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Traceability in agriculture and food supply chain: A review of basic concepts, technological implications, and future prospects

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Abstract

In recent times, the accurate and timely traceability of products and activities in the supply chain has become a new factor in food and agribusiness. Increasingly, consumers in many parts of the world demand for verifiable evidence of traceability as an important criterion of food product quality/safety. This trend has been underpinned by several market-pull factors including increasing global demand for food products originating from diverse sources, high incidence of food-related health hazards and increasing concern over the impacts of genetically modified organisms (GMOs) on the human food chain and the environment. In order to meet consumer demands for consistent supply of top quality, safe and nutritious foods, as well as rebuild public confidence in the food chain, the design and implementation of full backward and forward traceable supply chains from farm to end-user has become an important part of the overall food quality assurance system. Farmers, postharvest handling operators, marketers, research practitioners and policy makers need good understanding of the concepts and implications of supply chain traceability to assist in developing and implementing appropriate technological interventions to meet consumer demands for traceable agricultural supply chains. The objectives of this article are to: (a) review the concepts of supply chain management and traceability in agriculture, and (b) highlight the technological challenges in implementing traceable agricultural supply chains. Development of appropriate measurement tools for food product labeling and identification, activity/process characterization, information systems for data capture, analysis, storage and communication, and the integration of the overall traceable supply chain are essential for success.

Key words: Traceability, quality, SCM, ICT, identity preservation, labeling.

Introduction

The new agricultural economy is characterized by two main overriding features: (a) greater concentration/intensity of farms into smaller numbers with large sizes and rising influence of contract farming, and (b) the evolution of integrated supply chains linking producers and consumers. Such intensive agriculture relies heavily on electro-mechanical systems, irrigation, agro-chemicals, and basic raw materials that possess new traits such as genetically modified plants and animals. Under the new agricultural economy, these attributes of intensive farming create new challenges for sustainable production and processing practices that promote a balanced approach to the problems of food quality, safety, and good environmental stewardship.

Modern consumers demand food that is fresh, palatable, nutritious and safe. Furthermore, increasing number of consumers demand functional foods that offer specific health and nutraceutical benefits. With changing lifestyles and rising income in many parts of the world, increasing proportion of foods are prepared and eaten outside the home as convenience and restaurant meals. These market-pull factors also have major implications on the future of agriculture because they pose considerable challenges for maintaining food safety, environmental protection, and profitability of agriculture. The shift from quantity-oriented agriculture to new emphasis on quality, safety, functionality and sustainability, have placed new demands for the development and adoption of traceable supply chains. Assuring food traceability from farm to fork, implementing authenticity and diagnostic tests that detect and prevent food safety hazards and preserving the identity and wholesomeness of novel foods, have become essential elements of a quality assured agricultural supply chain management system. Traceability is a preventative strategy in food quality and safety management. However, when hazards or food scares occur, a good traceability system will facilitate timely product recall and determination of liability. The capability for full trace-back and trace-forward at any stage in the food chain is considered critical to addressing declining consumer confidence and general public concern about the rising incidence of food-related deaths and illnesses, which have been major public health issues in the developed countries. Advancements in information and communication technology (ICT) for data capture, storage and retrieval, non-destructive testing, and geospatial science and technology provide opportunities and challenges for agricultural engineers to contribute to the development of technological innovations for traceability from farm to fork. The aim of this paper is to discuss the importance and scope of traceability technology in modern agriculture. The specific objectives are to define traceability in agribusiness and to discuss the technological implications and prospects of implementing traceability in food supply chains from farm to plate.

Definition and Concept of Agricultural Supply Chain Management

The conceptualization of consumer products and services as supply chains is now a common practice in most industries. From the farming of basic raw materials to delivery of final products to the consumer, each different step in the entire production process is viewed as link in the chain. Supply chain management (SCM), therefore, represents the management of the entire set of production, manufacturing/transformations, distribution and marketing activities by which a consumer is supplied with a desired product. Some analysts refer to this as demand chain management to emphasize the focus on meeting consumer expectations[1]. The practice of SCM encompasses the disciplines of economics, marketing, logistics and organizational behaviour to study how supply chains are organized and how institutional arrangements influence industry efficiency, competitions and profitability[2]. Technological innovations in information sciences and engineering are increasingly playing vital roles in the vertical integration and coordination of supply chains through the application of hardware and software for measurements, data capture, analysis, storage and transmission. Two broad principal explanations can be advanced for the increasing interest in agricultural SCM: the industrialization of agriculture[3,4], and the uncertainty associated with variations in product quality and safety[5]. The trend towards vertical coordination of agricultural supply chains (ASC), reduction of government support (subsidies) for agriculture, globalisation and competition among producers, processors and suppliers, explosion in technological progress applicable to the agri-food industry, changing consumer demand and consumption patterns, etc, are some of the factors related to the concentration and industrialization of agriculture. The high variability in quality and magnitude that is characteristic of the agricultural environment (both production, handling and processing) and basic food raw materials creates uncertainty in the ability of the industry to assure a consistent supply of good quality and safe products to the consumer. As a result, the transaction cost (information, negotiation and monitoring) associated with market-driven (industrialized) agriculture and the uncertainty of product quality and safety has increased in recent times[2,6]. As individual businesses and global markets become highly efficient and cost-effective, competition has therefore shifted from 'between businesses' to within entire value chains. The ever-increasing adoption of SCM principles in agribusiness is perhaps one of the profound and long-term developments in business management relevant to agricultural traceability. Agriculture is inherently a fragmented industry, involving a diverse range of distinct enterprises (farmers, processors, marketers and distributors), and relies on inputs from various sources, often at distinct geographical locations. For instance, although some food products such as chicken and pork, have been subject to extensive vertical integration within the production and marketing chain, cattle on the other, may be produced on one farm, grown on another, finished on another, and between each stage, transported and sold through open markets, sometimes several times, before being purchased either in the open market or direct, deadweight, for slaughter[7]. With respect to grains and fresh fruit and vegetables, most marketers and processors obtain their supply from diverse sources (farmers, retailers, brokers) in order to meet marketing and production targets. From the marketing and processing perspectives, SCM is an essential tool for integrating the activities of the various suppliers within the company's operations in order to assure the consistent delivery of quality-assured products and services to the consumer. For the consumer and other stakeholders, SCM focuses on improving the performance of the supply chain through the delivery of guaranteed safe, desirable and good quality food in a cost-effective manner[8]. The increasing transaction costs of intensive agriculture and the need to reduce these costs, lies at the heart of interest in agricultural SCM. Based on experience from a broccoli SCM system in the UK, Grimsdell[9] proposed six fundamental requirements for an efficient supply chain between vegetable growers and the major retail customers: scale of operation, strategic alliances, production flexibility, continuity of supply, quality control, and communication. The author concluded that the most difficult aspect of the project was "putting down on paper the complex processes" (recording the quality and quantity of inputs, the tasks undertaken on the crops, etc) to guarantee due diligence and traceability. This conclusion highlights the importance of information and communication technology for successful implementation of a traceable supply chain management system. Increasingly, agricultural SCM must be conducted between firms under strategic alliances since most enterprises often represent a link or set of links in the overall supply chain of a product. Optimizing the entire supply chain, therefore, requires a level of information sharing, teamwork, cooperation and collaboration among the participating enterprises[10]. Given this scenario of interdependence, rapid interchange of data on products and activities among companies in a supply chain will reduce transaction costs[2]. The implementation of supply chain traceability as part of the overall quality management system in agriculture facilitates such data/information exchange by providing a mechanism for recording, storing, analyzing and transmitting relevant data on products and activities to designated stakeholders.

The Concept of Traceability in Food and Agribusiness

The term 'traceability' has become so widely used in recent times in various industries[11,13] that it is timely to examine the concept, particularly in relation to agriculture and food. Agricultural traceability simply refers to the collection, documentation, maintenance, and application of information related to all processes in the supply chain in a manner that provides guarantee to the consumer and other stakeholders on the origin, location and life history of a product as well as assisting in crises management in the event of a safety and quality breach. With respect to a food product, traceability represents the ability to identify the farm where it was grown and sources of input materials, as well as the ability to conduct full backward and forward tracking to determine the specific location and life history in the supply chain by means of records. It contributes to the demonstration of the transparency of the supply chain through the use of verifiable records and labeling[14]. Traceability adds value to the overall quality management system by providing the communication linkage for identifying, verifying and isolating sources of non-compliance to agreed standards and customer expectations. There are six important elements of traceability which put together, constitute an integrated agricultural and food supply chain traceability system:

(a) Product traceability - which determines the physical location of a product at any stage in the supply chain to facilitate logistics and inventory management, product recall and dissemination of information to consumers and other stakeholders.

(b) Process traceability - which ascertains the type and sequence of activities that have affected the product during the growing and postharvest operations (what happened, where, and when). These include interactions between the product and physical/mechanical, chemical, environmental & atmospheric factors which result in the transformation of the raw material into value-added products; and the absence or presence of contaminants.

(c) Genetic traceability - which determines the genetic constitution of the product. This includes information on the type and origin (source, supplier) of genetically modified organisms/materials or ingredients as well as information on planting materials (such seeds, stem cuttings, tuber, sperm, embryo) used to create the raw product.

(d) Inputs traceability - which determines type and origin (source, supplier) of inputs such as fertilizer, chemical sprays, irrigation water, livestock, feed, and the presence of additives and chemicals used for the preservation and/or transformation of the basic raw food material into processed (reconstituted or new) food products.

(e) Disease and pest traceability - which traces the epidemiology of pests, and biotic hazards such as bacteria, viruses and other emerging pathogens that may contaminate food and other ingested biological products derived from agricultural raw materials.

(f) Measurement traceability - which relates individual measurement results through an unbroken chain of calibrations to accepted reference standards[15]. To achieve this, measuring and test equipment and measurement standards are calibrated utilizing a reference standard whose calibration is certified as being traceable to a national or international standard[16]. The other aspect of measurement traceability relates to the property of the measurements (data and calculations) generated throughout the supply chain and their relationship to the requirements for quality. By focusing on the quality of measurements (rather than on a property of an instrument, it is possible to assure that the measurements are indeed adequate for the intended use[16]. To achieve this, each measured data must specify the environmental, operator, and geospatial and temporal factors, which are not related to the instrument but impact on the quality of the data.

In implementing a new traceability system or studying an existing one as part of routine quality management system or in the event of food safety and quality alert, these basic aspects must be addressed in order generate sufficient data to adequately evaluate the type, origin and location of the source of safety concern to enable corrective actions to be taken.Traceability is an information-based proactive strategy to food quality and safety management. It is a complimentary tool to other quality management programmes such as Hazard Analysis and Critical Control Points (HACCP) systems. A key strength of traceability chain management is that it facilitates the identification and isolation of hazards and implementation of effective corrective actions in the event of an incident. Thus, like point inspection and product testing, traceability by itself cannot introduce safety into the food process or handling process. When considered in isolation of other quality management systems, its traceability is not a sufficient condition to satisfy the safety requirements of the food chain. However, its strength lies in preventing the incidence of food safety hazards, and reducing the enormity and impact of such incidents when they occur by facilitating the identification of product(s) and/or batches affected, specifying what occurred, when and where it occurred in the supply chain, and identifying who is responsible. The benefits of integrating traceability into the overall quality agricultural management system are numerous, ranging from improvements in product quality and safety management, crises management in the event of a safety alert, and strengthening overall agribusiness coordination[14]. With heightening public scrutiny of the food supply chain and agriculture, many national and regional new food quality regulatory directives and laws have been enacted, leaving agriculture and food industries with little option but to implement traceability systems as part of the overall food safety and quality management programme. As agriculture continues to experience declining terms of trade and competition by other more financially lucrative industries, there are good reasons to believe that the concern about traceability will continue in global food trade. The search for cost-effective technological innovations for implementing accurate and reliable traceability systems is therefore an important challenge facing agriculture in the new globalised economy.

The Demand for Traceability in Agribusiness

The demand for traceability in agriculture has significantly expanded in the last few years with increasing incidence of food-related safety hazards and scares (such as footh-and-mouth disease, mad cow disease, microbial contamination of fresh produce, dioxin in poultry). The appearance of genetically modified organisms (GMOs) and the need for identity preservation of GMO and non-GMO agricultural chains has further exacerbated declining consumer confidence on food safety and the increasing concern over potential negative impacts of agriculture on the environment and ecological diversity. Closely related to these factors is the introduction of new food safety legislations that have placed responsibilities on producers, processors, caterers and other handlers in the supply chain to ensure food safety. The main tool that these operators will use to defend any subsequent liability will be the demonstration of "due diligence", which must demonstrate that every precaution has been taken to prevent contamination and subsequent food safety hazards. More than before, an essential feature of food quality management system is that finished products can be traced back to their raw material and thus to their original producer and previous handlers in the chain. In the same way, forward traceability is also essential to guarantee the location of products and facilitate their recall when safety and quality standards have been breached.

Technological Implications of Traceable Agricultural Supply Chains

Modern agriculture is highly knowledge-intensive and increasingly information-driven. With declining terms of trade affecting agriculture vis-à-vis other industries, technological innovations are necessary to reduce transaction costs and facilitate the production and consistent supply of top quality, safe and traceable products to meet consumer demands. Farmers, processors, marketers, handlers, consumers, governments and the general public have stakeholder interests in the safety and cost-effectiveness of global agri-food supply chains.

To implement traceable agricultural supply chains, technological innovations are needed for product identification, process and environmental characterization, information capture, analysis, storage and transmission, as well as overall system integration. These technologies include hardware (such as measuring equipment, identification tags and labels) and software (computer programmes and information systems).

Product identification technology: A major feature of any traceable supply chain is the ability to trace-back the history and consistently track the physical location of the products in the overall supply chain. To achieve these, accurate labeling is essential. The simplest technology to achieve this is to attach a tag to the basic raw material (e.g. the animal, plant or its constituent parts) and to transfer that data on the tag to the bar code of the food product. In the livestock industry, the ear-tag is commonly used and often contains a series of numbers and/ or alphabets, which codify specific information such as the breed, date of birth, farm, vaccinations, etc.

The use of computers and other information technologies have spurred the development of electronic identification (EID) systems, which include electronic tags with chips and hand-held scanners for reading, storing and transmitting the data to PCs for analysis and long-term storage. An important attribute of tags is that the materials must be resistant to rough handling and inclement weather. Advancements in material science have led the development of tags that are resistant to tear and wear and which can withstand harsh environmental conditions. Innovations in geospatial science and technology such as radio frequency technology and mobile tracking devices have the potential for collecting and transmitting data from tags to distant locations for storage and analysis. The simplest label on a food product often stores such information as the name of the product, batch/lot number, and price. Depending on the market sophistication and demand for information, other data that can be loaded are product origin, handling and storage conditions.

Quality and safety measurement technology: Ultimately, the success of traceability is measured by the consistent delivery of products to meet the expectations of the consumer and other stakeholders, as well the ability to ascertain the location of each product unit for effective recall in the event of a quality or safety breach. This requires accurate information on the maturity and quality attributes and safety status of the product, which must be measured and analyzed using appropriate instrument and procedures. Product specifications such as size (mass, dimensions), firmness (crispness, crunchiness) soluble solids, acidity, flavour, etc, are some of the physical, mechanical and chemical properties that may require measurement. Laboratory and on-line instruments such as the penetrometer, firmometer, twist tester, Instron machine, and Kiwifirm can be used to measure the firmness of fleshy products. Non-destructive tests based on force sensing, infrared and magnetic resonance imaging can also be used to measure firmness and other internal quality attributes. They can also be used to assess the presence of hazardous physical objects inside products. Models of these instruments are commercially available from various manufacturers and are currently used in industry and research laboratories. Procedures and equipment are also available for chemical analysis of product samples, equipment surfaces and the air to ascertain the presence of hazardous microbial contaminants.

Genetic analysis technology: The need to preserve the identity of product supply chains and the demand for genetic traceability have led to the development of procedures and measurement devices for the analysis of the genetic constitutions and contamination of foods and other biological products. DNA tests based on real-time PCR have been developed to detect and quantify GMOs and other transgenic materials. Giese[17] provides a good summary of several laboratory exhibits at a recent Institute of Food Technology Meeting & Food Expo for measuring product traceability and safety.

Environmental monitoring technology: Environmental conditions such as temperature and relative humidity, atmospheric composition of the air, including pollutants, impact on the quality stability and safety of food products. Instrumented environmental recording devices (such as gas analysers and biosensors) for monitoring these parameters are available and can be coupled to control systems.

Developments in geospatial science and technology: The integration of geographic information systems (GIS), remote sensing (RS) and global positioning systems (GPS)[18] offers considerable opportunity for site-specific agriculture and the derivation of data related to the agriculture products, on the farm and through the subsequent handling operations. Put together, these technologies enable data to be remotely collected on individual animals, plants, and blocks on a farm, which can be processed, transmitted and presented as visual spatial information on the bio-physical properties of the block, yield and selected product attributes. With respect to traceability, a vital feature of these technologies is the possibility to map the geospatial variability of selected attributes such as yield, product quality, animal movement, and disease epidemiology.

Software technology for traceability system integration: An effective traceability chain is an integrated system made of distinct components involving data collection using standards measurement procedures, the analysis, storage and transmission of the recorded information, and full backward and forward control system that permits the tracking of the product history. Such an integration of technologies relies on the application of appropriate information and computer system, and which links the traceability chain to a central database at the company, national or international level. Many researchers and commercial companies have reported the development and availability of full traceability systems that have been adopted in industry. Calder and Marr[7] described a trial traceability initiative based on electronic identification (EID), which enabled full traceability of farm animals. Harvey[19] recently reported an electronic data identification tag (EDIT) that includes a transponder as part of a typical ear tag, and a handheld, battery-powered electronic reader or terminal, which provides farmers with a fully integrated traceable livestock management tool. The electronic ear tag has the capacity to record all the details of an animal's life from its genetic and birth details, to treatment and productions. Many countries such as Canada and New Zealand have implemented national cattle identification programmes using various technologies that are based on the above principles. Examples of commercially available traceability software programmes[†] that have been reported include QualTrace, EQM (Enterprise Quality Management),[20] and Food Trak[21].

Future Prospects

Traceability has become a critical element in global agri-food business. Shifting patterns in consumer demand for sustainable agricultural practices (including environmental and animal welfare concerns) and ever-increasing demand for consistent supply of a range of top quality and safe products assure a future for traceability as an important element of the overall quality assurance system. Traceability presents both challenges and opportunities for educators, research and development practitioners and agribusinesses. Students in agricultural related disciplines need exposure to the concepts and principles of supply chain management and traceability to prepare them for the practical and management challenges that these present in industry. The trend to implementing traceability systems based on providing detailed documentation on the history of a product may enlarge to create a demand for traceability professionals in agribusiness and other life science industries. Developing cost-effective traceability technologies for both large and small-scale farmers and postharvest enterprises should receive priority attention by engineers and other science and technology experts working in agriculture and other biological industries. Farmers and food product handlers need training on the principles and procedures of traceability. With increasing concentration of global supply chains and enactment of new regulations on traceability in agriculture, technology transfer and rural development projects designed to improve the market-orientation and quality of products from small-scale farmers in developing countries must include appropriate tools to facilitate the traceability of their products and processes. Several technologies already exist, particularly in the livestock industry, for implementing traceable supply chains. Future innovations in DNA finger-printing, nanotechnology for miniature-machines, and retinal imaging and their integration into plant and livestock industries have considerable potentials for improving the speed and precision of traceability in knowledge-based agriculture. In view of the prospects for litigation arising from product liabilities, the development of relevant measurement and calibration standards related to product traceability demands the attentions of researchers and policy agencies dealing with food quality and safety. With the wide adoption of the Internet (World-Wide-Web) as a medium of communication and commerce, linking traceability chains for products to the home personal computer and/or television set based on individual an consumer identification system appears feasible and worthy of investigation. This will deliver real-time information to consumers on the quality and safety status of products and also permit speedy recalls when quality and safety standards are breached.

Conclusions

The emergence of traceable agricultural supply chains is the outgrowth of a long line of developments in improving food quality and safety management. In industries such as telecommunications, software development and airlines, security is the principal driver for traceability. In recent times, traceability has emerged as a new index of quality and basis for trade in agricultural products. This development has been catalyzed by rising incidence of food-related health hazards and high-profiled scares such as BSE, FMD, dioxin in poultry products, and microbial contamination of fresh produce. The decline in consumer confidence has been exacerbated by the introduction of genetically modified organisms, plants and animals into the human food chain. The purpose of agricultural traceability is to permit the full backward and forward tracking of a product and its life history (activities) in the supply chain, from farm to fork. It is therefore a preventative quality and safety management tool. A good traceability management systems allows for trace-back to the original producer as well trace-forward to individual consumers and indeed any step in the supply chain, for effective identification of products and management of recall when quality and safety standards are breached. From a consumer perspective, traceability helps to build trust, peace of mind, and increase confidence in the food system. For the grower and postharvest operators, traceability is part of an overall cost-effective quality management system that can also assist in continuous improvement and minimisation of the impact of safety hazards through rapid determination and isolation of sources of hazards. It also facilitates rapid and effective recall of products, and the determination and settlement of liabilities. Modern technological innovations already exist which can be applied to develop and implement an integrated agricultural traceability system. Advances in information and computer technology for information systems management; scanning and other digital technology for product identification, image capture, storage and display; nondestructive testing and biosensors for quality and safety assessment; and geospatial technology (GIS, GPS, RS) for mobile assets tracking and site-specific operations, are technological innovations that can be applied in a traceability system. Initial cost may be limiting, but several commercial products and software already exist, which can meet the needs of most medium farms and other agribusiness. Developing appropriate traceability technology for small-scale farmers, particularly in the least developed countries, offers considerable challenges and opportunities for researchers and development practitioners in this food and agribusiness. Future innovations in emerging technologies such as DNA fingerprinting, nanotechnology for miniature-machines, retinal imaging, and their integration into crop and livestock industries have considerable potentials for improving the speed and precision of traceability in knowledge-based agriculture. Traceability is an interdisciplinary concept that promotes documented transparency in the way we practice sustainable agriculture. It applies technological innovations to sound agribusiness practices in order to meet consumer demands for reliable and accessible information about the source and life history of products in the human food chain. Farmers, processors and handlers, and food policy experts need to be aware of future developments in this area to assist them in implementing appropriate traceability systems for their enterprises.

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