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ePedigree Traceability System for the Agricultural Food Supply Chain to Ensure Consumer Health

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Abstract: Sustainability relies on the environmental, social and economical systems: the three pillars of sustainability. The social sustainability mostly advocates the people's welfare, health, safety, and quality of life. In the agricultural food industry, the aspects of social sustainability, such as consumer health and safety have gained substantial attention due to the frequent cases of food-borne diseases. The food-borne diseases due to the food degradation, chemical contamination and adulteration of food products pose a serious threat to the consumer's health, safety, and quality of life. To ensure the consumer's health and safety, it is essential to develop an efficient system which can address these critical social issues in the food distribution networks. This research proposes an ePedigree (electronic pedigree) traceability system based on the integration of RFID and sensor technology for real-time monitoring of the agricultural food to prevent the distribution of hazardous and adulterated food products. The different aspects regarding implementation of the proposed system in food chains are analyzed and a feasible integrated solution is proposed. The performance of the proposed system is evaluated and finally, a comprehensive analysis of the proposed ePedigree system's impact on the social sustainability in terms of consumer health and safety is presented.

Keywords: agricultural food chain; food quality; food safety; social sustainability; electronic pedigree; RFID; sensors; EPCglobal network; performance analysis

1. Introduction

In the past few decades, people have become more cognizant of sustainability issues and its importance for the human life on this planet. The Brundtland Commission of the United Nation defines the sustainability as; "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [1]. John Elkington [2], further elaborated the concept of sustainability and presents the Triple Bottom Line approach, based on three important dimensions: (i) Environmental dimension (planet); (ii) Economic dimension (profit) and (iii) Social dimension (people health and welfare). The social dimension of sustainability is associated with people's well-being and includes many aspects; such as social justice, equality, food security, health and quality of life. However, in the food distribution chains, the aspects of consumer health and safety have gained much more attention due to the frequent cases of foodborne diseases, both in developed and developing countries [3]. As the products involve in the agricultural food industry intend for the human consumption, therefore, it is important to realize that any compromise on the food quality and safety directly affects the consumer's health and well-being. According to the World

Health Organization (WHO), unsafe food containing harmful bacteria, viruses, parasites or chemical substances, causes more than 200 diseases—ranging from diarrhea to cancer [4], and kills an estimated 420,000 people annually, and 40% of them are children under years of 5 [5]. Therefore, ensuring the food quality and safety in the food supply chain, for the consumer's health and safety, is very important for the sustainable social development in the food industry.

The modern food supply chains have become much faster and more complex due to the globalization and outsourcing of food products. The food industries face many new challenges to ensure the consumer health and safety e.g., contamination due to food degradation, food adulteration, fake labeling or counterfeiting. The quality of perishable food products changes rapidly due to inadequate temperature and poor relative humidity conditions of the pre-harvest stages as well as at the post harvest processes of cold chain distribution, transportation, and storage. It contaminates the food due to the growth of toxic fungus such as mycotoxin. A cold chain is a temperature-controlled supply chain that involves the storage and transportation of temperature-sensitive perishable food products, which are maintained within a certain temperature range in order to uphold the integrity of these products [6]. Research conducted by Sensitech Inc., Beverly, Massachusetts, United States, a leader in cold chain visibility solutions, shows that during transportation, the temperature-controlled shipments rise above the specified temperature in 30% of trips from the supplier to the distribution center, and in 15% of trips from the Distribution center to the store. Lower-than-permissible temperatures also occur in 19% of supplier-to-distribution center trips and 36% of distribution center-to-store trips [7]. Another serious challenge for the food supply chains safety is the adulterated and counterfeit food products. Due to the global trading and lack of any efficient tracing systems for the detection of adulteration, food products containing untested substances or non-approved hazardous materials could be easily introduced into the food supply chains of any country. In March 2016, Interpol announced the largest seizure of hazardous counterfeit food and drinks ever—more than 10,000 tons of fake food and one million liters of fake drink. The operation included 57 countries around the world, a coordinated initiative to protect the consumer health and safety [8]. In Europe in early 2013, it was reported that products labeled as containing beef were found to actually contain 80%–100% horsemeat. This crisis severely damaged consumers' confidence and trust in the European food industry [9,10]. In South Korea, there have been a number of cases reported related to illegal agricultural food distribution channels that disguised cheap imported agricultural food products as the quality products into the local food chains [11]. In addition to the consumer's health and safety aspects, incidents of food contamination and adulteration lead to the other direct and indirect social and economic problems in terms of production losses, products recall costs, increased health care and medical expenses, damage to reputation and brand name. The indirect cost dominates the recall cost as the loss of market value and reputation could lead to the total bankruptcy of the established brands [12], and dislocates hundreds of thousands of legitimate jobs due to the closure of local businesses [13]. The economic cost of foodborne illness in the USA alone is 50 billion to 80 billion dollars annually; it includes health care costs, lost productivity, and diminished quality of life [14].

To address the issues of food quality and safety, it is important to establish strict control and monitoring system in the food supply chains. Due to the increased consumer's demandfor better quality control and risks involved in the food supply chains, the governments of many countries are enforcing regulations for the food industry to implement the traceability systems in order to ensure the sustainable social development. Traceability is the ability to identify and trace the history, distribution, location, and application of products, parts, and materials to ensure the reliability of sustainability claims [15]. The United Nation Global Compact published the first guide on traceability, which highlights the importance and emphasizes the need for traceability for sustainability purposes in the supply chains [16]. The above discussion demonstrates that the traceability system for the control of food quality and safety significantly important for the sustainable social development in the food industry.

This study introduces an ePedigree traceability system based on the integration of three technologies: RFID (to track food products), sensors (to monitoring food conditions), and ePedigree (to combat counterfeit products). Radio frequency identification (RFID) technology is used to track the product movement by using RFID tags embedded with the Electronic Product Code (EPC). The EPC is a unique number that identifies products in the supply chain for the purpose of traceability. The RFID utilizes the EPCglobal Network specifications which are the collection of inter-related standards for hardware, software, and data interfaces to store, communicate and exchange product traceability data between different supply chain partners [17]. The Electronic Pedigree concept (usually referred as ePedigree or e-pedigree) is an anti-counterfeit methodology that records the chain of custody and ownership of a product as it moves through the supply chain [18]. This research aims to develop an efficient system, which can address challenges of food quality and safety in an integrated way in a single platform. Many studies have been proposed in the literature to monitor the quality of food in cold chains, but there is very limited research available to address the emerging food safety problem of counterfeit food products in the food supply chains. To the extent of our knowledge, there is no research work available which integrates the ePedigree concept in the food chains as an anti-counterfeit tool for the food safety issues. The integration of RFID and sensor technology with the ePedigree concept would help food suppliers to efficiently control the food quality and safety problems and consequently assists to improve the social sustainability in the agricultural food supply chains.

The rest of the paper is structured into further four sections as follows. Section 2 describes the related studies and the background of RFID technology, EPCglobal standard, electronic pedigree and the sensor network. Section 3 presents different implementation aspects, such as the cost analysis, methodology, architecture design and the digital signatures for the security of the proposed ePedigree system, Section 4 describes the performance analysis and the comprehensive impact analysis of the proposed ePedigree system on the social sustainability dimension, Section 5 presents the concluding remarks.

2. Literature Review

Many researchers emphasize the interdependence of the food quality, safety, and sustainability in relation to the consumer's health. Akkerman et al. reviewed the quantitative operation management approaches of the food industry related to the food quality, safety and sustainability and, demonstrated that the food quality and safety are included in wider definitions of sustainability [19]. According to Gladwin et al. the sustainability must surround the concept of security, which demands safety from chronic threats and protection from harmful disruption [20]. According to the European Commission Report, the sustainability in the food industry should address issues such as security of the food chain, health, safety, quality, affordability, and climate change [21]. Fritz and Schiefer [22], suggests that expressing the food quality and safety control systems into transparent food chains that are able to provide affordable food with high quality, are some of the challenges related to the sustainability of the food industry. Wognum et al. explores that how current technologies to enhance the transparency of food chains such as traceability system for food safety can assist to improve the sustainability [23]. The adoption of the good traceability system ensures food safety through early detection of deficiencies, minimizes the distribution of poor quality products, thereby, reduces the potential for consumer illness, bad publicity and recalls [24–26]. Food quality degradation is related to environmental conditions (such as temperature and humidity) and, insufficient control of temperature and humidity can lead to the growth of harmful bacteria and chemical reactions [27]. Wang et al. proposed an online rule-based decision support system for the transportation of perishable food products [28]. Ting et al. proposed a supply chain quality sustainability decision support system (QSDSS), to select a good logistical plan in order to maintain quality and safety in the food chains [29]. However, most of these studies focused on the issue of food quality, and the food safety issue of counterfeit food products is rarely addressed in the literature. So far, very limited work has been published on the topic of counterfeit food products in the food chains for consumers' safety. The proposed ePedigree traceability system provides a platform to monitor the food quality as well as to prevent the infiltration of counterfeit food products into legitimate supply chains. Most perishable food products have a strict environmental requirement when they are transported, as shown in Table 1. Perishable food products are those that rapidly degrade due to the growth of the harmful bacteria, which cause food-borne illness unless they are maintained under ideal ambient conditions.

Table 1. Transportation requirements for the perishable food products.

Product	Temperature (°C)	Humidity	Other Requirements
Cooked food	>60–63 (hot holding temperature)		
Chilled food	0–4 (higher temperatures than 4 °C cause faster growth of bacteria)		
Frozen food	≤ -18 (Equals or less than -18)		
Fresh fruits and vegetables	0–8	90%–95%	Appropriate concentration of O_2, He, CO_2, C_2H_4

Note: The temperature requirements for the food transportation can be varied in different countries depending on their regulations. (Source: [30,31].)

2.1. EPCglobal Network

The EPCglobal network consists of ALE (Application Level Event), Capturing Application, EPCIS (Electronic Product Code Information System) Repository, Accessing Application, Object Naming Service (ONS) and Discovery Service (DS). The ALE filters the RFID tag data collected from the RFID readers. Then, the filtered data transfers to the Capturing Application, which converts this data into the EPC events by adding business logic information. Finally, the EPC event data is transferred and stored in the EPCIS repository and the EPC ID is registered to the Discovery Service for queries. This data can be accessed using the Accessing application [17]. The function of the Object Naming Service (ONS) and the Discovery Service (DS) is providing the exact location of a specific EPC ID in question to the query client through the query application [32]. The EPCglobal standard defines four types of EPCIS events. First, the object event represents the observation of EPCs. Second, the aggregation event represents aggregations of items. Third, the quantity event represents the quantity of the products. Fourth, the transaction event represents the business transactions [33]. All the EPCIS events, contains various useful information related to products such as ID's of products, type of action (business process) during which specific EPCIS event occurs, Specific location where the EPCIS event occurs and read-point (RFID reader ID) of specific RFID reader which captures the specific EPCIS event. The EPCglobal standard provides an option in every EPC event called an extension point. These extension points can be used to include other information in the standard EPC event. In this paper, these extension points of the EPC events are used to store the ePedigree information and, temperature and humidity information related to the food products ePedigree.

2.2. Electronic Pedigree

According to the EPCglobal Pedigree standard, the ePedigree is structured in different layers named *initialPedigree*, *shippedPedigree,* and *receivedPedigree* respectively, which are appended as the product moves along the supply chain [34]. At first, the initialPedigree is created with the basic product information (e.g., Producer's name, product name, and serial number), and the item information (e.g., Lot number, harvest date, quantity, temperature, and humidity). Next, when the product is shipped to the next supply chain partner, the shippedPedigree is added. It contains information such as the sender name, receiver name, transaction information (purchase order number, sender address, and recipient address) and the sender signature information. After this step, the shipper's signature cannot be changed. Once the receiving party confirms the receipt of the product, the receivedPedigree is generated and the receiver's transaction information with signature is included. After this stage, the shippedPedigree and the receiver's signature are secured, and cannot be altered.

2.3. Sensor Network

To integrate RFID and sensor networks, a variety of possible architectures have been proposed in the literature. Kim et al. proposed an RFID and USN (ubiquitous sensors) based e-pedigree system to improve customer protection and transparency of distribution channels [35]. Mitsugi et al. reviewed the research and applications that integrate the RFID technology with the sensor network and proposed four types of the logical integration scenarios of WSN (*wireless sensor network)* with the EPCglobal network. (i) Logical integration at the Application level of the EPCglobal Network; (ii) Logical integration at the ALE level of the EPCglobal Network; (iii) Logical integration at the EPCIS level; (iv) Hardware (Sensor tags) and logical integration in the EPCglobal Network system [36]. A WSN consists of sensor nodes, which have sensing, processing and communication capabilities. The sensor nodes collect environmental information (e.g., Temperature and humidity); translate it into digital form and transfers autonomously through the gateway to a base station, where it is stored [37]. In addition, the integration solution should consider the cost factor and other limitations of the particular business. Zhang and Wang [38], proposed three system architectures that combine the RFID and WSN technologies at the hardware level. However, three proposed integration architectures do not provide any detail about the RFID and sensor data integration with the EPCglobal network. According to their proposed integration scenarios, the RFID and sensor technologies can be integrated into three ways:

(1) One way of integration is to embed the sensing capabilities within the RFID tags. Many RFID tags have sensors incorporated in their design and, thus, they are able to take sensor readings and to transmit them to the main server.
(2) Another way is to integrate the RFID readers with sensor nodes. In this scenario, the integrated RFID reader-sensor node acts as a smart node. Smart nodes are able to communicate with each other by creating an ad-hoc communication network. The integrated RFID reader-sensor node is able to function as a router to pass captured RFID and sensor data to the right destination.
(3) The third solution is mixed architecture. In the mixed architecture, RFID tags and sensor nodes are physically distinct devices and work independently, but they coexist in an integrated network and integrated logically. The main advantage of such a mixed architecture is the fact that there is no need to design a special hardware and thus, this type of integration is cost effective for many business applications.

Problem definition and approach of study: The main problems faced by the food industry, the consumers and the Governments in order to efficiently address the issues of food quality and safety is the lack of an economical and efficient traceability solution which can provide the complete visibility of food products in the supply chain and detect the unhealthy food product before it reaches the consumers. In addition, the food product data is mostly scattered at different locations and in the case of any foodborne incident, it takes a long time for the government regularity agencies to collect all information in order to trace the original source of contamination.

Based on the problem definition, an ePedigree traceability system is proposed to address these problems in order to ensure the food quality and safety throughout the entire supply chain. The ePedigree traceability system provides a secure, authenticated and economical platform, to maintain and verify the food quality, safety issues in the complete food supply chain and to provide the complete visibility and efficiently track the food safety problems as all the food product history data stored in a single database.

3. Methodology

3.1. Cost Analysis to Select an Economical Integration Solution

As the profit margins in the agricultural food chains are relatively low, it is crucial to address the cost factor of traceability system implementation and adopt most cost effective approach. For the agricultural food supply chains, this study suggests a mixed architecture of passive RFID tags and sensor nodes for integration. To understand the reason behind, a brief implementation cost analysis of the three RFID and sensors integration scenarios, explained in the first part of Section 2.3, is presented below.

The main components of these integration scenarios, mentioned in Section 2.3, are RFID readers, System software and services, RFID tags and sensor nodes.

- RFID Readers: Prices for fixed readers range between $10,000 and $20,000. The estimated cost of handheld readers is $3000 per reader [39].
- RFID System Software: There are various RFID middleware products on the market. The cost of the RFID middleware varies from as little as $25,000 for small organizations to several hundred thousand dollars for very large enterprises. Basically, the cost depends on the number of locations where it will be installed and the features of the software. The other major RFID system cost is the EPCglobal Network subscription cost for lookup services for products as they move through the global supply chain. The subscription cost starts at $300 annually for organizations with revenues of $100,000 or less to $75,000 annually for organizations with annual sales of $1 billion to $10 billion [40,41].
- Sensor nodes: The cost of the wireless sensor nodes for monitoring the environmental conditions range from $10 to several hundred USD [42,43]. The price varies from vendor to vendor and depends on the different functionalities of sensor nodes.
- RFID tags: The cost of passive RFID tags ranges from 10 cents USD for the basic passive RFID tag to $1 for the metal passive RFID tag. The simple active RFID tags cost range from $15 to $20 [39]. The active RFID sensor tags with sensor capabilities range from $10 to $100 [44].

The cost of the RFID tags is the main component in the RFID system implementation. Because the RFID tags cost is the variable cost and constitute the major portion of the whole system implementation cost. The other costs, including RFID reader, RFID software and sensor nodes are nearly fixed costs of an RFID-based traceability system.

- In the case of the first integration architecture of the RFID and sensor networks, defined in the previous Section 2.3, by using RFID sensor tags is one of the simplest ways of integration. However, tagging every food box with the active RFID sensor tag is highly costly and infeasible in the case of the low-cost agricultural food products. Although the prices of active RFID sensor tags are declining with time, but still they are far more expensive than passive RFID tags and economically not a feasible solution for the supply chain of cheap products where the retail price of such products is less than the RFID sensor tag's price.
- The second architecture for integration suggests the integrated RFID-sensor node, which acts as a smart node. As in the agricultural food cold chain, sensor nodes deploy in large numbers to control and monitor the environmental conditions of production, processing, storage and transportation facilities. The RFID reader-sensor smart nodes must be deployed in greater numbers to cover all the facilities. The cost of such RFID readers is very high, which is not a feasible solution for the agricultural food product. In addition, these smart nodes consume a lot of energy to collect, compress and transmit the RFID tag data and sensor data. That reduces the battery lifetime of smart nodes significantly and needs to be replaced many times in a year.
- The third integration approach of mixed architecture uses the passive RFID tags with the sensor nodes is the best suitable solution for the supply chain of cheap products such as the agricultural food products. The cost of passive RFID tags is very low as compared to active RFID tags and they can be integrated logically to the sensor nodes of the food cold chain network.

In the mixed architecture of integration, the RFID reader scans the food traceability data and transmits to the capturing application through the middleware and, the temperature and humidity data is gathered by sensor nodes. The RFID data and sensor data are two separate sets of information and need to be integrated into a single format. According to the AUTO-ID research lab, the integration of the RFID tag data and the sensor data can be performed at the ALE (Application Level Event) level interface of the EPCglobal network. The integrated RFID tag data and sensor data transmits from the ALE to the EPCIS capturing application [34]. The EPCIS capturing application combines the RFID tag data and the sensor data and then transfers it to the EPCIS repository for storage in the form of the EPCIS events. The sensor data added at the extension points of the EPC events with ePedigree data.

3.2. ePedigree System Scenario in the Agricultural Food Distribution

According to a study by the International Fund for Agricultural Development (IFAD) of the United Nations, smallholders manage over 80 percent of the world's estimated 500 million small farms and provide over 80 percent of the food consumed, in a large part of the developing world [45]. As most of the small farmers have very limited financial resources and every farmer cannot afford to purchase the RFID tags in large numbers to attach all food boxes. Therefore, this research considers a practical approach to facilitate the small farmers and places the minimum financial burden on them. We propose that the transaction between farmers and distribution center takes place in the simple food boxes along with the paper pedigree, signed by both farmer and distributor. The distributor repacks this lot into the RFID-tagged boxes, and stores data from the paper pedigree in the EPCIS repository. To generate and verify the ePedigress, the ePedigree Capture, and the ePedigree Query applications are used. The ePedigrees relate to the transaction of the product, so, the EPC transaction event is suitable to store the shipped and received ePedigrees. Figure 1 illustrates the flow of the food product and the information flow in the form of the EPC event data and the ePedigree data along with the sensor data in the entire food supply chain.

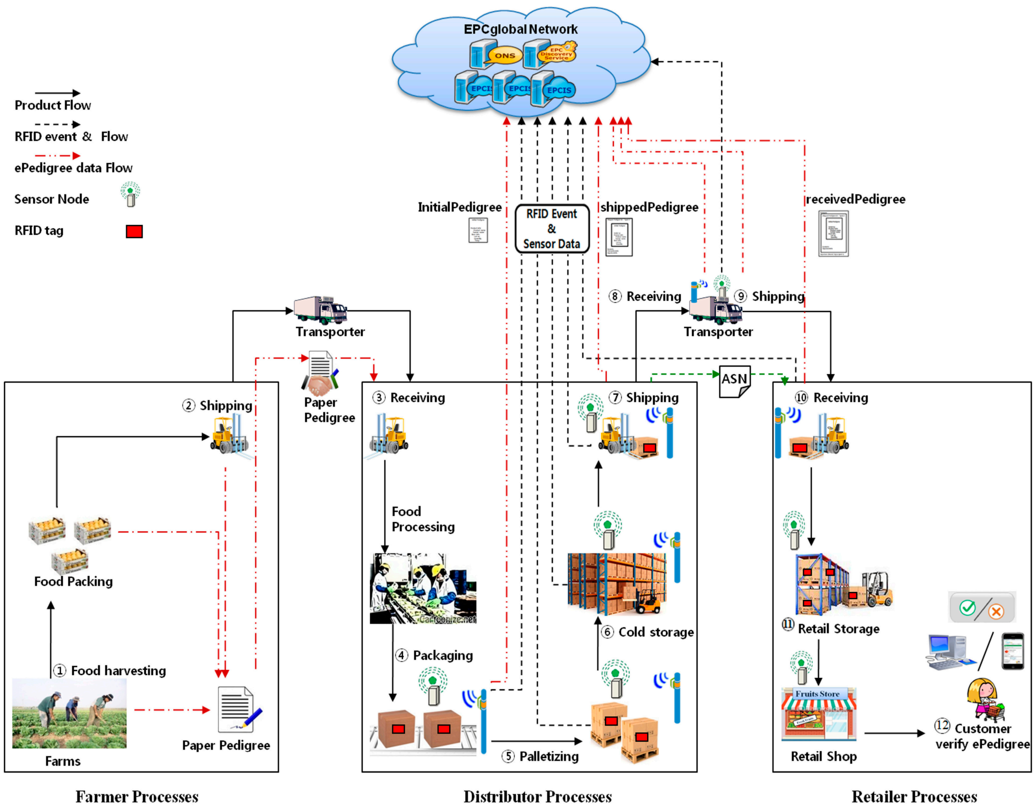

Figure 1. Information flow diagram for the ePedigree data and the EPC event data.

(1) Pre Step: The supply chain partners register to the ePedigree application in order to generate and verify the ePedigrees. In this way, only authorized users can access the product data. A farmer harvests the agricultural food crop and prepares it for packing.

(2) Farmer ships the agricultural food products in the untagged boxes to the distribution center along with the paper pedigree which includes the product information such as product name, harvest date, product expiry date, lot number, quantity, farmer's name and signature of the farmer as a proof of authenticity for all of the information provided in the paper pedigree.
(3) The distributor receives the shipment from the farmer and, verifies the food product condition and information from the paper pedigree. If the quality of food product is satisfactory, then the distributor signs the paper pedigree to confirm the receipt of the shipment. Farmer and distributor each exchange one copy of this paper pedigree document as proof of the transaction. In addition, the distributor makes sure that the one farmer's lot is not mixed with the other farmer's lot at the receiving stage. The distributor receives the different farmer shipments, packs in separate boxes.
(4) Distributor repacks the food product into the RFID tagged cases. When these food cases are read by an RFID reader, an EPCIS object event occurs and at the same time, a Pull-based data request is issued to the sensors installed in the same area to collect and transmit temperature and humidity data to the capturing application. The capturing application appends this data at the extension points of the EPCIS object event. At this stage, the distributor creates three ePedigrees, first, the farmer's initialPedigree, second, the farmer's shippedPedigree, and third, the distributor's receivedPedigree, using exactly the same data from the paper pedigree document. Finally, these ePedigrees are stored in the EPCIS repository.
(5) The distributor packs the food cases on pallets and the EPCIS aggregation event occurs.
(6) These food pallets are transferred to the Cold storage area for storage. When read by an RFID reader, the object event of the pallet occurs and is stored in the EPCIS repository.
(7) The distributor ships the food product to the retailer through a transporter. Before shipping, the distributor verifies the quality of the food product during his custody. If the condition of the food product is satisfactory, the distributor sends the shipment and generates the shippedPedigree with their signature. Then, the distributor sends the ASN (Advance Shipping Notice), which includes the EPC numbers of the incoming product to the retailer.
(8) The transporter receives the shipment from the distributor and generates the receivedPedigree which is stored in the EPCIS repository. The receivedPedigree includes the signature of the transporter and appends with all the previous ePedigrees. The temperature and humidity in the receivedPedigree are gathered from the sensors in the cold storage facility.
(9) The transporter ships the container to the retailer. On arriving at the retailer's facility, the shippedPedigree of the transporter is generated and stored in the EPCIS repository. The shippedPedigree includes transporter's signature and appends with all the previous ePedigrees. The temperature and humidity data collected from the sensors installed inside the shipping container. In some cases, there can be more than one distributor involve in the supply chain before retailer. In such cases, transportation step may occur more than once before final delivery to the retailer.
(10) The retailer scans the RFID tags attached to the products in the shipment and match the EPC numbers of food products with the EPC numbers sent by the distributor in the ASN to verify that no counterfeit or poor quality food products are added in the shipment during transportation. Then, the retailer sends a query to verify the previous ePedigree data with temperature and humidity history of the food products in the upstream supply chain. If the data are within acceptable limits, the retailer accepts the product by adding their signature in the receivedPedigree and stores in the EPCIS repository. The retailer's receivedPedigree appends with all the previous ePedigrees.
(11) The retailer stores the received shipment of food product into cold storage and then, subsequently displays it to the retail store for sale.
(12) When a consumer buys the food product from the retailer store, the consumer can check the complete food product's quality information in the form of complete ePedigree by using the

ePedigree Query Application which can be accessed on the computer at the retailer store as well as on the smartphone of the consumer. If the ePedigree status of the product is acceptable, the consumer buys the product.

3.3. Ensuring ePedigree System Security with Digital Signatures

The proposed ePedigree traceability system applies the digital signatures to ensure the distribution of the quality food products and prevent the infiltration of counterfeit products in the supply chain. The digital signature is a mathematical technique to display the authenticity of any digital document. With a digital signature, the consumers and supply chain partners can trust that the food product and the information contain in the ePedigree document is authentic and is not altered at any stage. The sender cannot repudiate originality of the sent ePedigree document. This research uses RSA (cryptosystem) algorithm to encrypt the food product information in the ePedigrees as recommended by the Pedigree Ratified Standard [34]. The RSA algorithm uses two keys linked with each other, a public key and a private key. Every supply chain partner has their own unique private and public keys. A key server, managed by the administrator of the ePedigree system, is responsible for assigning public and private keys to every supply chain partner. The digital signature is generated using the sender's private key and is verified using the sender's public key. The sender encrypts ePedigree information with their private key as a signature and sends its public key with the ePedigree document to the receiver. Before decryption of sender's ePedigree information, the receiver verifies from the key server that the public key presented in the sender's ePedigree document belongs to the declared sender. If the owner's identity of the public key presented in the ePedigree document is same with the sender's identity, then the receiver decrypts the sender's signature by using the sender's public key, otherwise reject the shipment.

Furthermore, if the contents of the ePedigree document are altered after signature, then the signature verification fails at verification stage. Every supply chain partner verifies the quality of food before delivery to the other supply chain partner and the food quality is maintained and monitored during transportation. In addition, most of the product data are contained in the ePedigree document, captured automatically by sensors and RFID readers. The sender cannot manually change the data in the capturing application. Therefore, the supply chain partners can trust the ePedigree document information after the verification process. In such way, the risks of the contaminated and counterfeit food products distribution along the supply chain to the final consumers can be minimized.

3.4. ePedigree System Architectural Framework

The proposed ePedigree system comprises of two main components. (i) ePedigree Capture Application and; (ii) ePedigree Query Application. The food product information stores in the EPCIS repository and resides in the EPCglobal Network, which acts as a third party service provider.

The ePedigree Capturing Application facilitates the authorized users (supply chain partners) to easily collect and generate the ePedigrees during food product distribution processes. The ePedigree Capturing Application collects the food product traceability data and the temperature and humidity data directly from the RFID readers and sensors respectively, so that, the users (supply chain partners) cannot manipulate this information manually.

The ePedigree Query application provides users (consumers, Government regularity agencies, and supply chain partners) a simple and convenient way, so that, they can easily place inquiries to trace the food product history. The users can check the complete ePedigree history, verified with the signatures of supply chain partners, from the farm to the retailer store by using computers as well as using smart phones. Figure 2 shows the screenshot of the query result interface containing an ePedigree history table of the food product in the complete supply chain.


Pedigree History

No	Pedigree	ProductName	Producer	Address	HarvestDate	ExpirationDate	Temperature	Humidity	Sender	Receiver	Signature
1	Initial Pedigree	Banana	John Farmer	Busan	2016-01-30	2016-02-01	13	85			
2	Shipped Pedigree			Busan			15	91	John farmer	Sam Distributor	Signature verified
3	Received Pedigree			Daegu			14	89	John farmer	Sam Distributor	Signature verified
4											
5	Shipped Pedigree			Daegu			15	87	Sam Distributor	Jack Transporter	Signature verified

Figure 2. Screenshot of web-based query result interfaces for the ePedigree History.

Figure 3 illustrates the screenshots of the temperature and humidity graphs and the traceability map view on an android smart phone. The user can easily understand the pattern of the temperature and humidity data in the upstream supply chain from the graphical representations and can analyze whether the food is in good condition or not. The traceability map helps users to track the product's location and movement in real-time.

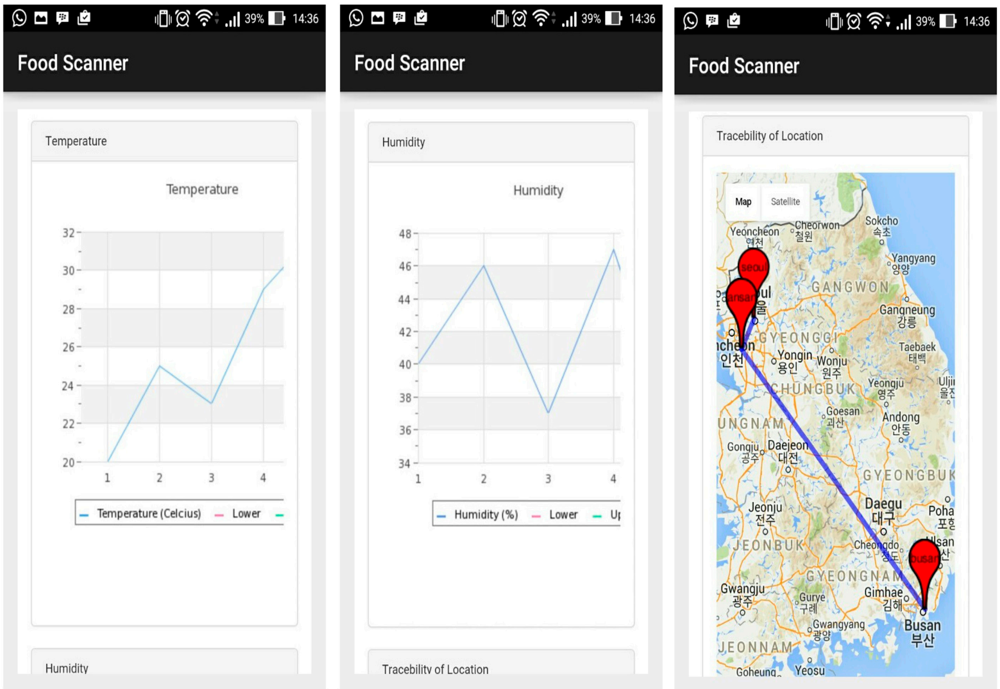

Figure 3. Screenshots of Temp and Humidity graphs and Traceability Map for the android application.

3.5. Performance Evaluation of the ePedigree Traceability System

As the proposed ePedigree system is the integration of three different technologies: RFID, sensors, and ePedigree. It is worthwhile to analyze the effect of the integrated data on the performance of the proposed ePedigree traceability system. The performance is analyzed in terms of data capture and data query and is compared with the traditional RFID traceability system which only contains the traceability data without the ePedigree and sensor integration.

We present a simple query execution model to compare the performance of both traceability systems. When a user sends a query to check the history of a specific food product's ID, this request directed to the ONS to find the address of the DS which contains the address of the EPCIS repository holding data related to the product's ID [33]. After obtaining the EPCIS address, the ePedigree Query Application access to the EPCIS repository and extract product information about the required product's ID. Figure 4 depicts the query execution model of the EPCglobal network.

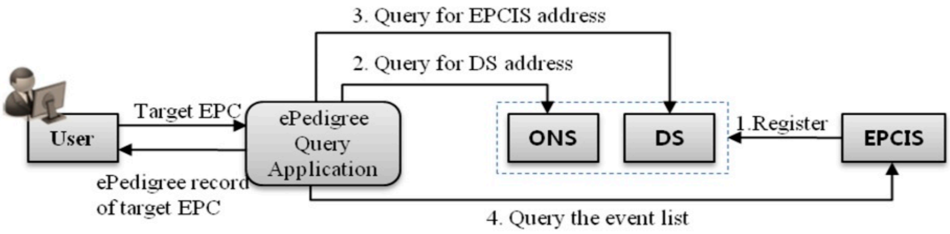

Figure 4. Query execution model for the EPCglobal Network.

4. Results and Discussion

In this section, we provide the results of the performance evaluation in terms of data scalability of the proposed ePedigree traceability system in the Section 4.1 and finally, a comprehensive impact analysis of the proposed ePedigree system on the social sustainability dimension is presented in the Section 4.2.

4.1. Results of Performance Evaluation

We evaluated the performance of the ePedigree traceability system in two different scenarios. Our experiment scenarios are summarized as follows;

- First, the performance comparison in terms of data capture between the proposed ePedigree traceability system and the RFID traceability system.
- Secondly, the performance comparison in terms of data query between the proposed ePedigree traceability system and the RFID traceability system.

The Figure 5a shows the capturing cost of the RFID traceability data against the capturing cost of the ePedigree integrated traceability data. The horizontal axis shows the number of the product records being stored in the EPCIS repository. It is clear from the plot that the difference in terms of time cost for data capture between the traditional RFID traceability system and the proposed ePedigree traceability system is not too much significant. It means that the integration of ePedigree data with the RFID data and sensor data will not significantly affect the scalability of the proposed ePedigree system. The Figure 5b shows the query processing cost to retrieve the RFID traceability data against the cost of the query to retrieve the integrated ePedigree data of the product. The performance of the proposed ePedigree system is almost similar to the RFID traceability system. From the both graphs, it is evident that there is no significant difference in the performance in terms of the data capture and data retrieval between the proposed ePedigree traceability system and the traditional RFID traceability system.

This analysis facilitates the implementation of the proposed ePedigree traceability system in the food supply chains. As the ePedigree traceability system provides many more benefits for the food industry as compared to the RFID traceability system without ePedigree integration. The proposed ePedigree system provides the complete visibility of food products from farmer to retailer. It reduces the chances of food degradation due to the continuous monitoring of food products at all stages. The integration of ePedigree ensures that the good quality food products move along the supply chain at every transaction between supply chain partners. Furthermore, it significantly reduces the chances of counterfeit food products entrance into the legitimate supply chains.

In all plots, the horizontal axis represents the number of products being queried at each point and the vertical axis represents the time cost in milliseconds for capturing and retrieving product data from the EPCIS repository. One product record represents one EPCIS event.

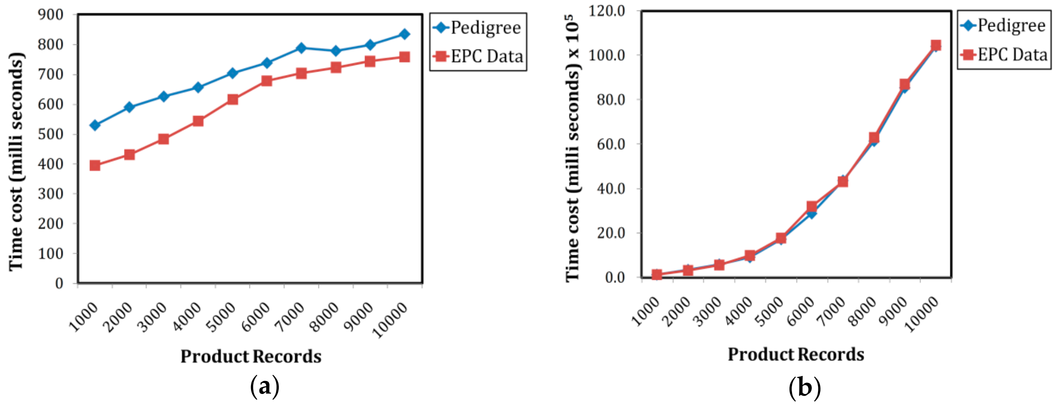

Figure 5. Performance comparison between the RFID traceability system and the proposed ePedigree traceability system: (**a**) Capturing costs of the RFID traceability system vs. ePedigree traceability system; (**b**) Query cost of the RFID traceability system vs. the ePedigree traceability system.

4.2. Impact Analysis of the ePedigree Traceability System on the Social Sustainability Dimension

This section provides a detailed analysis of the proposed ePedigree traceability system's effect on the social dimension of sustainability, specifically in terms of the consumer's health and safety.

Protection of Consumer Health and Safety: As we explained in the introduction section that the risks to consumer's health, due to food quality and safety hazards are the focal concern of the social dimension of sustainability in the food industry. The fact that the nature of the agricultural food industry is different from other products makes this problem more complex and need more efficient solutions. Due to globalization, the trade has been expanded beyond the borders of countries and communities. That increases the distance between the food source and consumers, and most consumers have no contact with the places where their food is produced. The consumers do not have control over the food quality and without any authentic information system it is hard to decide whether the food is safe to consume or not. The products involve in the agricultural food chains are very sensitive to the environmental conditions and has a low shelf-life, if proper conditions are not provided, they can easily be contaminated. The ePedigree traceability system provides an effective and efficient platform to ensure the consumer health by efficiently monitoring the food quality and safety in the complete life cycle of the food products. The proposed ePedigree system integrates three different technologies into one system and hence, provides multiple benefits for the food chains in a single platform. Integration of RFID allows the traceability of food product in the complete supply chain and provides the complete visibility of agri-food products from farm to the retailer. In this way, the consumers can validate the food product history from the first point to the last point of food chains. It can reduce not only the chances of the consumer's sickness but also can boost the confidence and satisfaction of the consumers on the food firms. On the other hand, for the distribution of food products, the temperature and humidity controls are essential factors; it can affect the process of perishable food degradation and the growth of the harmful bacteria. The sensor network integration in the ePedigree traceability system makes it possible to maintain the proper ambient conditions of the perishable food products and thus, maintain the quality during its distribution. The temperature and humidity controls also extend the shelf-life of the food products. Another emerging challenge for the food businesses is the adulterated, counterfeit and mislabeled food products, which pose a serious threat to consumer's health and food businesses reputation. The low quality and contaminated food products can easily be infiltrated in the food chains due to the lack of any mechanism to validate the authenticity of such food products. According to a published research report, olive oil represents 24%

of reported adulteration cases, fruit juices 12%, spices 11%, milk 14% and sweeteners 8% are associated with fraud [46]. The digital signature concept in the proposed ePedigree traceability system provides a robust and effective counterfeiting mechanism to address this vulnerability of the food supply chains efficiently. The digital signature algorithm is capable of effectively detect and minimize the chances of counterfeit food products entrance into the supply chain. In the proposed ePedigree system, at every transaction stage, the supply chain partners verify the condition as well as the previous ePedigree record of food products in the upstream supply chain. As the counterfeit food product with fake labels will not have any ePedigree record in the database of the ePedigree system, thus, consumers and supply chain partners can reject such products. In the case of the food-borne disease outbreak, the major problem faced by the government agencies is to locate the exact source of the contamination as early as possible, in order to contain the epidemic spread of foodborne disease. Due to the lack of any efficient traceability system, the information and data collection about the contaminated food is a long and time taking a process which sometimes takes several weeks. In the meantime, the disease can affect many more people and can generate panic in the general public. In such cases, the ePedigree traceability system provides an effective platform to identify the real source of the contamination in a short time period, as all the food product information is available at the central location and can be accessed easily. In such way, the epidemic spread of the foodborne disease outbreak can be contained timely and can minimize risks to people's lives.

Ensuring food Quality by Enforcing Transparency in food chains: Furthermore, with the implementation of the ePedigree system, the real information about food quality in the complete supply chain is available to the consumers and governmental regulation authorities, and makes it relatively easy to identify the source of contamination. The supply chain partners compel to be more attentive with their processes and closely monitor the food quality, in order to save their business reputation and to avoid the higher penalties. As a result, the consumer gets higher-quality and safe food products, and the risks involve to consumer health and social welfare can be controlled significantly. As the risks to consumer health reduce, it reduces the medical expenses of consumers and their productivity loss also reduces by reducing chances of illness due to food poisoning.

Local Businesses Protection and Facilitate Sustainable Social Growth: The absence of any efficient traceability system for counterfeit food products can entice food suppliers to outsource cheap and poor quality food products and introduce into the local market for higher profit gains. Apart from the health and safety issues, such actions can harm the local food companies' businesses, which provide quality food products to the local consumers. The profit and business loss of such local brands force them to closure or downsizing, which can dislocate hundreds and thousands of jobs and can create serious social development issues such as diminishing quality of life, social and financial insecurity, increasing depression and anxiety in society. Furthermore, the counterfeit food products, mostly supplied by unregistered companies reduce governments' revenue and taxes, as unregistered companies do not appear in the governments' tax nets, at the same time they reduce the market share and profits of the registered companies. As a result, this deprives governments' revenue for vital public services and puts more burden on taxpayers. The implementation of the proposed ePedigree traceability system can provide an efficient platform to food suppliers as well as for governments to protect the local businesses and increase the social development and growth.

5. Conclusions

In the agricultural food industry, the social aspect of sustainability in terms of the consumer's health and safety has attained utmost importance due to the frequent crises of food contamination and the emerging threat of counterfeit food products. An efficient and economical approach is essential to ensure the food quality and safety for the sustainable social development in the food industry. This article proposes an ePedigree traceability system, which integrates the RFID technology, sensor networks, and ePedigree concept, to efficiently control and maintains the food product quality throughout the entire supply chain. The proposed ePedigree traceability system provides the complete visibility from farmer to retailer and facilitates the consumers and government inspectors to easily verify whether a food product is safe for consumption or not. The concept of ePedigree with digital signatures significantly reduces the chances of counterfeit food products entrance into the food supply chain. It provides a quality check at every transaction between supply chain partners in order to detect the hazardous food products and enforce the food suppliers to become more attentive with their processes to ensure food quality. As a result, it increases the consumer's trust and confidence in the food industry. In the event of the foodborne disease outbreak, it can easily track the source of contamination in a short time and helps to take preventive actions in order to stop the epidemic spread of disease. The performance comparison of the proposed ePedigree traceability system and the RFID traceability system is also presented in order to compare the scalability cost of the proposed integrated ePedigree traceability system. The results showed that there is not a significant difference in performance of both traceability systems in terms of scalability of data. This analysis facilitates the food suppliers to implement the ePedigree traceability system in the food industry. As the ePedigree traceability system can provide multiple benefits with the same scalability cost, such as the food product traceability, monitoring of food condition and the prevention of the counterfeit products. Finally, the impact of the proposed ePedigree traceability system on the social dimension of sustainability is analyzed in detail. Apart from the aspects of ensuring consumer health and safety, the implementation of the ePedigree traceability system in food supply chains also provides other social advantages such as the reduction of the medical expenses, reduce the chances of business loss of food companies and consequently saving thousands of jobs and facilitates the sustainable social growth.

The current focus of our study is on the post-harvest processes, but for future work the ePedigree traceability system can be further extended to the pre-harvest stages to monitor and collect the information about the crop harvesting conditions from the farmer. The ePedigree traceability system can also be extended to monitor the environmental sustainability dimension. The supply chain partners can also include information about the carbon footprint of every process from farm to the retail store. This will provide the complete life cycle assessment of that specific agricultural food product and can be used as an additional competitive or regulatory tool. In this research, we used the digital signature as an anti-counterfeit and authentication tool, this aspect can be further improved by providing some kind of intelligent ability to detect counterfeit product automatically such as by using data mining or some neural network approach.

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