More than half of the food sold in the world

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is processed food (IMAP 2010). Meanwhile, the global packaged food market has a promising future, whose value will reach over 2.2 trillion US dollars by 2021 (Euromonitor 2016). New challenges in the traceability of food processing stages, such as batch mixing, do not exist for agro-foods. Therefore, much attention has been paid to traceability during the food processing stage. Methods for improving traceability, related to processing flow analysis, batch mixing simulations, and batch optimization modeling, are presented. Measuring traceability performance is important for analyzing the effectiveness of these different improvement methods.

In this paper, traceability progress in food processing is reviewed. Specifically, the food supply chain and processing stages are analyzed in Section 2 and problems, methods, and performance evaluations are described in Sections 3, 4, and 5, respectively. Section 6 compares different methods and application scenarios and performances. Finally, some new traceability trends in food processing are addressed, including artificial intelligence, blockchain, and big data.

2. Supply chain and food processing

2.1. Food supply chain

Supply chain is a recent phrase, which came from logistics in the early 1980s. As an integrated system with a common target, a supply chain is an inventory management method that can optimize the progress from raw material to final products (Cooper and Ellram 1993; Christopher 1998). In the 1990s, supply chain management (SCM) development was enhanced by the introduction of the term "value chain" (Porter and Millar 1985). Value chain is a process in which every activity links to each other and enhances the value of the product or service. Together with SCM, organizational and management research has contributed to the development of a network approach (Webster 1992). SCM investigations eventually led to the marriage of supply chain and network approaches (Lazzarini, Chaddad, and Cook 2001). Thus, a supply chain integrates processes conducted by networks, consisting of horizontal and vertical links between interlinked and codependent organizations cooperating to organize and enhance material and data movement throughout the processing chain (Wiersinga et al. 2010).

A FSC is a system in which persons and organizations start with fresh agricultural products, and with the support of machines, deliver food products to consumers (Kozlenkova et al. 2015). FSCs, one of the main manufacturing sectors in the global economy (Fritz and Schiefer 2009), bring great benefits to people from all walks of life (Tamplin 2018). Major changes have occurred in FSCs in recent years, including globalization, consolidation of food categories at every FSC level, and commoditization (Roth et al. 2008; Wible, Mervis, and Wigginton 2014). In commoditization, food products are traded in large quantities as common commodities and sourced world-wide to minimize costs (Astill et al. 2019). FSCs have improved due to these trends, which influence the traceability of food products. Traceability systems and recall management can be beneficial for improving food safety in global supply chains (Mattevi and Jones 2016).

The two major kinds of food supply chains pertaining to vegetable or animal product production and distribution are as follows (Scholten et al. 2016):

- Fresh agricultural product supply chains (such as fresh vegetables, flowers, and fruit) involving growers, auctions, wholesalers, importers, exporters, retailers, and specialty shops and their input and service suppliers. The intrinsic characteristics of the beginning product are untouched and the main processes are handling, conditioned storage, packing, transportation, and trading.
- Processed food supply chains (such as portioned meats, snacks, desserts, and canned food products) start with raw agricultural products and end with processed consumer products with enhanced value and, very often, prolonged shelf lives.

2.2. Food processing

Food processing is a series of actions done to food with dedicated targets before it is available. Fresh and inedible agricultural products are converted to more stable and palatable foods and beverages for human consumption (International Food Information Council Foundation 2010). Processed food occupies an important place in human history; processing allows food to be available in the desired form whenever needed (Floros et al. 2010). Processing also provides rich nutrition for human health (Miclotte and Van de Wiele 2020). Processes in food manufacturing include milling, cooling/freezing, smoking, heating, canning, fermentation, drying, and extrusion cooking, which change food components. These changes can improve or worsen food quality (Weaver et al. 2014). Food additives, in particular, are an important element of food processing, which can improve quality, prolong shelf life, and increase food safety (Kumar et al. 2015). Any step in the food supply chain may require processing from collection or capture (e.g., flour milling or fish canning) to the production of prepared foods (e.g., bread, biscuit, noodles, yogurt) (Augustin et al. 2016).

Traditional food processing continues to provide people with food. Meanwhile, new emerging food processing technology to improve food quality and processing efficiency is becoming increasingly important. Newly developed technologies, including high-pressure processing, pulsed electric field, cool plasma, UV irradiation, and ultrasound, improve food shelf life and change food characteristics (Knorr et al. 2011; Sánchez-Moreno et al. 2009; Tao and Sun 2015).

3. Problems in processed food traceability

3.1. Traceability implementation in primary agro-food

Identification labels, such as bar codes or serial numbers, can be attached to the product or packaging, making traceability simple for primary agro-food. Defining a traceable resource unit (TRU) is required for the implementation of

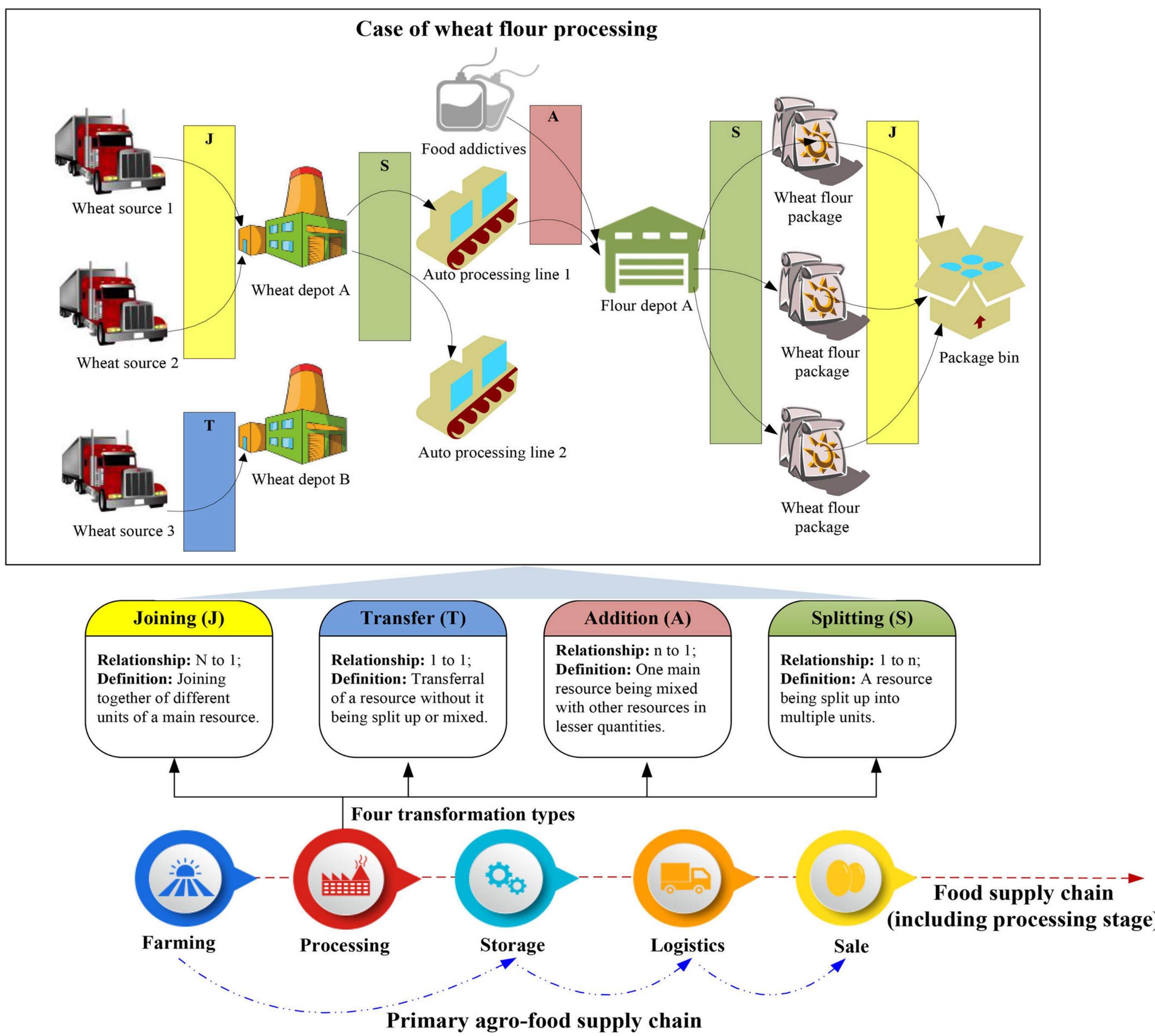

Figure 1. Resource transformations in food processing stage.

traceability systems (Fan et al. 2019). A TRU must be unique and accurate and contain the necessary data that will accompany the TRU through a supply chain (Olsen and Borit 2013). TRUs that are commonly used in food supply chains include batches, trade units, and logistical units (Aung and Chang 2014). A batch is a quantity of material from a given process in the supply chain. A trade unit is a component delivered from one supply chain enterprise to another. A logistical unit is a trade unit, generated by an enterprise before transportation or storage (Karlsen, Donnelly, and Olsen 2011).

Rapid development in information and communication technologies has contributed to enhanced traceability of primary agro-food (Sun and Wang 2019). Integration of identification technologies like barcodes and radio-frequency identification (RFID) into traceability systems facilitate swift product and batch identification (Luvisi et al. 2012; Yang et al. 2016). A key advance in traceability systems is the inclusion of wireless sensory networks combined with portable devices that allow for real-time and on-scene monitoring and collection of environmental and farming data (Qian et al. 2015; Steinberger, Rothmund, and Auernhammer 2009). Furthermore, FSCs can be enhanced by decision support systems (DSSs), which assist in the decision to accept or reject food products and/or intervene. DSSs are based on documentation of raw data, personal knowledge, and/or models to identify food safety issues (Qian et al. 2018).

3.2. Main problems in processed food traceability

A series of storage/carrying actions and unit operations constitute a complete food production process (Dabbene and Gay, 2011). Indeed, food industries use many elements in liquids (e.g., milk, vegetable oils), powders (e.g., cocoa, powdered milk, flour, yeast), crystals (e.g., sugar, salt), and

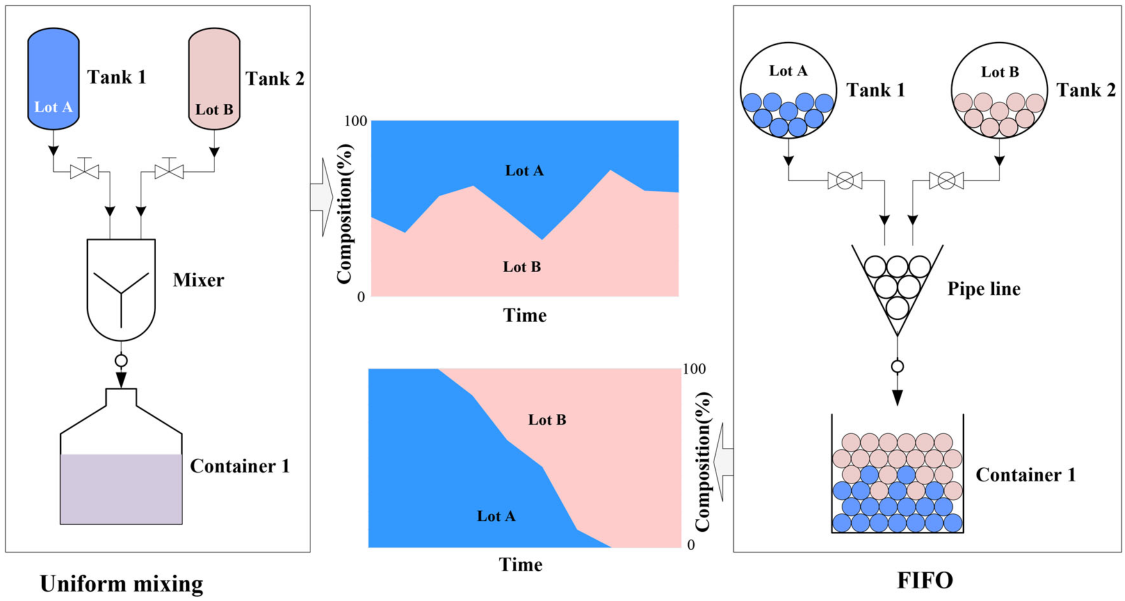

Figure 2. Two types of batches mixing diagram in the food processing stage.

grains, which are stored in large silos or tanks that are seldom emptied in one go. As a result, more than one batch is stored in a container at the same time. In a plant, multiple production lines may be consuming a material while final products are formed, packed, and made available for sale. In many cases, production involves multiple steps, which are implemented at separate production stations. The mixing of various raw or intermediate components is sometimes required. Physical, chemical, and microbiological processes, including heating, cooling, concentration, and pasteurization, are sometimes needed. Finally, production lots are created. When the material moves to the next point, the retrieved material may be a mixture of materials from different batches that are stored in separate containers or produced at different stages (Comba et al., 2013).

Traceability is the ability to identify the origin of each component of the intermediate or end product. This information is important in determining the quantity and position of production portions influenced by defective materials fed into the supply chain at any point. This can be illustrated using the example of animal slaughtering. During the slaughtering process, meat is divided into retail cuts. In general, an animal that weighs 1200 pounds will produce a carcass of 700 pounds, which results in 400 pounds of retail meat. There is the possibility, during this process, of mixing meat from different animals (Shackell 2008). Traceability requires that an identifier be tracked from the original animal through the production chain to the cut of retail meat. Approximately 10% of liver samples mismatch with the originating animal, as demonstrated by Heaton et al. (2005). The mismatch of sample and source creates many inaccuracies for retail cuts (Crandall et al. 2013).

A great challenge for traceability in food processing stems from resource transformations (Schwägele 2005). Transformation can be joining, transfer, addition, or splitting (Donnelly, Karlsen, and Olsen 2009). Using wheat flour processing as an example, it includes four transformation scenarios. Figure 1 summarizes all of the relationships about resource transformations and the case. Resource joining is the operation of combining different units, such as dispatches of different wheat to one wheat depot, i.e., many repetitions of one relationship (Dupuy, Botta, and Guinet 2005). Resource transfer is the operation of sending a resource from one point to another without splitting or mixing, such as transporting a truck with wheat to an independent wheat depot, i.e., a one to one relationship. Resource addition consists of mixing one main resource with another lesser quantity resource, such as adding reasonable food additives into wheat flour to meet quality improvement and stability requirement, i.e., a many to one relationship. Resource splitting is an operation of dividing resources into multiple groups, such as dividing a depot of wheat into many auto processing lines, i.e., a one to many relationships. Therefore, compared to primary agro-food traceability, the main problems for traceability in food processing are the variety of raw materials, batch mixing, and resource transformation.

4. Methods to implement traceability in food processing

According to the batch mixing features, the food processing stage can be divided into two types, as shown in Figure 2. One type is uniform mixing, such as dairy processing or wheat flour manufacturing. In this type, lot A and lot B flow into a mixer at the same time. The composition of lot A and lot B is controlled by a flowmeter. The other type is first in first out (FIFO), such as fruit grading. In this type, lot A and lot B enter the pipeline sequentially. The difference from uniform mixing is that the mixing phase only exists in a special time range and 100% lot A or lot B exists at other times. To achieve traceability in the food processing stage, related methods were performed from the view of physical separation in different lots, defining and associating batches, isotope analysis and DNA tracking, processing flow dynamic simulation, data statistical models, and internal traceability system development.

4.1. Physical separation in different lots

In the food processing industry, raw materials and other related elements are provided by different suppliers. To reduce the recall risk, separating batches in the plant is one possible approach. Using fluids as an example, the use of different vessels and thorough washing between batches can achieve safe and sound separation of lots. Cleaning-in-place is a good procedure to avoid contaminating batches with each other when water and detergent pass through production equipment. Total separation of different supply lots is required for some products, such as foods that are produced to meet religious requirements (e.g., Kosher or Halal certification) or products that need to meet specific military safety standards and constraints (Rahman et al. 2017). However, in a majority of cases, cleaning processes, which represent a high cost due to the consumption of abundant energy, manpower, and cleaning agents, become undesirable to maintain the flow of liquid/granular raw material for continuous production systems (such as milk production) (Comba et al. 2013).

4.2. Defining and associating batches

Currently, defining large batches, by referring to production time instead of their precise ingredients, is a popular approach for food processing traceability systems. However, in the case of large lots, inadequately detailed data about lot composition has resulted in numerous costly recalls that perpetuated bad perceptions (Comba, Belforte, and Gay 2011). In addition, labels, markers, and identifiers are difficult to directly connect to different lots. Markers based on RFID technology that facilitate on-line traceability for continuous granular flow production via the introduction of tracers into grains (e.g., chemical compounds or radioactive tracers) have great potential (Ketterhagen et al. 2007; Kvarnström, Bergquist, and Vännman 2011).

RFID systems have been developed for tracking, logistics, and anti-counterfeit intentions in the food industry. A comprehensive RFID traceability system for high value, pressed, long-ripened cheese production was utilized (Barge et al. 2014). In the cheese processing, various techniques for attaching labels to the cheese and systems to automatically identify materials at different stages of cheese production were developed (Figure 3.). The movement of items during each stage of cheese production, including handling in the maturing room and warehouse, delivery, packing, and selling, was automatically recorded.

The markers should not deteriorate food integrity and quality in any way and must be safe for the consumer. As a result, RFID-based traceability systems require devices for the safe removal of tracking devices from the end product (e.g., before grain grinding). Small food-grade tracers, which can be added directly into grain during harvest were developed (Lee et al. 2010; Liang et al. 2012) (Figure 3.). The tracers contain a small data-matrix code printed in food-grade ink with information linked to the product origin. The tracer contains edible materials like sugar or cellulose which are safe for consumers (Hirai et al. 2006). However, collecting and identifying these tracers requires the disruption of production. Thus, this approach is predominantly an off-line solution, which can be used for modeling and validation purposes. To overcome tracing deficiencies, an automatic separation and identification apparatus for grain tracing systems based on grain tracers was designed and developed (Liang et al. 2019).

4.3. Isotope analysis and DNA tracking

Raw material features are important for food safety and quality. To trace the geographical origin of raw material, stable isotope analysis is an effective approach. Stable isotope analysis has been used somewhat successfully in identifying and differentiating food products, like meat, milk, cereal crops, wine, and oil (Zhao et al. 2014; Zhao, Zhao, and Yang 2020). Identification of the origin of defatted dry beef samples from Korea, USA, Mexico, Australia, and New Zealand using carbon, nitrogen, and hydrogen isotope ratios was performed (Horacek and Min 2010). A trend in carbon isotope differences was associated with meat origin. Using multi-element stable isotopes, lambs originating from different areas of Italy were discerned with a 97.7% accuracy (Perini et al. 2009). Using isotope ratios of oxygen from water and carbon from ethanol, wines from various regions in southern Brazil were distinguished. Based on hydrogen, carbon, and oxygen stable isotope ratios and 14 other elements (Dutra et al. 2011), 8 European production areas for 95% of olive oil samples were distinguished (Camin et al. 2010).

DNA is inalterable during all animal life and it is present in every tissue (Dalvit et al. 2008). Therefore, it is possible to identify components in food and overcome the limits of conventional traceability systems using DNA (Sardina et al. 2015). Microsatellite genotyping is characterized by many alleles at each locus, codominant inheritance, high variability, and easy genotyping (Rodríguez-Ramírez et al. 2011; Yan et al. 2016). This technology was successfully used to differentiate meats combined in equal quantities from different sources, meats from different sources combined in different amounts, ground beef combinations sourced from different cities, and various lots of ground beef patties. However, when lots included more than 10 individuals, the accuracy of this technique was inadequate (Shackell et al. 2005). The IdentiGEN Company started collaborating with Canadian investigators to develop a traceable DNA-based batch identifier, which can distinguish between manufacturing batches of ground beef packages to optimize traceability (Meat Trade News Daily 2012).

4.4. Processing flow dynamic simulation

The problem of fluid product traceability was first addressed in the case of continuous processing (Skoglund and Dejmek 2007). In this case, a dynamic simulation was used to model the changeover of lots of a liquid product in a pipe. The fuzzy traceability concept was introduced due to the appearance of fractions of products generated from the limited combination of two successive batches. Furthermore, a new virtual batch was presented and a formalized lot definition was specified in ISO Standard 22005/2007 (Dabbene, Gay, and Tortia 2014). A criterion, the composition-distance, was defined to determine the homogeneity of a lot based on its composition of raw materials that need to be tracked (Comba et al. 2013). The composition-distance is used to assess differences in the components of supply-lots (raw materials) between two products, leading to a formal definition of homogeneity: two portions of a product can be considered homogeneous (part of a single lot) when their composition-distance is lower than a given quantization level. This method complies with the most recent regulation for genetically modified (GM) product management and traceability, stating that products can be labeled GM-free if the GM content is below 0.9% (European Commission 2003a, 2003b). Homogeneous product lots (called cohorts) and their movement along a production line can be controlled using compartmental models. Compartmental models enable composition tracing of raw material and portions of products and have been successfully applied to establishing the precise thermal conditions of fluid products subjected to continuous and discontinuous mixed flow conditions (Comba, Belforte, and Gay 2011).

To optimize traceability in a continuous process, a flow-based simulation with process data was presented (Van Puyvelde 2006). One case of this simulation approach was used in iron ore processing. RFID methodology to trace pellets in the distribution chain can aid short-term traceability (Berquist 2012). The other case was to investigate the impact of process interruptions, recognize cause and effect relations, and support governing in case of process disturbances. Levels of the chemical content were determined by the simulation forecasts and the errors were within an acceptable range (Kvarnström and Bergquist 2012).

Bill of lots (BOL) with Petri net tracing modeling was used to optimize traceability in wheat flour production (Wang et al. 2018). The construction process and information tracing of BOL were detailed, allowing the accurate tracing of product information and key node activity information. Using a practical example, a wheat flour batch list was set up to prove Peri net's accuracy and the tracing method feasibility. The number of recalled batches and hazards was reduced compared with the conventional approach in the simulation combining BOL and Petri net.

4.5. Data statistical models

In most contexts of food processing, traceability is not a definitive judgment, but a variable and statistical management process with inherent uncertainty (Haleem, Khan, and Khan 2019). Statistical models play an important role in food processing, as shown in apple tracing in a packhouse. Apples arrive at packhouses in bulk bins and are transferred in bulk, via a water dump, to the grader handling single apples, where the apples are sorted into packaging lines and placed in homogeneous packs (color or size) Bollen, Riden, and Cox (2007). Different batches of apples may be mixed when they flow into the water dump and, subsequently, into the packaging lines. Although apples are discrete items, their fluidized flow is analogous to small particle flow. A set of statistical models to link the probability of originating in a certain bin to any individual fruit in a package was proposed by measuring the arrival sequence of 100 blue marker balls (Riden and Bollen 2007).

The batch dispersion model was presented by Dupuy, Botta, and Guinet (2005) to solve traceability in a French sausage manufacturing process. The model was built to reduce recalls to the lowest level when products were described as a 3-level "disassembling and assembling" material bill. Furthermore, a 4-level batch dispersion model, which included raw materials, components, semi-finished products, and finished products, was developed (Lobna and Mounir 2011). Graphical tools such as the Gozinto graph (Kemény et al., 2008) model easily enabled visualization of downward and upward dispersions.

With the increments of batch levels in the batch dispersion model, improved model calculation efficiency is necessary. Intelligent algorithms, such as a genetic algorithm (Tamayo, Monteiro, and Sauer 2009) or particle swarm optimization (Maiyar and Thakkar 2019), provide good support. A genetic algorithm was applied to the batch dispersion model to optimize the sequences of a fresh-cut vegetable manufacture order and select different batches of materials (Xing et al. 2015). The application of this model resulted in a decrease in the average recall rate and optimization of production efficiency.

4.6. Internal traceability system development

The internal traceability of raw materials going into the final product is in the interest of food manufacturers (Moe 1998). In most cases, food processing traceability is an internal system, combining operation procedures and quality control measures (Lupien 2005).

A database is an essential element for an internal traceability system (Göransson, Nilsson, and Jevinger 2018). In a grain elevator traceability system, the data management system saves any relevant information connected to grain lots, including produce and quality information (Thakur, Martens, and Hurburgh 2011). The system can find information on incoming, internal, and outgoing lots and relate information from single incoming grain lots to outgoing shipments. Information in a comprehensive dataset can be utilized for mass flow optimization, resource optimization, and operational efficiency improvement of the grain elevator.

Table 1. Summary of recent studies (2004–2015) that focus on evaluating TS.

Scale	Concept	Description	Reference
Recall effects	RC	Recall costs (RC) are directly linked to the material that has been recalled.	Dabbene, Gay, and Tortia 2014
	BDC	Worst-case recall cost (WCRC) is the greatest quantity of product to be recalled when a batch of raw material is of questionable quality.	Dabbene and Gay 2011
	ARC	Average recall cost (ARC) is calculated based on the average mass of product that will be potentially recalled when an unsafe incoming material has been identified.	Dabbene and Gay 2011
TRU	Precision, breadth, and depth	*Precision* reflects the degree of assurance with which the tracing system can pinpoint a particular food product's movement or characteristics. *Breadth* describes the amount of information the traceability system records. The *depth* of a traceability system is how far back or forward the system tracks.	Golan et al. 2004
	Granularity	*Granularity* defines the scale of traceable units; greater granularity correlates with finer scales.	Bertolini, Bevilacqua, and Massini 2006
	Precision	The *precision* of TS can be evaluated as the ratio between IUs at two points in the supply chain.	Bollen, Riden, and Cox 2007
	Granularity	The traceable size of the unit, so-called *granularity*, affects the precision of product traceability.	Riden and Bollen 2007
	Purity	*Purity* is defined as the percentage (in terms of composition) of an output lot sourced from a single raw material input lot.	Riden and Bollen 2007
	Access	*Access* describes the speed with which tracking and tracing information can be communicated to supply chain members and the speed with which the requested information can be disseminated to public health officials during food-related emergencies.	McEntire et al. 2010
	Granularity	In many supply chains *granularity* is the consequence of a combination of tradition, short-term convenience and use of available facilities. The simple implementation of a finer granularity by itself has no value unless it provides greater precision.	Dabbene and Gay 2011
	Granularity	*Granularity* describes different levels of traceable units, and is determined by the size of a traceable unit and the number of the smallest traceable units necessary to make up the traceable unit at a specific granularity level.	Karlsen, Donnelly, and Olsen 2011; Karlsen et al. 2012
	Capability, reliability, rapidity, and precision/accuracy	*Capability* is the ability of retrieving the information required without any error and may be determined by the *reliability* of the tools, procedures, and information sources used. *Rapidity* refers to speed of responding to information requests regarding the trade items. *Precision/accuracy* is the ability to pinpoint a particular food product's movement.	Mgonja, Luning, and Vorst 2013
Comprehensive granularity	Comprehensive granularity	*Comprehensive granularity* is a comprehensive and quantifiable granularity concept, combing precision, breadth, and depth.	Qian et al. 2017

Batch information recording in the internal traceability system is the bond linking data and product. A Wheat Flour Milling Traceability System (WFMTS) was created through transformations in raw material, processing, and final product batches (Qian et al. 2012). Encoding rules were designed for relationships amongst batches. QR code labels (2D barcodes) were applied to small wheat flour packages and RFID tags were applied to wheat flour bins to document logistic information automatically. Although system costs rose by 17.2%, sales income improved by 32.5%, supporting the implementation of WFMTS in middle to large wheat mill companies.

4.7. Blockchain-based approaches

According to an analysis by Feng et al. (2020) of relevant studies published between 2005 and 2019, research interest in blockchain technology dramatically increased between 2017 and 2019, especially for studies related to the keywords "blockchain-based traceability". It has been shown that blockchain-based traceability has a significant influence on food supply chains in terms of transparency and accountability (Tama et al. 2017; Kshetri 2018), traceability and fraud prevention (Hang, Ullah, and Kim 2020), security and authentication, cybersecurity and protection, etc. (Banerjee, Lee, and Choo 2018).

To demonstrate the advantages of blockchain-based food traceability systems in real food supply chains, some companies have developed trial application systems (Kamilaris, Fonts, and Prenafeta-Boldύ 2019). Walmart and Kroger were the first companies to apply blockchain in their supply chains, with the technology first being applied to Chinese pork and Mexican mangoes. The application results showed that when using blockchain technology, it took only a few seconds to determine the source and the transport path of mangoes from farm to supermarket, compared to 6.5 days without the use of blockchain.

5. Performance evaluations

Performance evaluations for traceability in food processing play an important role not only for system implementation plans before development, but also for analyzing system performance after using the system. Evaluation using recall effects focuses on the traceability result. More process factors were considered in TRU evaluation. Comprehensive granularity acted as a novel method to evaluate traceability performances. Table 1 summarized the performance evaluations.

5.1. Evaluation using recall effects

The ability to minimalize the amount and cost of product recalls is a direct illustration of a traceability system's performance. Recall costs (RC) are directly linked to the material that has been recalled. Recall costs are dependent on various factors, including the following items (Dabbene, Gay, and Tortia 2014):

- tracking of batch sizes using traceability system;
- methods in which batches of diverse materials are processed and combined to produce the final product;
- management and maintenance of batch separation.

Dupuy, Botta, and Guinet (2005) proposed a method of estimating RC, using downward and upward dispersion indices and the batch dispersion cost (BDC) of the traceability system. Total batch dispersion of a system equals the sum of the downward and upward dispersion indices. Thus, a traceability system linked to batch dispersion can be used to assess the active path (links) numbers between raw materials and final products.

Many companies are interested in the largest possible amount of a potentially recalled product. Thus, the worst-case recall cost (WCRC) index was introduced (Dabbene and Gay 2011). WCRC is the greatest quantity of product to be recalled when a batch of raw material is of questionable quality. Similarly, the average recall cost (ARC) index is calculated based on the average mass of product that will be potentially recalled when an unsafe incoming material is identified.

Because there are often large numbers of variables and constraints in the optimization model, the use of genetic algorithms (GA) was addressed (Tamayo, Monteiro, and Sauer 2009). Unfortunately, the use of GAs resulted in unfavorable solutions, even for medium-size problems, as demonstrated by the application of GA to the sausage case (Dabbene and Gay 2011).

5.2. Evaluation based on TRU

Moe (1998) recommended using TRUs for batch processes. A TRU is defined as a "unique unit with its own characteristics in terms of traceability." Width, depth, and precision were applied to characterize traceability objects (Zhang, Bai, and Wahl 2012; Banterle and Stranieri 2008). The concept of "access" was proposed through four criteria for judging traceability (McEntire et al. 2010). Access is the rate at which supply chain members can be tracked, the tracing information obtained, and the requested information distributed to public health officials during food-related emergencies.

The concept of a TRU was expanded by Bollen, Riden, and Cox (2007) with the introduction of the identifiable unit (IU). An IU is a unit of product that is uniquely identifiable. The magnitude of an IU coincides with the granularity of a traceability system. Batch size and number determine the granularity. Finer granularity indicates more detailed product information and a traceability system that functions at a more detailed and range-limited level when products are recalled (Karlsen et al. 2012). Granularity influences the precision of product traceability, if a product is tracked at a fine granularity level with small IUs. Under this situation, IUs can be combined to reach the necessary precision (Riden and Bollen 2007).

Figure 3. Two cases of food processing batches tracing with RFID. a. RFID tag in cheese wheel before (on the left) and after (on the right) the brushing phase (Barge et al. 2014). b. Example of data matrix code printed on tracer surface (Liang et al. 2012).

Other factors used to measure traceability include purity, capability, rapidity, and accuracy. Purity was applied to processing transformations in a horticultural packhouse (Riden and Bollen 2007) and capability, rapidity, and accuracy have been utilized in fish processing plants (Mgonja, Luning, and Vorst 2013).

5.3. Evaluation with comprehensive granularity

Most of the above-mentioned evaluation indicators describe traceability from one point of view, but they lack an integrated viewpoint. Qian et al. (2017) presented a comprehensive and quantifiable granularity model. This model describes differences in traceability unit size, information capacity, and trace depth. Granularity comprehensiveness was indicated in a 3 D framework that combined precision, breadth, and depth. Quantifiability was embodied in an indicator system that had two layers and seven indicators, and in an evaluation model of granularity. Layer one is focused on precision, width, and depth. The second layer is comprised of indicator sub-factors, including external trace units, internal flow units, IU conversion, collected information content, information update frequency, forward tracking distance, and backward tracing distance. Five scores rating the assignment method are used to calculate the indicator's overall score. The analytic hierarchy process (AHP) method confirmed the indicator weight. Weight values for the indicators were 0.1985, 0.1141, 0.0872, 0.1870, 0.1248, 0.1442, and 0.1442, respectively. A weighted sum model was used to determine the evaluation value. A higher evaluation indicates a larger granularity.

6. Comparison analysis of different methods

Different methods are suitable for different scenarios in food processing and the performance of different methods vary. A comparison of different methods is shown in Table 2. All six methods, including physical separation of different lots (*M1*), defining and associating batches (*M2*), isotope analysis and DNA tracking (*M3*), processing flow dynamic simulation (*M4*), data statistical models (*M5*), and internal traceability system development (*M6*), are suitable for the application scenario of FIFO. In the UM scenario, *M1* and *M2* are not suitable because of unclear and inseparable batch boundaries.

As a comprehensive evaluation index, traceability granularity, including precision, breadth, and depth, was adopted to compare the six methods. Because of the physical separation feature in different lots, *M1* had high precision, which allowed clear identification of every batch. The evaluation of *M1* indicated a high cost and difficult operation. Meanwhile, limited information content, low information update frequency, and short tracing distance led to low breadth and depth for *M1*. The capacity of batch tracking is weak using either barcodes or RFID, especially in the batch mixing stage. Therefore, *M2* had low precision and intermediate breadth. Because of the stability of isotopes and DNA in raw materials, semifinal products, and final products, *M3* had good application potential with high precision and depth. *M3* also brought a high cost to tracing food. *M4* and *M5* had similar performances in precision, breadth, and depth, based on the data analysis using dynamic simulation and statistical data modes. The two methods focused on the food processing stage and ignored the up-step and down-step information, which resulted in low depth. Through

Table 2. Comparison of different methods and its suitable application scenarios and performance evaluation.

	Suitable application scenarios in food processing		Performance evaluation with comprehensive granularity		
Methods	FIFO	UM	Precision	Breadth	Depth
Physical separation in different lots (*M1*)	Appropriate	Inappropriate	High	Low	Low
Defining and associating batches (*M2*)	Appropriate	Inappropriate	Low	Middle	Low
Isotope analysis and DNA tracking (*M3*)	Appropriate	Appropriate	High	Low	High
Processing flow dynamic simulation (*M4*)	Appropriate	Appropriate	Middle	Middle	Low
Data statistical models (*M5*)	Appropriate	Appropriate	Middle	Middle	Low
Internal traceability system development (*M6*)	Appropriate	Appropriate	Low	High	Middle

information systems, information content is wide and update frequency is high. Therefore, *M6* had a high breadth.

Different methods have different advantages and disadvantages. These methods are not isolated. The combined application of different methods should consider the specific application scenarios in food processing to improve granularity.

7. Trends driven by novel technologies

Recently, some novel technologies, such as AI, big data, and blockchain, have been developed (Creydt and Fischer 2019; Pearson et al. 2019; Pollard, Namazi, and Khaksar 2019). These technologies also provide effective improvements for traceability performance in food processing.

- Batch mixing optimization with AI: Through analyzing the characteristics of product batch mixing in the food processing stage, a flexible batch mixing model can be established. Using artificial neural networks, genetic algorithms, and so on, the multi-objective model can be optimized to decrease recall costs and improve traceability granularity.
- Quality forecasting with big data: Through integrating food processing data on quality, safety, and nutrition features, a big data platform was established. In addition, quality forecasting will be developed based on evaluating hazard grade and finding quality transfer characters.
- Credible traceability with blockchain: The relationship among raw material suppliers, food producers, and food distributors will be described. Through a cooperative mechanism, a traceability platform will be established with the structure of digital fingers, distributed ledger structures, and security measurements.

8. Conclusions

Processed food faces a unique set of challenges in establishing traceability systems because of the variety of raw materials, batch mixing, and crossing of safety information, compared to primary agro-foods. Related methods from the perspective of physical separation in different lots, defining and associating batches, isotope analysis and DNA tracking, statistical data models, and blockchain-based approaches have been conducted and proven useful. Traceability is evaluated based on recall effects, TRUs (traceable resource units), and comprehensive granularity. Different methods have different advantages and disadvantages. The combined application of different methods should consider the specific application scenarios in food processing to improve granularity. On the other hand, novel technologies, including batch mixing optimization with AI, quality forecasting with big data, and credible traceability with blockchain, are presented in the context of improving traceability performance in food processing.

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