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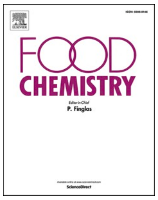

Implementation of relevant fourth industrial revolution innovations across the supply chain of fruits and vegetables: A short update on Traceability 4.0

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ABSTRACT

Food Traceability 4.0 refers to the application of fourth industrial revolution (or Industry 4.0) technologies to ensure food authenticity, safety, and high food quality. Growing interest in food traceability has led to the development of a wide range of chemical, biomolecular, isotopic, chromatographic, and spectroscopic methods with varied performance and success rates. This review will give an update on the application of Traceability 4.0 in the fruits and vegetables sector, focusing on relevant Industry 4.0 enablers, especially Artificial Intelligence, the Internet of Things, blockchain, and Big Data. The results show that the Traceability 4.0 has significant potential to improve quality and safety of many fruits and vegetables, enhance transparency, reduce the costs of food recalls, and decrease waste and loss. However, due to their high implementation costs and lack of adaptability to industrial environments, most of these advanced technologies have not yet gone beyond the laboratory scale. Therefore, further research is anticipated to overcome current limitations for large-scale applications.

1. Introduction

Tracing the journey of food from farm to fork has gained increased interest over the last decade due to the increased complexity of food supply chains as well as recent food fraud scandals and food safety incidents, such as increased mislabelling and fraud reports, the horsemeat-as-beef incident in the European Union in 2013, among others (Hassoun et al., 2020; Robson et al., 2020; Visciano & Schirone, 2021). Food traceability has become even more important over the last two years because of the outbreak of COVID-19 and its considerable impacts on food traceability systems and food supply chains. The concept of traceability can be understood, in a wider perspective, as being closely associated with other related terms, including authenticity, authentication, fraud, and adulteration (Brooks et al., 2021; Fanelli et al., 2021; Hassoun, Abdullah, et al., 2022). Developing an effective traceability system can improve food quality and safety, enhance transparency, and reduce the costs of food recalls, as well food waste and loss (Qian et al., 2020; Samarasinghe et al., 2021; Yu et al., 2022).

A wide range of techniques and measurement approaches have been applied to verify the authenticity of food products, ensure high quality and safety, and detect possible fraudulent practices (Grundy et al., 2023; Hassoun et al., 2020). Food traceability common measurement methods include isotope analysis, DNA tracking, and chromatographic methods. Recently, more advanced analytical approaches, such as profiling and fingerprinting techniques have been developed although some challenging issues related to specificity, accuracy, and precision remain

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(Ballin & Laursen, 2019; Grundy et al., 2023; Lu et al., 2020; Qian et al., 2022; You et al., 2022).

Over the last few years, a considerable progress has been made, which has been accompanied by recent innovations and technological advances spurred by the advent of the fourth industrial revolution (Industry 4.0). Industry 4.0 has emerged in recent years as an interdisciplinary field that combines physical, digital, and biological trends, such as Artificial Intelligence (AI), Big Data (BD), the Internet of Things (IoT), smart sensors, blockchain, and robotics, among others (Hassoun et al., 2023; Hassoun, Aït-kaddour, et al., 2022; Hassoun, Bekhit, et al., 2022). The concept of “Food Traceability 4.0” was recently proposed by Hassoun, Abdullah, et al. (2022) referring to the implementation of smart traceability systems from farm to fork using Industry 4.0 technologies, especially blockchain, IoT, AI, and BD.

The objective of this review is to give a quick update on recent advances in research and applications of Traceability 4.0 in the fruits and vegetables (F&Vs) sector. The paper will first give a general overview of the most commonly used traceability tools, followed by a brief introduction of Traceability 4.0 enablers. Application of relevant Industry 4.0 technologies, including AI, IoT, blockchain, and BD on F&Vs will be then reviewed. Finally, challenges and future research needs will be outlined.

2. Common traceability tools

The supply chain of F&Vs is quite long and complex, comprising primary production activities from on-farm (Fig. 1) to processing activities (such as sorting, trimming, grading, drying, freezing, and canning), transportation, and marketing. This complexity makes it challenging to track every step of a product’s journey from farm to fork. Several techniques and analytical approaches have been applied for many years in order to provide an assessment of a food’s traceability, safety, and quality.

Chemical/biochemical, biomolecular, and isotopic techniques are the three analytical methods that are commonly employed for determining the authentication of F&Vs Application of multivariate statistical analysis to the data obtained using these techniques is found to help obtain more accurate outcomes. Prior to the use of a classification method, many studies employ unsupervised exploratory principal components analysis (PCA) and cluster analysis methods. The main discrimination techniques include linear discriminant analysis (LDA), partial least squares-discriminant analysis (PLS-DA), and k-nearest neighbours (KNN). A number of factors, such as sample size, homogeneity, the description of class criteria, and the number of input variables could influence the selection of the most suitable classification method. Therefore, more than one classification method should be used while determining food authentication (Kamiloglu et al., 2022).

Chemical/biochemical methods used for the authenticity and traceability of F&Vs include chromatographic, spectrometric, and spectroscopic techniques (Table 1). Chromatography allows the identification and quantification of individual molecules that characterize the F&Vs.

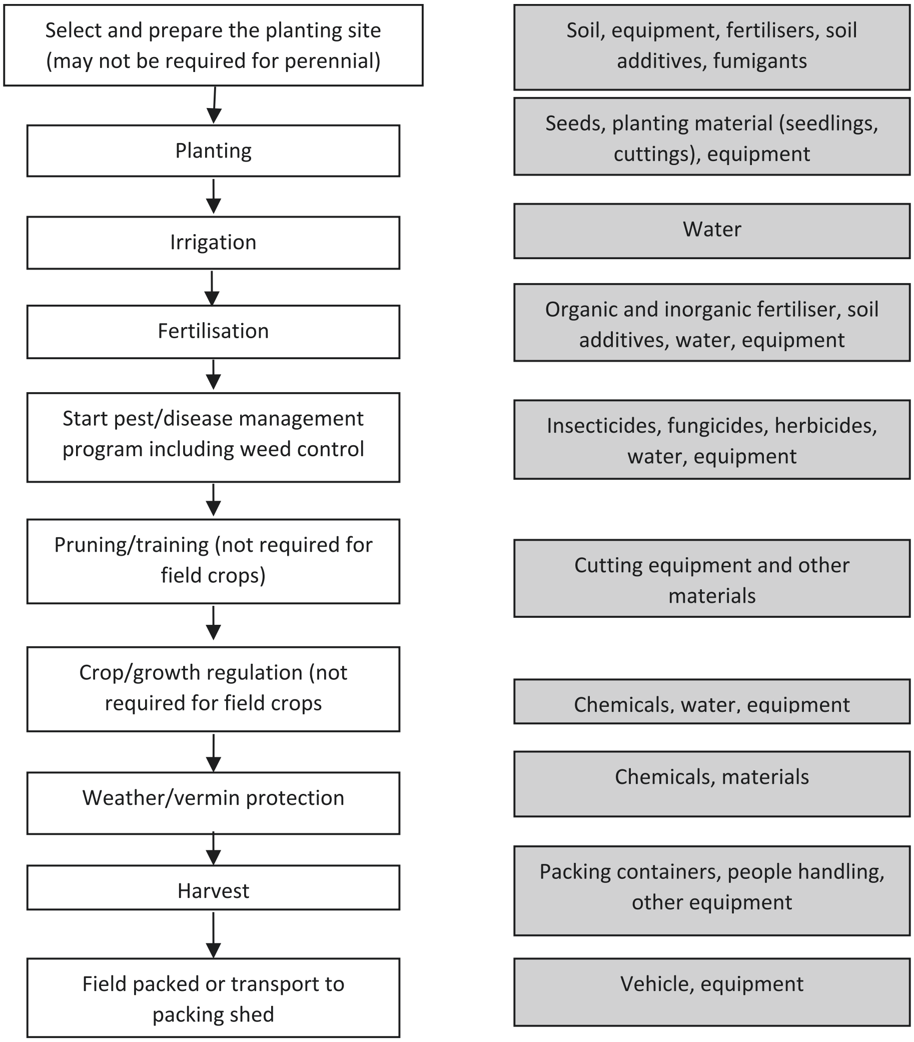

Fig. 1. A flowchart showing the main on-farm production activities in the fruits and vegetables (F&Vs) sector.

Table 1
Examples of common analytical tools used to access the traceability of fruits and vegetables (F&Vs).

Fruit/ Vegetable	Genotype/ Origin	Instrument/ Chemometrics	Discriminating marker(s)	Reference
Avocados	131 avocados from different producing regions: Spain, Brazil, Chile, Colombia, Kenya, Mexico, Peru, and South Africa	ICP-MS and IR-MS / PCA, PLS-DA	Elemental composition	(Muñoz-Redondo et al., 2022)
Chili pepper	Three different Capsicum species: *Chinense, Annuum*, and *Baccatum*	GC–MS / PCA, HCA	Volatile compounds	(Trovato et al., 2022)
Citrus fruits	22 Citrus cultivars including 8varieties of oranges (*Citrus sinensis* O.), 7 of lemons (*Citrus limon* B. and *Citrus latifolia*), 3 of tangerines (*Citrus reticulata*), 2 of pomelos (*Citrus maxima*), and 2 of hybrids (*Citrus reticulata* × *Citrus maxima*) from Sao Francisco Valley, Brazil	HPLC-DAD-RID / PCA	Polyphenols, simple sugars, organic acids	(Coelho et al., 2021)
Citrus fruits	4 varieties of Citrus fruits: lemon, dekopon, sweet orange and pomelo	NMR/PCA, PLS-DA	Main and minor components including carbohydrates, phenolic compounds, aromatic acids, amino acids, and organic acids	(Pei et al., 2022)
Jujube	114 jujube cultivars from China	Genome Analysis Toolkit	DNA fingerprinting	(Song et al., 2021)
Lemon and lime	Lemons (*Citrus limon* L. Burm.f. cv. 'Verna') and Tahitian limes (*Citrus* × *latifolia* [Yu.Tanaka] Tanaka)	HPLC-DAD and NMR / PCA	Coumarin and psoralen profiles, quantitative NMR spectroscopy	(Jungen et al., 2021)
Peaches	150 samples from six regions in China	IR-MS and ICP-MS / PCA, LDA, OPLS-DA	Stable isotopes (δ^{13}C, δ^{2}H, δ^{18}O) and multielement analysis	(Li et al., 2021)
Peaches and nectarines	4 varieties: *Venus, Nectaross, Rome Star*, and *Zee Lady* from 2 geographical areas of Southern Italy: Sibari Area (Calabria region) and Metaponto Area (Basilicata region)	HPLC-ESI-MS, UV–vis, ATR-FTIR, NMR, ToF-SIMS/ PCA, Cluster analysis	Polyphenolic compounds, antioxidant capacity, sugars, organic acids, peptides	(Tamasi et al., 2021)
Red grapes	4 varieties of red grapes: Merlot, Feteasca Neagra, Pinot Noir, and Muscat Hamburg	FTIR and Raman / PCA, HCA	Spectral data	(Radulescu et al., 2021)
Tomatoes	Pachino cherry tomatoes cv. Eletta belonging to the same lot of production	XRF/ PCA, Cluster analysis	Elemental composition	(Panebianco et al., 2022)

ICP-MS: Inductively Coupled Plasma Mass Spectrometry, IR-MS: Isotope Ratio Mass Spectrometer, PCA: principal component analysis, PLS-DA: Partial Least Squares Discriminant Analysis, GC–MS: Gas Chromatography–Mass Spectrometry, HCA: Hierarchical Cluster Analysis, HPLC-DAD-RID: High Performance Liquid Chromatography coupled with Diode Array Detection and Refractive Index Detection, NMR: Nuclear Magnetic Resonance, LDA: Linear Discriminant Analysis, OPLS-DA: Orthogonal Partial Least Square Discriminant Analysis, UV/Vis: Ultraviolet–Visible spectroscopy, ATR-FTIR: Attenuated Total Reflectance Fourier transform infrared spectroscopy, HPLC/ESI-MS: High-Performance Liquid Chromatography/Electrospray Ionization Tandem Mass Spectrometry, XRF; X-ray Fluorescence.

High-performance liquid chromatography (HPLC) and gas chromatography (GC) are the most common techniques that are used to determine the authenticity and traceability of F&Vs (Aguiar et al., 2020; Mostafidi et al., 2020). Coelho et al. (2021) identified the polyphenols, simple sugars, and organic acids in 22 *Citrus* cultivars, including orange (*Citrus sinensis* O.), lemon (*Citrus limon* B. and *Citrus latifolia*), tangerine (Citrus reticulata), pomelo (*Citrus maxima*), and hybrid (*Citrus reticulata* × *Citrus maxima*) varieties, using HPLC coupled to diode array (DAD) and refractive index (RID) detectors. PCA analysis revealed the grouping of Citrus according to the species or variety. Overall, the authors concluded that the associations found in the analysed samples could be used as a basis for authentication of Citrus fruits as assessed by the distinctions found between the phenolic profiles, sugars and organic acids (Coelho et al., 2021). HPLC-DAD was also successfully used to analyse six different sugars synthesized using 1-phenyl-3-methyl-5-pyrazolone with aid of response surface methodology, giving relatively high reproducibility and sensitivity (Wang et al., 2020). In another study, Trovato et al. (2022) determined the volatile compounds of three different species of chili peppers (*Chinense*, *Annuum*, and *Baccatum*) using solid-phase microextraction (SPME) combined with GC coupled to a mass spectrometer (MS). In *Capsicum annum* species, acids and ketones were present in high amounts, whereas *Capsicum chinense* and *Capsicum baccatum* mainly contained esters and aldehydes, respectively. Moreover, PCA and hierarchical cluster analysis (HCA) of the volatile profiles enabled a model to be built to differentiate between the different Capsicum species. In a similar study, 15 Chinese jujube (*Ziziphus jujuba* Mill.) cultivars were analysed by GC–MS and divided into 5 clusters through HCA and PCA according to their content of volatile compounds, including aldehydes, alcohols, acids, ketones, and esters (Wang et al., 2019). The same authors determined the compositions of the Chinese jujube cultivars of reducing sugars and organic acids using HPLC-UV and their composition of minerals using inductively coupled plasma-optical emission spectrometry (Wang et al., 2018).

Spectroscopic techniques have the advantages of being rapid and non-destructive as well as requiring simple sample preparation (Wang et al., 2021). Among them, nuclear magnetic resonance (NMR) spectroscopy, infrared spectroscopy and Raman spectroscopy are the most common instrumental methods that are applied for the determination of traceability in F&Vs (Meenu et al., 2019; Wadood et al., 2020). Pei et al. (2022) analysed the main and minor components in four varieties of citrus fruits, including lemon, dekopon, sweet orange, and pomelo using NMR spectroscopy combined with PCA and PLS-DA. The authors concluded that their results provided a feasible platform for the traceability analysis, adulteration identification and chemical composition analysis of Citrus fruits (Pei et al., 2022). Another study by Radulescu et al. (2021) investigated the applicability of Fourier transform infrared (FTIR) and Raman screening spectroscopic techniques to differentiate between grape berry parts according to their variety and vineyard type (conventional and organic). The multivariate statistical analysis allowed a distinction between samples obtained from conventional and organic vineyards for each grape variety for all grape berry parts (Radulescu et al., 2021).

The multivariate statistical analysis of fused data from chromatographic and spectroscopic techniques can be a powerful tool for obtaining more reliable results while determining the authenticity and traceability in food products (Kamiloglu, 2019). Jungen et al. (2021) used HPLC-DAD to analyse coumarin and psoralen profiles in different sections of lemons and limes as well as their juices. The discriminating markers for lime were found to be isopimpinellin, bergapten and 5-geranyloxy-8-methoxypsoralen. The differentiation between the samples was also possible with quantitative NMR spectroscopy, while the best results were achieved when combined NMR and HPLC data on coumarins and psoralens (Jungen et al., 2021). Similarly, Tamasi et al. (2021) also combined various analytical techniques including rheological, thermo gravimetric (TGA), chromatographic (HPLC-ESI-MS), spectroscopic (UV–vis, ATR-FTIR, NMR), and spectrometric (ToF-SIMS) analysis with chemometrics to characterize the varietal and geographical origin of yellow-fleshed peaches and nectarines. Another recent study used Near Infrared (NIR) spectroscopy in combination with chemometrics for authentication and traceability of intact lemon fruits; Limone di Sorrento Protected Geographical Indication (PGI) (cv Ovale di Sorrento) and Limone Costa D'Amalfi PGI (cv Sfusato Amalfitano) (Ruggiero et al., 2022). The results showed that the application of NIR spectroscopy on intact PGI lemons can discriminate cultivars and geographical origins, allowing the authors to conclude that this technique could be a useful tool to avoid fraud of high-quality products. The same technique was used in an earlier study to address the geographical origins and authentication of Chinese *Ganoderma lucidum*, giving accurate classification results (Fu et al., 2017).

Some studies investigated the elemental compositions of F&Vs in order to trace their geographical origin. Accordingly, Muñoz-Redondo et al. (2022) determined the composition profile of 46 macro, micro and trace elements in 131 avocados from different regions including Spain, Brazil, Chile, Colombia, Kenya, Mexico, Peru and South Africa using inductively coupled plasma mass spectrometry (ICP-MS) combined with PLS-DA. The statistical model was applied to combined data of elemental profile and stable isotopes achieving a high prediction accuracy (98 % correct classification) of Spanish and non-Spanish avocados. In another study, Panebianco et al. (2022) used X-ray fluorescence (XRF) to yield elemental pattern and statistical analysis to establish a rapid and reproducible method for the assessment of the origin of Sicilian tomatoes. PCA and cluster analyses revealed that the tomato samples clustered according to their production lot. Furthermore, the results obtained with XRF were also confirmed by comparing the elemental analysis results measured with ICP-MS.

Biomolecular techniques used for the traceability of F&Vs are based on their DNA or protein composition. Song et al. (2021) developed single nucleotide polymorphism (SNP) markers and validated them by genotyping 114 accessions of Chinese jujube germplasm. The authors proposed that the SNP markers that they developed could be used for the authentication of premium jujube products. A similar investigation was carried out on eight jujube cultivars from Ningxia, China, using SNP genotyping (Zhang et al., 2022a). High-quality SNP profiles were generated for all samples suggesting that this DNA fingerprinting technique could enable rapid cultivar authentication of jujube fruits. In a recent study, a molecular method based on real-time PCR approaches was developed to detect olive and soybean oils as potential adulterants of argan oil (Amaral et al., 2022). The results showed that the proposed technique can be used as reliable and high-throughput tools to authenticate argan oil and prevent fraud.

Regarding the isotopic techniques, stable isotopes based on isotope ratio mass spectrometry (IRMS) have been used to trace the geographical origin of F&Vs. Li et al. (2021) conducted a study to discriminate 150 peach samples from six regions in China using stable isotope data coupled with multielement analysis. In order to develop classification models that could trace the geographical origin of peach samples, the ratios of 3 types of stable isotopes (δ^{13}C, δ^{2}H and δ^{18}O) and the contents of 18 elements were determined. PCA results were able to distinguish the peaches from coastal and inland regions, mainly attributed to isotope ratios of H and O. Moreover, LDA and orthogonal partial least squares-discriminant analysis (OPLS-DA) also provided differentiation of the peaches from different regions. In another study, stable isotopes (including δ^{2}H, δ^{18}O, and δ^{13}C) were used in combination with soluble sugars and to organic acids to explore the regional characteristics and trace the geographical origin of Fuji apple obtained from 3 different regions in China (Zhang et al., 2022b). The results showed that the soluble sugars including sorbitol, glucose, fructose, and sucrose, as well as the stable isotopes δ^{2}H and δ^{13}C are closely related to regional conditions and can, therefore, be used to discriminate between the samples from the three regions.

3. Traceability 4.0 technologies

Most of the commonly used traceability tools have challenging issues that limit their applications in routine analysis in real industrial environments. A recent review paper gave a general overview of traditional and emerging techniques (e.g., genomic methodologies, spectroscopy, mass spectrometry, liquid chromatography mass spectrometry, and elemental analysis) used to determine adulteration, and confirmed that there is no single method developed and approved to support legislative requirements in the food supply chain (Grundy et al., 2023). Another recent publication summarized recent advances in metabolomics coupled with multivariate analysis allow promising results in the context of food fraud, and highlighted the importance of developing data fusion to enhance food authenticity (Mialon et al., 2023). The same conclusion was reached by Xu et al. (2023) who underlined the superiority of non-destructive analysis based on multi-source information.

More interestingly, Traceability 4.0 enablers, especially AI, IoT, blockchain, and BD are being increasingly applied to tackle complex real-world challenges associated with food traceability (Fig. 2).

AI is one of the core technologies of Industry 4.0 and has enabled tremendous transformations in the way data are measured, stored, manipulated, and analysed. This branch of computer science simulates human thinking and intelligence, learning ability, and storage of knowledge (Mavani et al., 2022; Misra et al., 2022; Zhou et al., 2022). Currently, there is an AI revolution sweeping across the world, offering huge opportunities in all sectors, including agriculture and food. For example, growing research shows that AI and its branches, including machine learning and deep learning play significant roles in food

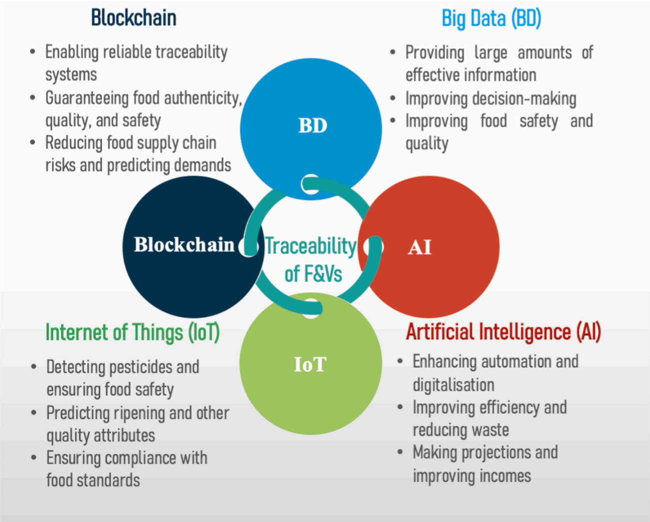

Fig. 2. The main enablers of Traceability 4.0 in the fruits and vegetables (F&Vs) sector.

adulteration detection (Goyal et al., 2022; Kumar et al., 2021).

IoT encompasses different technologies that allow connecting physical objects so that they can exchange data within a network. Sensors are core components of IoT systems that collect information, which is then processed via software to show relevant results to stakeholders. The data that these sensors collect is then used to make more informed decisions. IoT architecture is made of several interconnected layers. Jagtap, Garcia-Garcia, et al. (2021) presented an IoT architecture based on four layers: sensing, network, service, and application layers. This IoT architecture was integrated into a framework to reduce food waste generation and energy and water consumption in the food manufacturing sector. IoT has a number of further applications in the food sector, such as in food production, logistics, resource and waste management, safety, quality, and traceability (Jagtap, Duong, et al., 2021).

The term "blockchain" refers to a distributed database of all digital transactions or events that can be verified at any time in the future (Antonucci et al., 2019). A chain is created by encrypting transaction data in chronological sequence so that it can maintain unalterable records. The blockchain architecture model is composed of six levels: data, network, consensus, incentive, contract and application (Zhang et al., 2022c). Current food supply chains, particularly those connected to large distribution platforms, have a significant number of participants dispersed along the chain, resulting in poor information exchange and potentially unreliable data among participants (Wang et al., 2021). In addition, customers today demand fair, sustainable and safe food production processes. There is widespread agreement that the blockchain can increase transparency in agri-food supply chains (Bhat et al., 2021). In this context, a good traceability system gives the ability to track the movement of a food or feed through one or more specific stages of production, processing, and distribution.

BD is a new and emerging domain referring to different types of structured and unstructured data coming from different sources and origins, e.g., multimedia, smartphones, IoT sensors, and satellite imagery (Jin et al., 2020; Marvin et al., 2017). BD has become so powerful and valuable to the extent that some references refer to it as the new oil of the 21st century (Özdemir & Hekim, 2018). BD can offer new opportunities in different areas of research and applications, such as providing predictive insights into various steps in the food supply chain, helping take real-time decisions, improving efficiencies, forecasting, food safety, and minimizing food waste (Jin et al., 2020; Rejeb et al., 2022).

4. Applications of Traceability 4.0 technologies in the sector of fruits and vegetables

4.1. Artificial Intelligence (AI)

The use of AI in traceability for supply chains of F&Vs is concentrated in two contextually related areas: computer vision and supply chain efficiency. Building a more reliable, cost-effective and high-speed logistics infrastructure reduces waste and improves efficiency (Lamberty & Kreyenschmidt, 2022). Poor storage techniques, losses in transportation and border crossings, and waste throughout the grocery supply chain are all challenges that farmers, industry and governments are continuously trying to solve (Tagarakis et al., 2021). AI supported traceability systems may be used to plan routes for delivery and help identify targets for improvement within the supply chain by employing technologies, such as IoT and blockchain (Xu et al., 2021). Moreover, developing intelligent traceability solutions may also enhance brand characteristic and improve the image of cooperative agriculture (Gao et al., 2019). A lack of information in the supply chain can lead to price manipulation by intermediaries, causing price fluctuations that may negatively affect farmers and consumers. AI can be used to analyse past data to make projections which can be shared with farmers and other supply chain actors. Removing the information asymmetry can lead to better incomes for producers and a fair price for consumers.

AI together with computer vision can provide quality assessment of fresh F&Vs. Such systems may be trained on characteristics, such as colour and size as well as other parameters specific to various F&Vs. Human bias is thus removed, providing faster and more objective results with greater consistency. Following sorting, automated packing systems can attach source and lot numbers for traceability to enable quick identification of safety hazards, such as contamination or disease (Zhou et al., 2022).

Numerous applications of AI in the supply chains of F&Vs already exist. The motivations for implementing traceability solutions vary and may include one or more of the following: waste reduction, legislation compliance, yield improvement, certifications, border crossings, cost reduction and risk mitigation (Hassoun, Abdullah, et al., 2022). For example, Dimitra Technology is seeking to increase the currently small number of fruit producers in Brazil that have implemented innovations related to Industry 4.0 by introducing AI solutions that are accessible to all farmers. Machine learning solutions help monitor fields, detecting disease, soil quality and water usage to provide farmers with actionable data to increase yields by up to 20 %. Dimuto, a company founded in Singapore but with a global clientele, digitizes agrifood supply chains using AI and blockchain technology with a current focus on fruit farming and distribution. Digital asset devices are used to stamp each piece of fruit with a QR tag and record an image as the fruit moves along the supply chain. Data analytics and significant cloud storage capacity are required to store the blockchain records of millions of pieces of fruit. TOMRA, a Norwegian multinational company specialising in the provision of sensor-based sorting systems, is the first provider of AI for blueberry grading. TOMRA has created a library with hundreds of thousands of reference berries which have been hand-labelled for training their algorithms. More variety-specific and seasonal-specific images are being added to the library.

Ag Next Technologies in association with NAFED and Arunachal Pradesh Agriculture Marketing Board (APAMB) is using AI-based rapid quality assessment of organic kiwi from the eastern Himalayan state and implementing comprehensive traceability. QR code mapping is employed so that end-consumers may trace the supply chain back to its origin. BIOMETIC has developed the Q Eye, a smart optical sorter with AI and 3D reconstruction for external quality analysis of F&Vs. Even the smallest surface defects can be detected such as calyx cuts on apples. Q Eye XP is an X-ray inspection system with AI for internal quality control of boxed F&Vs detecting defects such as rot, corkiness or foreign bodies.

AI has many important applications in the food industry (Addanki et al., 2022). The combination of machine learning methods with vision technology is referred to as computer vision and AI driven food industry (Kakani et al., 2020). Now that AI is maturing, data-intensive methodologies in support of analytical processes, such as those linked to image recognition, vibrational spectroscopy and mass spectroscopy may be replaced or supplemented with predictive AI for the development of new analytical methodologies (Ayres et al., 2021).

A method has been developed to help identify varieties and turgor of potato tubers based on digital images, computer vision, and artificial neural network techniques (Przybyl et al., 2019). This study found that the neural network with the best quality of learning balanced against the lowest validation error was the Multilayer Perceptron (MLP). Fig. 3 shows the relation of the MLP to other neural network architectures.

Olive oil extracted from olive fruits is known for its high quality, but its relatively high cost compared to other oils makes it prone to adulteration. Therefore, advanced techniques, such as AI traceability solutions, are being applied to prevent the fraud (Przybył et al., 2020). Although adulteration may be detected through chemical analyses, the process is costly and takes time. Consequently, machine-learning and AI-based methods combined with fluorescence sensor, ultrasound, dielectric/laser spectroscopy or electronic nose have been developed for quality control and authentication of olive oil (Ayed et al., 2022). In another recent study, AI model based on neural networks was applied to analyse spectral data obtained from visible and near infrared spectroscopy used to assess the geographical origin of extra virgin olive oil (Violino et al., 2020). Important wavelength ranges related to the absorption of phenolic components, carotenoids, chlorophylls, and anthocyanins were identified and used in the development of a portable device that can be used as a reliable tool to fight fraud in this oil.

Dried F&Vs have also garnered considerable interest within the academic community. A computer vision system has been developed based on four separate machine learning techniques to obtain uniform dry bean classification (Koklu & Ozkan, 2020). Acoustic waves travelling across the surface of strawberry fruit supported by neural networks have demonstrated effectiveness in recognizing dried strawberry fruits (Przybył et al., 2020), thus providing a fast and effective tool for analysing the degree of ripeness and crispness in the industrial processing of drying fruit. Similarly, image analysis and artificial neural networks have been used to classify the quality of convectively dried carrot (Koszela et al., 2021). Industrial spray-drying using dried strawberry juice has been analysed for textural properties using artificial neural networks, scanning electron microscopy and a digital camera (Przybył et al., 2018). Results confirm that this technique can be used for the rapid evaluation of the quality of fruit powders in industrial spray drying. Two different neural network models have been developed to predict mass-dependent parameters and drying time of pomelo peel that underwent freeze-drying, forced-convection drying, and microwave drying (Kırbaş et al., 2019).

AI has also been studied in the context of supply chains for F&Vs. Poor supply chain management and lack of quality monitoring can increase postharvest losses and reduce competitiveness (Samarasinghe et al., 2021). AI may be used to model storage processes; improve the climate control for stored products; model respiration rate; predict moisture content; and control drying processes. The traceability of a supply chain can be significantly increased through integration of machine learning and IoT architecture into the quality monitoring system (Shanmugasundaram et al., 2020).

The carrot supply chain in North Sumatra, Indonesia has been investigated for quality parameters such as appearance and internal quality as related to environmental conditions during transport using machine learning (Adaptive Neuro-Fuzzy Inference System) (Kailaku & Djatna, 2022). Ningxia cabbage heart is another example in which a traceability system of cold chain agricultural products has been studied (Zhuangzhuang, 2020). An intelligent traceability management system for Golden Pear (Aodong Fruit and Vegetable Planting Cooperative, China) was established for the automatic monitoring and data collection of environmental parameters of agricultural land production, as well as the collection of customer data on the e-commerce platform, using a prediction model of agricultural production capacity and potential customer groups based on the combination of a neural network algorithm with relevant Big Data analysis (Gao et al., 2019).

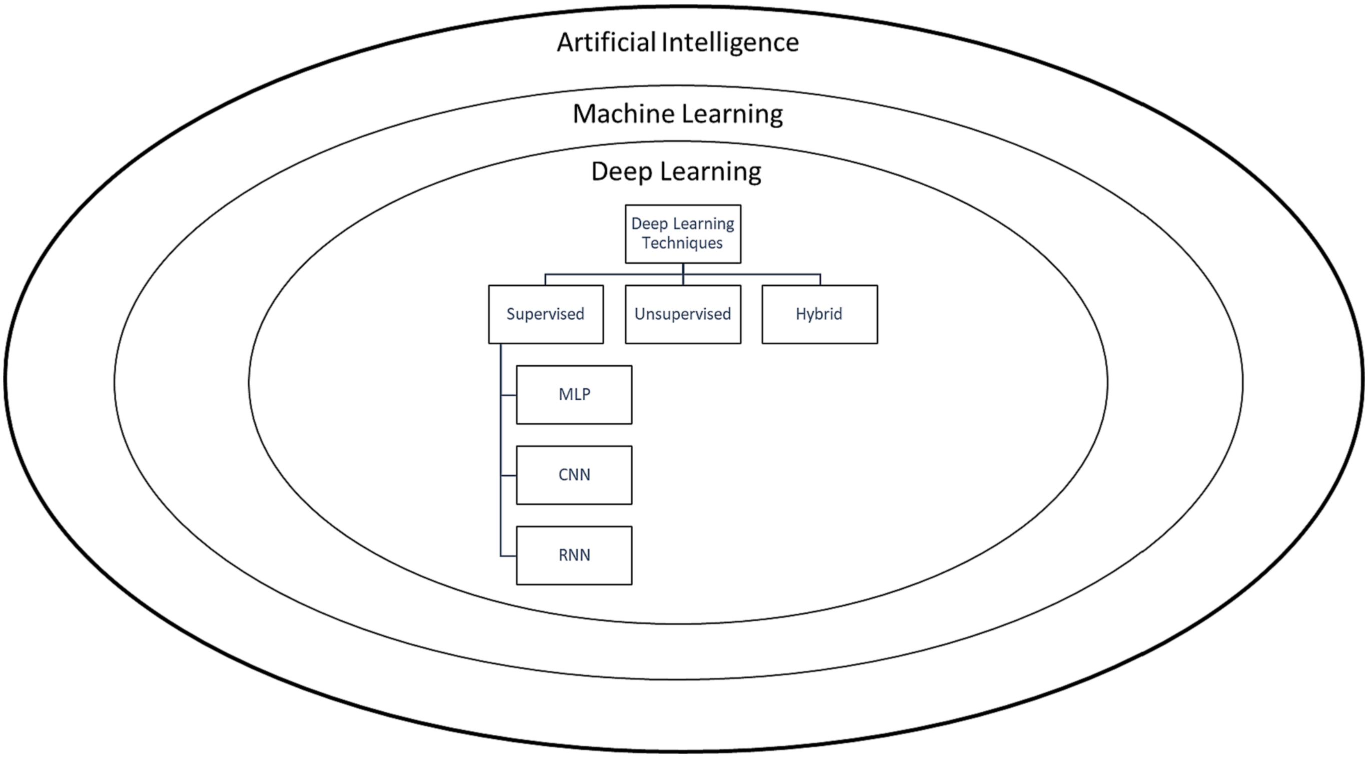

Fig. 3. A taxonomy of neural network architecture (based on (Sarker, 2021)).

4.2. Internet of Things (IoT)

The applications of IoT in the F&V sector are broad, as shown in Fig. 4, including the detection of pesticides to enhance F&V safety (Kanmani et al., 2020), the prediction of F&Vs ripening in quality assessment (Mishra et al., 2019), sharing live data to support logistics operations (Jagtap, Bader, et al., 2021), irrigation and plant protection (Moysiadis et al., 2021), on-tree fruit monitoring (Behera et al., 2021), and detection of infections (Jiang et al., 2021). All these applications help to optimise F&V operations for planting, growing, harvesting and distribution, as well as to ensure compliance with food standards.

Particularly, traceability is being increasingly valued by food supply chain actors and consumers. IoT can support food traceability by recording live data and sharing it seamlessly with the interested customer or supplier. Such data include information to identify the different businesses involved from farm to fork and date when the food product is at every stage. For consumers, the most interesting information about the businesses involved is mainly about location, particularly for planting and harvesting, and the agricultural practices involved, such as the use of chemicals or organic practices. Some examples of the use of IoT to support food traceability include work by Li et al. (2017), who developed an IoT-based tracking and tracing platform that uses QR code and radio frequency identification (RFID) technologies to share data of pre-packaged food in its supply chain, and by Alfian et al. (2020), who developed a traceability system that uses RFID and IoT sensors to track and trace perishable food and integrates them into machine-learning models to detect the direction of passive RFID tags.

Commercially-available traceability systems in the F&V supply chain often do not cover the entire length of the supply chain nor rely on open and transparent interoperability standards (Tagarakis et al., 2021). To address this, these authors developed a novel IoT-based system, namely AgroTRACE, to monitor the quality of F&V across the entire food supply chain and consequently improve traceability. Indeed, various IoT technologies were implemented at different stages, starting from the field level to the consumer and back to the field, bringing added value to fresh produce supply chains. Further examples include work by Li et al. (2021), who proposed a low-cost IoT quality traceability identification code for F&Vs using IPv6-based Linux server and HBuilder development platform. Zhao et al. (2015) combined IoT with database and RFID technology to collect information such as humidity, air temperature and humidity, illumination and CO_2 concentration, and store such data, to have more information about the production environment of vegetables and consequently improve their traceability. Zeng et al. (2021) combined IoT, QR code traceability technology and cloud Big Data to enhance traceability of Golden Pears.

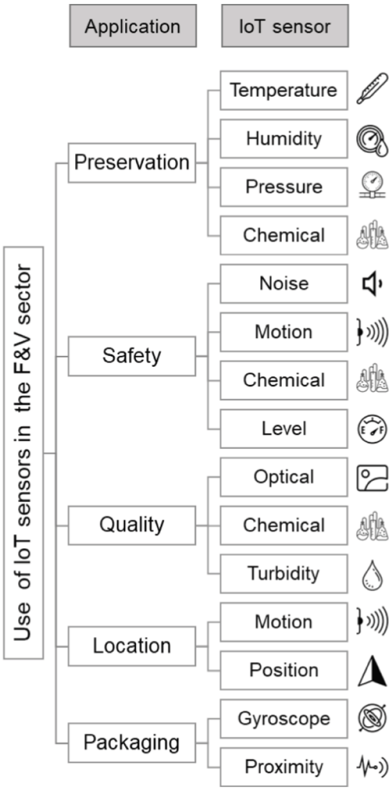

Fig. 4. Applications of the main IoT sensors in the fruits and vegetables (F&Vs) sector.

Several of such IoT devices and applications have already reached the market. For instance, Hugh Lowe Farms use IoT to monitor the growing conditions of their strawberries and track their delivery (Hortidaily, 2022). DiMuto uses video of agricultural products before packaging is sealed, digitise it using IoT with QR and bar codes, and consolidates documentation associated with transactions (PYMNTS, 2022). Siemens developed a cloud-based IoT system, namely MindSphere, for food traceability (Siemens). Big food companies, such as Cargill, Tradin Organic, International Flavors & Fragrances, Olam Food Ingredients, are using digital technologies like IoT to optimise their traceability and supply chain operations (Food Ingredients First, 2021).

IoT can also be used along with other Industry 4.0 technologies to further improve food traceability. For instance, IoT is able to provide data on materials, products and processes to the blockchain, which can ensure further transparency and security (Balamurugan et al., 2021; Deloitte, 2017; Feng et al., 2020; Lin et al., 2018).

In spite of its clear advantages, IoT still has some challenges to overcome before it is more widely implemented in the food sector, in particular in the F&V sector. The most relevant technological challenges are lack of interoperability, lack of connectivity in rural regions, data processing power, lack of clear data governance and data anonymity, security and privacy (Ayed et al., 2022). Other challenges include the large economic investment needed to set up the systems, the stakeholders' reluctance to install and use such systems, and the risk of counterfeiting. To address such counterfeiting risk, Zeng et al. (2021) designed a traceability code encryption algorithm for F&Vs.

In conclusion, IoT offers valuable opportunities to collect, store and share live data that can be used to improve decision making and therefore improve traceability of F&Vs.

4.3. Blockchain

An efficient traceability system must include quantitative and qualitative information about the final food product and its origin (Demestichas et al., 2020). The body of research material on the direct or indirect relationship between blockchain and traceability in the agri-food chain (either alone or in combination with other 4.0 technologies) has increased dramatically in recent years. A search of the Scopus database (performed on of 24 September 2022 including the terms blockchain and traceability and food or agriculture in the title, abstract or keywords) yields a total of 270 publications from 2018 (articles, reviews, and book chapters in English). However, there are not many specific studies on the use of blockchain for traceability in the fruit and vegetable supply chain, as only 15 papers have been found to date.

Zhang et al. (2022) illustrated how blockchain could guarantee the authenticity, integrity, and immutability of transaction information, which could ideally eliminate the need for third parties for traceability and control. It could also predict demand and transaction decisions, improving efficiency and satisfying the interests of all parties. Xie et al. (2022) proposed an integrated machine-to-machine traceability data generation system as a starting point for the implementation of blockchain for the automated acquisition of data related to apple products. The system consists of an integrated IoT-based hardware system, a smart farm cloud (SFC) platform and a mobile application. In a similar vein, Yang et al. (2021) designed and implemented a traceability system for fruit and vegetable agricultural products based on a trusted blockchain. The results showed that the system increases query efficiency, secures sensitive data and ensures data accuracy and reliability in supply chain management.

The relationships between blockchain and the perceptions of risks by different stakeholders have been analysed. According to Dua et al. (2022), blockchain features, such as traceability, certifiability, trackability, and verifiability can help reduce some supply chain risks, which can have a favourable impact on intermediaries' attitudes and customers' purchase intentions. In addition, Zhai et al. (2022) demonstrated that consumers' perception of health risks has a significant positive impact on their intention to buy blockchain-traceable fresh fruit in China. In another study, Xu et al. (2021) proposed an urban fruit traceability model based on blockchain for IoT to reduce the risk of urban fruit fraud and poor quality. The traceability model enables the design of a consensus mechanism and a blockchain smart contract model.

Recently, Ayed et al. (2022) discussed how different DNA traceability techniques in combination with other 4.0 technologies, such as blockchain, IoT and AI can offer a reliable method to certify and authenticate healthy food products, in particular for olive oil. For the case of extra virgin olive oil, Conti, (2022) proposed a traceability system that uses currently available and low-cost digital technologies, with the possibility to be integrated into a database for public authority controls and that allows the consumer to easily carry product information using their NFC-enabled smartphone. The low cost and ease of use of the proposed system allows it to be adopted for small and micro farms, products with regional characteristics and organic production. Furthermore, Shih et al. (2019) developed a simulation system for controlling the production and sale of organic vegetables based on blockchain technology, and in particular on the Ethereum cryptocurrency. This system can improve sales of organic vegetables and ensure the veracity of production and sales records. In addition, Sumathi et al. (2022) proposed a blockchain technique to ensure communication between farmers, investors and traders of bananas and other foodstuffs. The proposed method is more accurate and profitable compared to the conventional approach. Fig. 5 summarises some of the most important benefits of blockchain for traceability in the contemporary fruit and vegetable supply chain found in the literature.

Despite the potential benefits of blockchain, its adoption in the fresh fruit supply chain remains limited by a number of issues, such as the ambiguous attitude of some stakeholders towards blockchain, the dependence of blockchain on IoT architecture, which is currently at the stage of conceptual or small-scale commercial experimentation (Zhang et al., 2022c). Saurabh & Dey, (2021) analysed the case of the grape wine supply chain, and found that disintermediation, traceability, price, trust, compliance, and coordination and control are factors that can influence actors' adoption intention. In a similar vein, based on the attitudes and opinions of companies and customers, Osei et al. (2021) identified the main factors influencing blockchain adoption in the fresh produce supply chain, including fruit and vegetables: novelty of the technology, supply chain characteristics, open data issues, cost-benefit analysis and the role of public stakeholders. It can be said that academia has so far focused on unstructured experimentation of traceability solutions associated with blockchain, and it is clear that there is a need to develop and test traceability solutions in the real world, especially when considering the feasibility and cost-related features (Rosen et al., 2022). The future also seems to be marked by the need to mature the combination of blockchain technology with other Industry 4.0 technologies, such as Big Data, IoT, AI, RFID, near field communication (NFC), and biotechnology (Bhat et al., 2021).

4.4. Big data (BD)

Technological advancements within the food supply chain have led

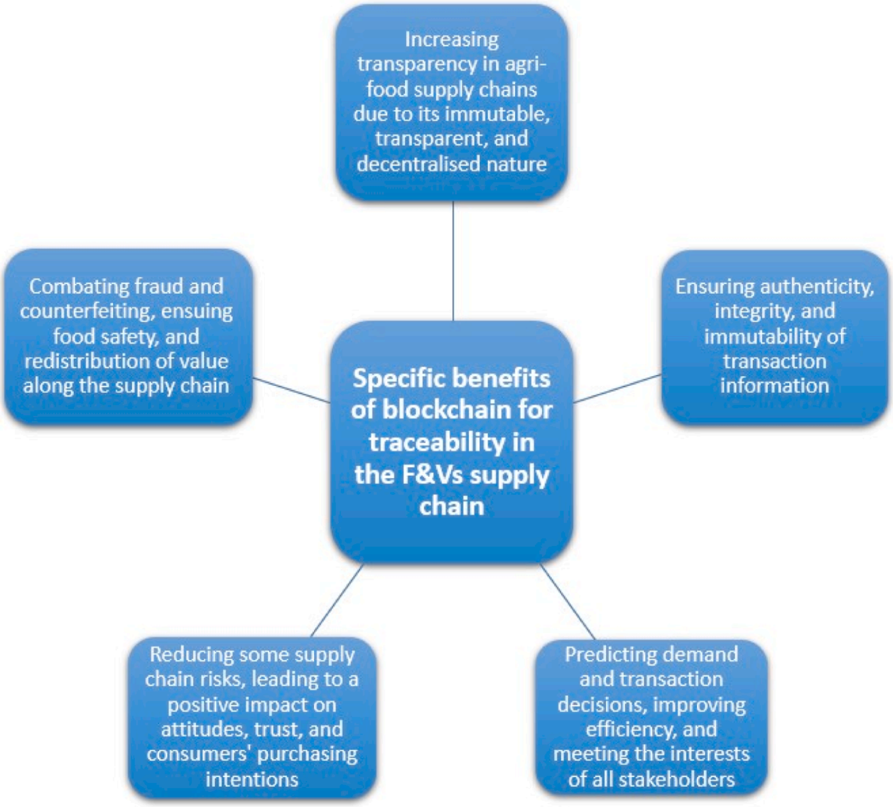

Fig. 5. Benefits of blockchain for traceability in the fruits and vegetables (F&Vs) supply chain.

to the data growing exponentially. These data, termed as Big Data (BD), is generated in supply chain from various points and sources, different forms, and variety, and produced at variable rate with inconsistencies. But it is the Big Data Analytics (BDA) which has made the food sector smarter and efficient, optimised operations, ease in monitoring and analysing of customer behaviour, and reduction in overall time, cost, and waste. BDA helps in analysing huge and varied data to reveal unknown patterns, correlations, and other meaningful insights.

Many publications highlighted the potential of BD to enhance food safety (Jin et al., 2020; Marvin et al., 2017; Talari et al., 2021). BD can be used in combination with other advanced technologies (such as blockchain, IoT, next-generation sequencing) to alert food safety risks in the food supply chain. For example, Donaghy et al. (2021) reported that BG can be applied with blockchain and IoT in the context of a dynamic risk management system for food safety microbiology to enhance traceability for retrospective and real-time management of foodborne cases. BD combined with AI and IoT could be developed for many applications in smart farming and precision agriculture (Misra et al., 2022). More examples of BD applications in the in fresh produce supply chain, i.e., F&Vs are shown in Table 2.

5. Conclusions and future trends

This review has provided a short overview of the implementation of common traceability tools used for fruits and vegetables (F&Vs), as well as the latest developments and advances in digital innovations and other emerging technologies. F&Vs are an essential part of a healthy diet, but the quality of fresh produce deteriorates rapidly after the harvest. Moreover, the complex supply chain of these foodstuffs makes it difficult to trace them reliably from farm to fork. In the horticulture industry, fraud and adulteration practices could occur at any stage of food production, processing, or shipping, resulting in not only a lower quality, but more importantly a potential risk to food safety and authenticity, hence the importance of implementing an effective traceability system.

Traceability relies on transparency and can guarantee high food quality and safety and provide detailed information about the origin of food products, species, and production methods. Application of some common traceability approaches, including chromatographic analysis (e.g., HPLC-MS and GC–MS), spectroscopic methods (e.g., NMR and FTIR), and isotopic techniques (such as IRMS) could successfully assess and authenticate F&Vs based on differences in their physiochemical profile. However, each of these traceability tools has its own advantages and limitations. For example, most of the physico-chemical methods, and biomolecular techniques are time-consuming and destructive, while spectroscopic techniques need more development effort to make them suitable for industrial real-time applications.

Recently, the concept of Food Traceability 4.0 has emerged alongside Industry 4.0, highlighting the use of fourth industrial revolution technologies to enable digital, intelligent, and real-time food traceability systems along food supply chains. This work has shown that AI, IoT, blockchain, and BD are among the main Traceability 4.0 enablers in F&Vs.

AI is one of the core elements of Industry 4.0 and can be seen as the driving force for other Industry 4.0 technologies, such as BD, blockchain, IoT, smart sensors, 3D printing, among others. AI can enhance digitalization and automation in agriculture and the food industry, improving the efficiency of F&Vs supply chain, and decreasing food waste and food loss. AI algorithms could be developed and embedded in a mobile application to help consumers detect adulteration issues (e.g., origin of food, proper labelling of organic products, additive-free food products) in food products using their smartphone.

IoT has the potential to deliver valuable solutions to different food and agricultural sectors, including the horticulture industry. IoT-based sensors, QR codes, and RFID technologies could help to implement smart food traceability systems by providing a wide range of information on the origin of F&Vs agricultural practices, and the application of

Table 2
Big Data applications in fresh produce supply chain.

Area of application	Use of Big Data	Reference
Soil	To enhance better cultivation practices for retaining soil fertility. To expedite the collection, analysis and sharing of data	(Hou et al., 2020)
	To uncover hidden patterns from soil datasets and obtain the necessary information for identifying soil conditions, such as nutrients, pH levels and soil moisture	(Finger et al., 2019; Kolipaka, 2020)
	Provide more detailed insights into the data characteristics of soil and support farmers in their crop yield predictions and decisions	(Rajeswari & Suthendran, 2019)
	To find out fertilizer recommendation classes on behalf of existing soil nutrition composition	(Garg et al., 2019)
Water	To increase water use efficiency	(Ciruela-Lorenzo et al., 2020)
	To assess annual agricultural conditions, set annual agricultural production plans, and ensure the efficient use of water and the prevention of land degradation	(Zhang & Huisingh, 2018)
	To assist in water audits and policy formulations. To create predictive algorithms that can cope with the stochasticity of the environment. To combat water shortages and maintain the sustainability of water systems in water stressed regions	(Weersink et al., 2018)
	To monitor water quality	(Kamilaris et al., 2018)
	To achieve accurate predictions of soil water patterns, properly manage agricultural water resources, and increase crop yield	(Cai et al., 2019)
	To optimize water consumption, minimize permanent loss of water and overcome issues of water accessibility	(Reynolds et al., 2018)
Crop/plant management	To effectively obtain critical information on crop cultivation and improve their productivity	(Carbonell, 2016)
	For effective crop management, higher operational efficiencies, cost reductions, and risk minimization	(Gašová et al., 2017)
	To ensure precise dosage of crop pesticide sprays, thereby increasing the marketability of the crop, farm returns, and environmental sustainability	(Saiz-Rubio & Rovira-Más, 2020)
	To create knowledge about plant performance (e.g., stress tolerance, nutritional quality, overall crop) in diverse climatic conditions, soils, and management regimes	(Halewood et al., 2018)
Waste management	To identify the sources of food waste in the supply chain. To produce a reliable analysis of the extensive misuse of supply chain resources	(Kamble et al., 2020)
	To reduce the potential economic waste associated with supply chain activities by making effective decisions	(Lioutas et al., 2022)
	To develop proactive practices to support resource recovery from waste	(Sgarbossa & Russo, 2017)
	To use image processing and IoT-based data analytics to reduce food waste	(Jagtap et al., 2019)
	To eliminate waste by utilizing consumer complaints made in retail stores or rely on social media data	(Mishra & Singh, 2018)
	To develop a Big Data cloud-computing framework to assist farmers in measuring their carbon footprint in a cost-effective manner	(Singh et al., 2018)
		(Jakku et al., 2022)

(continued on next page)

Table 2 (*continued*)

Area of application	Use of Big Data	Reference
Traceability management	To improve their process control, optimize material use, and manage production more efficiently. To improve supply chain traceability and create value for consumers, retailers, processors, and growers	
	To increase levels of visibility, traceability, transparency, authenticity, and quality of food products	(Kamble et al., 2020)
	To support food traceability and make supply chains more consumers driven	(Lioutas et al., 2022)
	To monitor supply chain and trace any contaminated food products to their source	(Khanna et al., 2018)
New product development	To reduce costs and time needed for new product development	(Jagtap & Duong, 2019)

pesticides, among others. Such data is crucial to ensure food safety and compliance with food standards. Additionally, IoT combined with databases could meet and satisfy consumers' needs for information about product storage and transportation conditions, such as relative humidity, lightness, and CO_2 concentrations.

In recent years, blockchain has been one of research hottest topics due to its promising potential to reduce supply chain risks, ensure safety, and prevent fraud. Blockchain could also predict demand and transaction decisions, improve efficiency, and satisfy the interests of different stakeholders. BD technology is about processing large amounts of data, leveraging this data, and optimizing practices toward achieving precision agriculture and farming, and smart factories. For example, BD can provide useful information about soil, water, crop/plant management, waste management, traceability management, and new product development.

It is well understood from this literature review that the application of AI, blockchain, IoT, and BD in the F&Vs supply chain sector is still in the developing stage. At the moment, limited concrete solutions have been built and executed whereas the current body of work consists mostly of suggestive and prescriptive research. The lack of technical skills required to handle and implement Traceability 4.0 enablers (i.e., AI, blockchain, IoT, and BD), high cost, lack of adaptability to the existing industrial environment, the need for standard protocols and guidelines, and issues related to data security and privacy are among the common obstacles that have been identified by many of the reviewed studies. Further research focusing on interdisciplinary work and cross-disciplinary collaboration is expected in the coming years to accelerate the move toward the implementation of Traceability 4.0 in the F&Vs sector.

CRediT authorship contribution statement

Abdo Hassoun: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Senem Kamiloglu:** Writing – original draft, Writing – review & editing, Supervision. **Guillermo Garcia-Garcia:** Writing – original draft. **Carlos Parra-López:** Writing – original draft. **Hana Trollman:** Writing – original draft. **Sandeep Jagtap:** Writing – original draft. **Rana Muhammad Aadil:** Writing – original draft. **Tuba Esatbeyoglu:** Writing – original draft.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Senem Kamiloglu is one of the guest editors of the special issue entitled "Postharvesting chemistry and biochemistry of fruits and vegetables".

Data availability

No data was used for the research described in the article.

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