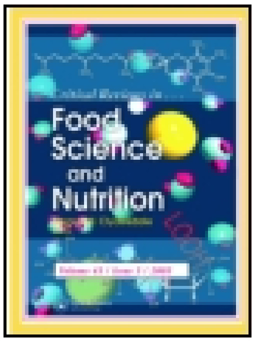

Taylor & Francis
Taylor & Francis Group

Critical Reviews in Food Science and Nutrition

ISSN: 1040-8398 (Print) 1549-7852 (Online) Journal homepage: http://www.tandfonline.com/loi/bfsn20

Recent Developments in Smart Freezing Technology Applied to Fresh Foods

Ji-cheng Xu, Min Zhang, Arun S. Mujumdar & Benu Adhikari

To cite this article: Ji-cheng Xu, Min Zhang, Arun S. Mujumdar & Benu Adhikari (2015): Recent Developments in Smart Freezing Technology Applied to Fresh Foods, Critical Reviews in Food Science and Nutrition, DOI: 10.1080/10408398.2015.1074158

To link to this article: http://dx.doi.org/10.1080/10408398.2015.1074158

Accepted author version posted online: 13 Oct 2015.

Recent Developments in Smart Freezing Technology applied to Fresh Foods

Ji-cheng Xu[1], Min Zhang [1*], Arun S. Mujumdar[2] Benu Adhikari [3]

[1] *State Key Laboratory of Food Science and Technology, Jiangnan University, 214122 Wuxi, Jiangsu, China*

[2] *Department of Bioresource Engineering, McGill University, Quebec, Canada*

[3]*School of Applied Sciences, RMIT University, Melbourne City Campus, VIC3001, Australia*

*Corresponding author: Professor Min Zhang,

Email: min@jiangnan.edu.cn.

ABSTRACT

Due to the increased awareness of consumers in sensorial and nutritional quality of frozen foods, the freezing technology has to seek new and innovative technologies for better retaining the fresh-like quality. In this article, we reviewed the recent developments in smart freezing technology applied to fresh foods. The application of these intelligent technologies and the associated underpinning concepts has greatly improved the quality of frozen foods and the freezing efficiency. These technologies are able to automatically collect the information in-line during freezing and help control the freezing process better. Smart freezing technology includes new and intelligent technologies and concepts applied to the pretreatment of the frozen product,

 ACCEPTED MANUSCRIPT

freezing processes, cold chain logistics as well as warehouse management. These technologies enable real-time monitoring of quality during freezing process and help improve product quality and freezing efficiency. We also provided a brief overview of several sensing technologies used to achieve automatic control of individual steps of freezing process. These sensing technologies included computer vision, electronic nose, electronic tongue, digital simulation, confocal laser, near infrared spectroscopy, nuclear magnetic resonance technology and ultrasound. Understanding of the mechanism of these new technologies will be helpful for applying them to improve the quality of frozen foods.

Keywords Fresh foods, Smart, Freezing technology, Food process

ACCEPTED MANUSCRIPT

INTRODUCTION

Frozen food processing technology is used for extending the storage-life and preventing food spoilage by maintaining subzero temperature during the entire postharvest food chain including raw material acquisition, processing, storage and transportation (Geidobler and Winter, 2013; Barresi et al., 2009; Campanone et al., 2002). Due to the rapid development of mechanization and automation of freezing equipment, frozen food technology is making great progress (Cuibus et al., 2014; Laguerre et al., 2013; Petzold and Aguilera, 2009). However, the contemporary frozen food technology also has some inherent shortcomings such as deterioration of taste and flavor in products as well as high energy consumption (Li and Sun, 2002; Kiani and Sun, 2011). Due to the increased awareness of consumers on the sensorial, nutritional and functional properties in foods, the processed foods require to meet stringent quality requirements. Consumers desire not only choice in variety of processed foods, but also want to see enhanced quality and nutritional value. This trend has created an environment which requires continuous innovation in processing technologies (James et al., 2015). Hence, the traditional frozen food industry technology needs to be upgraded. Thus, the intelligent food processing technologies have become the research theme of great interest.

The understanding of the frozen food technology including the prediction and control is difficult yet essential if fresh-like quality has to be preserved for longer time. Processors of frozen foods are constantly in search of methods that would allow them to detect and monitor the

 ACCEPTED MANUSCRIPT

process in real time in order to improve the quality of frozen foods and reduce the energy consumption. If a frozen food technology is able to collect information automatically from every aspect of freezing process in order to arrange, judge, and send out control instruction or manage directive, it can be referred to as smart freezing technology (Simpson et al., 2007).

Introduction of intelligent technology in frozen food processing is a major step forward next to mechanization and automation. Smart freezing technology combines mobile internet, cloud computing, big data storage with food processing to make it more intelligent (Giannakourou and Taoukis, 2002; Bosca et al., 2013). The concept and the technology associated with the smart frozen food technology including the intelligent pretreatment of frozen products, intelligent production processes, intelligent cold chain logistics as well as intelligent warehouse management enable real-time detection and monitoring of frozen food processing for improving the product quality and reducing the losses.

The aim of this article was to provide an overview of the recent developments in smart freezing technology relevant to fresh foods. Important aspects of this technology applied to gain better understanding, prediction and control of frozen food processing are discussed. Advanced sensing technologies used to achieve automatic control of individual steps of smart freezing technology are also briefly discussed.

INTELLIGENT PRETREAMENT OF FROZEN PRODUCTS

ACCEPTED MANUSCRIPT

Before quick-freezing, food materials must undergo pretreatment such as selection, sorting, removal of foreign materials and evaluation of freshness. However, in the traditional food processing, these operations are mostly carried out manually or by using low level of automation both of which are inefficient with high reject rates. Thus, the traditionally frozen food technology is costly as it requires an input of large manpower (Patel et al., 2012; Li, 2013). To satisfy high efficiency, high quality and cost effectiveness in inspection and grading of agricultural and food products, it is necessary to improve the quality evaluation aspects by using intelligent and more efficient methods (Du and Sun, 2006). Application of intelligent analysis and sensing technologies such as computer vision, electronic nose and electronic tongue in automated and non-destructive in-line inspection systems is cost-effective means for accomplishing intelligent pretreatment (Table 1).

Computer Vision

Computer vision utilizes an image capturing instrument (camera), a computer (for data storage and processing) and an information processing software to simulate the human visual system (Sun, 2004). The core of computer vision includes two steps, i.e. capturing the image of a target with a camera and analyzing the information from a digitizer using appropriate algorithm to achieve the required measurement and classification. With the rapid expansion in the processing capability of computers and analytical ability of image analysis software, the computer vision is increasingly being applied to the quality evaluation of diverse range of processed foods (Rodríguez-Pulido et al., 2013). This development has created opportunities for innovating smart freezing technology. Davies (2009) reviewed developments and application of machine vision in agriculture and food including fruit, grain, meat and fish. This review showed that the computer vision technology was increasingly used in food and agricultural industry for inspection and quality evaluation.

Computer vision is also promising in pretreatment of food materials, especially for automatic grading and sorting (Wu and Sun, 2013). Liang et al. (2009) proposed a vision-based automatic raw fish handling system to speed up fish cleaning and weighing. They used a camera to capture the projected images of fifty tilapias and investigated the relationship between the live weight and the projected area using regression analysis. It was found that a tilapia's weight was highly correlated with its projected area and it could be used to estimate its live weight. Chong et al. (2008) developed an eggplant grading machine using six CCD cameras as the sensing device to acquire six images per fruit covering the entire surface of the eggplant and designed an algorithm to extract its features such as length, diameter, volume, curvature, color homogeneity and surface defect. While evaluating the ability of the algorithm and grading machine in grading the eggplant fruits, they reported that the system had yielded higher production capacity compared to the manual grading.

Computer vision systems are increasingly being used in industry for quality inspection and grading of agricultural and food products as they can provide rapid, and objective assessment in

ACCEPTED MANUSCRIPT

hygienic setting and in affordable cost. However, there still are some difficulties in the broader adaptation of the machine vision in food processing industry (Vijayarekha, 2012). Large number of images is produced by a machine vision system which requires large digital storage. The speed of the currently available image capture devices is still failing to meet modern manufacturing requirements. Moreover, computer vision being the simplest simulation or mimicking of human vision, it cannot adapt to rapidly hanging conditions quickly as human eyes do. Thus, the future direction or development in computer vision is that it behaves more like the human vision system.

Electronic Nose

Electronic nose also known as smell scanner was developed in 1970s to mimic mammalian olfactory system. It is a device designed to detect and discriminate complex odors using an array of sensors and pattern recognition techniques (Zutphen, 2014; Pearce et al., 2006). Advances in electronics, biochemistry, aroma-sensor technology, and artificial intelligence made it possible to develop electronic nose system capable of measuring and characterizing volatile aroma compounds with high sensitivity, reproducibility, and reliability. The above mentioned advanced technologies have made it possible to develop a wide variety of new e-nose applications suitable for agricultural, cosmetics, environmental, food, manufacturing, military, pharmaceutical industries and for regulatory agencies (Wilson and Baietto, 2011, 2009). The analysis of food

ACCEPTED MANUSCRIPT

freshness, quality, ripeness and shelf-life is one of the most promising industrial applications of e-nose technology (Hong et al., 2012; Li et al., 2014; Tian et al., 2012).

Musatov et al. (2010) evaluated the ability of an e-nose comprised of metal oxide microarray sensors and a linear discriminant analysis (LDA) based pattern recognition to evaluate meat freshness. Their results showed that an utmost of two exposures of standard meat samples to the e-nose were sufficient for the instrument to adequately recognize a freshly prepared meat. This study highlighted the fact that the e-nose is suitable for evaluation of product freshness in food industry. The e-nose is characterized by high level of accuracy and adaptability and relatively low cost. El Barbri et al. (2008) used an e-nose system to evaluate freshness of fish (sardines) in real-time. In order to make the instrument small and portable, six tin dioxide based gas sensors were used to analyze the fish samples. These authors also designed a data acquisition system using a microcontroller and portable computer to acquire and analyze real-time sensor data. The results indicated that the e-nose is a suitable instrument for evaluating the freshness of sardines.

E-nose is very useful instrument for the analysis of food freshness, quality, ripeness and shelf-life. However, it requires a large data set for modeling, calibration or learning step before actual measurements. Furthermore, the ability of e-nose to absorb volatile compounds emitted by the test samples greatly affects the detection ability.

Electronic Tongue

Another new method employed in intelligent frozen products pretreatment is the application of electronic tongue (Iliev et al., 2006). The electronic tongue system consists of sensors and complementing electronics designed to mimic human olfactory organ. The first electronic tongue designed for aroma analysis was introduced at the beginning of the 1980s and developed into better functioning form in 1990s (Rudnitskaya et al., 2002). With the advent of bionic and computer technologies, the electronic tongue as an artificial intelligence sensor has received increased interest in research and food quality analysis (Baldwin et al., 2011).

Taste assessment is an integral part of sensory evaluation of food and it has traditionally been performed by trained human panel. The concentration of different taste compounds in a sample is determined using a wide range of methods underpinned by physical, chemical, microbiological and sensory measurement principles. These traditional methods have good precision and reliability but they are destructive, time-consuming, and unsuitable for in situ or real-time monitoring. To overcome these pervasive disadvantages in quality assurance of foods, nondestructive, efficient, and on-line measurement and analysis methods are required for which the electronic tongue is one of the viable alternative (Escuder-Gilabert and Peris, 2010).

The electronic tongue is used for pretreatment of intelligently frozen products, especially for the evaluation of food freshness. Gil et al. (2008) developed a low-cost and easy to use electronic tongue device to evaluate the freshness of sea bream fish (Sparus aurata). The results showed that the electronic tongue can be utilized to evaluate the freshness of fish with confidence. In an yet another development, Han et al. (2014) developed a new method of detecting fish freshness nondestructively by combining electronic nose and electronic tongue. The test results showed that the combined system with appropriate chemometric analysis can be used to evaluate fish freshness conveniently and nondestructively. All of the above mentioned works laid the foundation for the application of electronic tongue to evaluate and classify the meat freshness.

The technology associated with electronic tongue is developing rapidly and making it more effective in distinguishing and quantifying sourness, sweetness, bitterness, and other basic tastes in food and edible products. Today's electronic tongue technology requires further improvement in speed, reproducibility, consistency and robustness. In addition, commonly encountered drift in sensor parameters, difficulty in calibration and standardization of electronic nose devices is impeding wider use of this system in food analysis. Significant research and development effort is required to enable the electronic tongue system to better replicate the human olfactory system.

INTELLIGENT PRODUCTION PROCESSES

The freezing process is a relatively complex, dynamic and nonlinear operation. It involves various physicochemical changes associated with heat (temperature) and mass (moisture) transfer. Industrial freezing systems consistently aim to design and develop intelligent processes which ensure a predefined quality in frozen products. There are still great limitations regarding

ACCEPTED MANUSCRIPT

the control of the critical intermediate steps and end-point processes in traditional quick-frozen systems which is impeding the production of high quality frozen products (De Beer et al., 2007). Thus it is imperative to introduce more advanced technologies which enable on-line monitoring and control of quality parameters and help optimize the production process.

A number of new technologies including digital simulation, confocal laser scanning spectroscopy, near infrared spectroscopy, nuclear magnetic resonance, and ultrasound (Table 2) have been employed recently in order to control the production process and to evaluate the quality of quick-frozen foods. These technologies are capable of providing reliable quality information throughout the production process, help improve the quality of frozen foods, and enhance the efficiency of quick-frozen process as well as saving energy (Jannot et al., 2004; Gieseler et al., 2007).

Digital Simulation Technology

In food processing, the design of better performing freezing process is an extremely important in guaranteeing the frozen food quality, reducing cost and prolonging the shelf-life of food materials. The new advances in digital computer technology are stimulating the development and use of various numerical simulations (Saad and Scott, 1997; Ramakrishnan et al., 2001).

Numerical simulation which combines the fundamental theory of freezing with computer technology is applied in the realm of food freezing to predict the freezing time, rate of freezing and the movement of freezing front within the product (Lemus-Mondaca et al., 2011). The application of numerical simulation reduces time and resource required for validation, effectively shortens the development cycle and associated cost of new products, and enables a faster response design changes (Huan et al., 2003). Studies have shown that the application of a suitable mathematical model together with numerical simulation of freezing process helps make the quick-freeing process of food materials significantly more efficient.

Moraga et al. (2012) compared the finite difference and finite volume numerical simulation methods to predict the temperature distribution in a cylindrical meat sample during freezing. In these simulations, the thermo-physical properties of meat, such as density, specific heat and thermal conductivity were assumed to be non-linear function of temperature. The simulation results obtained from both the numerical methods were compared with the experimental data. Results showed that the finite volume method was able to simulate the freezing process and to predict the freezing time of the sample more realistically. Santos et al. (2010) undertook simulation of a three-dimensional irregular frozen bakery products using finite element method. By comprising the simulation results with experimental data for chilling and freezing, the authors found that the finite element based numerical simulation can predict the complex quick-freezing process reasonably well.

The digital simulation technology has shown that it is capable of providing solution to the technical problems encountered during freezing of foods with high accuracy and considerable stability. However, it is difficult to solve the nonlinear mathematical problem when the thermophysical properties change with temperature as well as with time as the freezing process is temperature and time dependent. A number of physical phenomena, such as mass and heat transfer, the formation of nuclei and crystal growth, vitrification as well as mechanical strain occur during freezing. All of these phenomena directly affect the accuracy of the mathematical models; research in this area is not yet sufficiently mature.

Confocal Laser Technology

An understanding of the nature of microstructure of biological tissues during freezing helps to understand the mechanisms responsible for the freezing-induced injuries and allows monitoring of the progress of the freezing process. Freezing of tissue generally proceeds transiently and spatially in three-dimensions. Therefore, observation of all the three dimensions is required in real time to understand the changes in the microstructure of tissues during freezing. However, the commonly used optical and electron microscopic methods require fixation of the sample and only produce two-dimensional images and that there is an urgent need for technologies to address these problems. The confocal laser scanning microscopy (CLSM) provides is one of the best method to address the above problem. The CLSM was developed in the 1980s and it is increasingly being used ever since (Ishiguro and Horimizu, 2008). The main feature of CLSM is the capability of generating three-dimensional optical tomograms of biological materials at high spatial-resolution without fixing or slicing of a sample.

ACCEPTED MANUSCRIPT

Frozen dough is commonly used in the food industry; however, the structural changes due to the formation of large ice crystals impair its baking performance. Baier-Schenk et al. (Baier-Schenk et al., 2005) used a CLSM coupled with a freezing stage to observe the real-time changes in ice crystal structure during quick freezing of dough. The results showed that formation of ice crystals even at entrapped air-dough interface can be imaged by CLSM and that it is a powerful instrument for real time monitoring of the frozen foods including dough. Arellano et al. (2012) used confocal beam reflectance measurement (FBRM) technique on-line to track the ice crystal size during the manufacture of ice cream. The acquired data was used to adjust the manufacturing conditions and the so produced ice cream had smoother texture and better palatability. It was found that FBRM enables very good observation of ice crystal size in real time which can be used as a reference to adjust the freezing process.

It is worth noting that CLSM is capable of capturing three dimensional images online which can be used to monitor and control the freezing process. In order to better understand the freezing process and the mechanism of food freezing, CLSM it is better to use CLSM together with other equipment. CLSM technology also requires continuous improvement such as the development of new software in order to make it more versatile instrument for real time monitoring of freezing process of foods.

Near Infrared Spectroscopy Technology

Near infrared spectroscopy (NIR) is an electromagnetic radiation having wavelength between the visible and infrared, i.e. from 780 nm to 2526 nm. The principle of NIR spectral analysis is the use of each molecule's unique infrared absorption spectra to identify the molecules. Near-infrared reflectance spectroscopy (NIRS) is being widely used for routine analysis because it is highly efficient, inexpensive and does not generate waste (Barbin et al., 2013; Uddin et al., 2005).

United States began to explore the application of NIR in 1960s to determine the moisture, protein, fat contents of grains and plant leaves. Subsequently, the potential of near infrared spectroscopy (NIRS) as a fast and non-destructive method for detecting and quantifying moisture, protein, fat contents in foods was evaluated (Hernández-Hierro et al., 2014; Morsy and Sun, 2013). NIR can rapidly detect freezing parameters of food materials in real time and enables monitoring of the progress of freezing (Karlsdottir et al., 2014; Cheng et al., 2014). Tøgersen et al. (2003) measured the fat, moisture and protein contents of 55 frozen beef samples on-line buy using NIR. The results showed that on-line analysis of chemical composition of food materials makes it possible to better control the production process so that the end products with uniform and consistent quality could be produced.

Freeze drying process starts after most of the water in a material is converted into ice. This process consumes large amount of energy and takes long time to complete (Jiang et al., 2014). Hence, there is urgency in the industry to apply intelligent technologies to monitor the entire freezing process noninvasively and in real-time to maximize the process efficiency. De Beer et al. (2009) developed a process analytical technology (PAT) by incorporating Raman and NIR spectroscopic methods for rapid, non-invasive and online process monitoring. The results showed that the application of this combined method allowed continuous and significantly better monitoring of freeze drying process and minimizing the product defect and loss.

NIR spectroscopy can be adapted in in intelligent quick freezing processes. However, NIR spectroscopy can only determine the surface properties of a material due to short wavelength and it is insensitive to the presence of impurities. Furthermore, the NIR systems are relatively expensive as multiple sensors have to be installed for monitoring of freezing process in real time.

Nuclear Magnetic Resonance Technology

The quick-freezing process alters the internal moisture and solute distribution in food materials which leads to changes in important quality indicators, such as loss in water-holding capacity and increase in shear resistance of muscle (Sanchez-Alonso et al., 2014). If the moisture distribution can be measured rapidly during freezing, the freezing rate can be controlled which will then minimize the problem associated with the quick freezing. The conventional methods are able to measure the average moisture content but not its distribution within the heterogeneous food system.

Nuclear magnetic resonance (NMR) is capable of detecting the changes in the hydrogen atoms and, hence, it is capable of measuring the distribution of water within foods (Lee et al., 2002). Advantages of using MRI technology in quick-freezing of foods are that the measurement is fast, non-destructive, and non-invasive. NMR can provide the information regarding movement and distribution of moisture, and the physical state of foods (Piras et al., 2014).

Hills et al. (1997) investigated the distribution of unfrozen water and ice in cellular tissue using NMR for the first time. The results showed that the movement of ice front is not as sharp as is normally considered, rather that there is a broad spatial region over which ice and liquid water co-exist. The content of ice was shown to increase towards the outer surface of sample as the freezing progressed. Sanchez-Alonso et al. (2012) studied the application of low field (LF) NMR to estimate the quality of hake (Merluccius merluccius) which was frozen at -10oC for 6 months. The results showed that LF NMR can be used to determine the distribution of ice predict the changes in the quality of frozen foods.

However, NMR instruments are currently much more expensive than any other instruments used in characterizing frozen foods. The cost is the major limitation of using NMR for routine tests. However, as the NMR technology improves further and the cost becomes more affordable, this technology will be more frequently and broadly used as an intelligent characterization technology.

Ultrasound Technology

Food is a complex multiphase system containing many water soluble solids. The water content in food materials cannot be completely converted into ice. Hence, the ice content is one of the most important parameters of frozen foods (Carcione et al., 2007; Sigfusson et al., 2004). Ice content in frozen foods can be calculated using a number of methods. Differential scanning calorimeter (DSC) is able to measure the ice content accurately; however, it cannot be used for in-line measurement of ice and it is also a destructive method. MRI can be used to measure the ice content; however, it is technically complex and is expensive (Aparicio et al., 2008).

The transmission speed of ultrasound wave is significantly higher in solids than in liquid. These characteristics of ultrasound can be used for on-line monitoring of ice formation and movement of ice front. Ultrasound can be transmitted through opaque materials including most foods, packaging materials and process equipment. In addition, the ultrasound-based instruments are relatively cheap, robust, respond fast and also easy to automate.

Gülseren et al. (2008) investigated the propagation of ultrasound in partially frozen sucrose solutions with varying ice content which were degassed before freezing. They reported that different degree of attenuation of ultrasound signals occurred in in samples containing different percentage of ice. Abrupt changes in ultrasound velocity and attenuation indicated to the completion of melting which could be easily used to establish the phase boundary. Gülseren et al (2007) also measured the ultrasound velocity in aqueous solutions of sucrose and glycerol and orange juice as a function of concentration and temperature and estimated the ice content of these samples. They successfully estimated the ice content in these samples by measuring the speed of ultrasound through them.

Ultrasound technology can be applied for the development of intelligent products and processes. This technology is relatively inexpensive, robust, allows fast measurement and automation. The main limitation of this technology is that there is no explicit relationship between the ultrasound signals and the quality parameters of frozen foods. Thus, it is difficult to interpret the results and link them with quality attributes of the frozen foods.

INTELLIGENT COLD CHAIN LOGISTICS

According to Food and Agricultural Organization of United Nations (FAO), approximately 1.3 billion tons of food materials were lost or wasted globally in 2013 which was equivalent to the one-third of production of that year. One of the most important reasons for this extent of loss is the lack of proper temperature management during food transport. The loss of food during transportation can be significantly reduced if the temperature of the transported product is measured and supplied without delay (Jedermann et al., 2014; Tan and Zhang, 2014). For example, there are many food items in a frozen food logistics center at any time. If there is system that monitors the temperature and shows that one particular item is warmer than the others, then that particular item can be expressly processed or brought into the freezing warehouse.

Moreover, the contamination of frozen foods by microorganism can reduce their shelf-life and causes safety concern. Thus, there is a great interest in the food industry in developing accurate, cost-effective, and reliable methods or instruments to evaluate the microbial load real-time. An alternative concept to address this need is to develop intelligent cold chain logistics (Suppakul, 2012).

Intelligent cold chain logistics which make use of advances in sensor, communication and computer technologies is one of the best ways of temperature management during food transport (Trebar, 2015; Liao et al., 2015). In this system, the sensors measure the temperature, humidity, commodity information, and the operating status of refrigeration system in real time. This system is also able to automatically adjust the settings if necessary and helps save the labor cost, improves the product quality, and ensures the safety of the product. The data from the cold chain logistics system is transferred to internet so that the cold chain operator and the consumer can obtain the product information in real time (Kuo and Chen, 2010; Lu et al., 2013). The schematic diagram of an intelligent cold chain logistics system is presented in Fig.1.

Research is increasingly being conducted aiming to integrate the frozen food cold chain operation with the internet technology. Wu et al. (2013) proposed a cold chain scheme which integrates the internet, radio-frequency identification (RFID) and general packet radio service (GPRS) technologies, to monitor and manage the refrigerated transport trucks. These authors showed that this system is useful to improve the quality of fresh food and to ensure the food safety. Abad et al. (2009) compared the efficacy of RFID smart tags developed for real-time traceability and cold chain monitoring with commonly used temperature data loggers. The results showed that the RFID based system had advantages such as no need of human participation, no need of visible tags for reading, rapid data exchange, and higher resistance to to humidity and environmental conditions.

INTELLIGENT WAREHOUSE MANAGEMENTS

Cold storage is an important element that affects the production and distribution of frozen foods. The production and distribution capacity of any frozen food enterprise is directly affected by the capacity of cold storage. The application of the automated and intelligent warehouse management greatly reduces the disadvantages associated with the manual labor intensive operation, such as poor accuracy and operating efficiency, high equipment and product failing rate, and consumption of high energy (Hamm et al., 2008; Oró et al., 2014).

Intelligent storage management system makes use of automation, internet and other advanced technologies to track of changes in refrigerated storage temperatures and immediately alerts the operators whenever something goes wrong (Starfrost, 2009). The intelligent warehouse management is comprised of four important elements. The first element is intelligent cooling system which includes automatic operation and monitoring of cooling system, and control of the cold storage temperature. It also includes automatic air defrost technology. The second element is intelligent security systems which includes refrigeration system equipped with automatic measurement, protection, fault tips and alarm. The third element is intelligent information system which includes purchase, shipping and cold storage management. The goods are handled using 'first-in, first-out' basis and also the goods produced earlier will receive shipping priority. The fourth element is the intelligent transport system which includes automatic transfer of goods and automatically rejects goods which do not meet the system requirement in terms of size and weight (Table 3).

The application of intelligent cold storage system significantly reduces the labor costs. It also comes with many advantages such as better safety, energy saving, high efficiency and better environmental protection. Increasing number of researchers are working on these system as it represents the future trend in cold chain logistics.

Sun (2012) discussed the key differences between intelligent and non-intelligent cold storage systems and highlighted various problems associated with the research and development of automatic-control system of the cold storage. These problems included predictive control of process parameters, reliability of equipment, and local and global control. The author proposed that these problems could be addressed by introducing artificial neural network, genetic algorithms and the least squares methods. Kim et al. (2015) introduced a freshness assessing instrument consisting RFID and other sensors, This instrument could wirelessly provide the information of a product in real-time throughout the supply chain. In addition, they developed an algorithm, which process the information on cost, shelf-life, product quality, and it could be used to control the temperature and humidity levels during the frozen storage. This algorithm allowed

 ACCEPTED MANUSCRIPT

the users to dynamically control/alter the temperature and humidity during freezing and helped reduce storage cost and increase the product shelf life.

CONCLUSIONS AND FUTURE OUTLOOK

In this article, we reviewed and systematically analyzed the recent developments in smart freezing technology applied to fresh foods. Smart freezing technology is intended to improve the quality and increase the volume of frozen food products. Intelligent freezing technology incorporates and integrates the novel ideas and technologies applied to frozen product pretreatment, production processes, cold chain logistics as well as warehouse management. Several advanced sensing technologies applied to achieve intelligent automatic control of individual steps in freezing process are also briefly discussed.

The fresh food or perishable product market has experienced a rapid expansion in the past decade. The research in the smart freezing domain ought to be seeking to develop intelligent systems for the entire industry chain. The collaboration among the enterprises specializing in upstream (pre-harvest) and downstream (food processing) processing chain is vital in developing innovative technologies and applying those technologies in the smart freezing industry.

ACKNOWLEDGEMENTS

The authors thank the financial support from China National Natural Science Foundation (Contract No. 21176104) which has enabled us to carry out this study.

REFERENCES

Abad, E., Palacio, F., Nuin, M., Zárate, A. G. d., Juarros, A., Gómez, J. M., and Marco, S. (2009). RFID smart tag for traceability and cold chain monitoring of foods: Demonstration in an intercontinental fresh fish logistic chain. *Journal of Food Engineering*. **93** (4):394-399.

Aparicio, C., Otero, L., Guignon, B., Molina-García, A. D., and Sanz, P. D. (2008). Ice content and temperature determination from ultrasonic measurements in partially frozen foods. *Journal of Food Engineering*. **88** (2):272-279.

Arellano, M., Benkhelifa, H., Flick, D., and Alvarez, G. (2012). Online ice crystal size measurements during sorbet freezing by means of the focused beam reflectance measurement (FBRM) technology. Influence of operating conditions. *Journal of Food Engineering*. **113** (2):351-359.

Baier-Schenk, A., Handschin, S., von Schönau, M., Bittermann, A. G., Bächi, T., and Conde-Petit, B. (2005). In situ observation of the freezing process in wheat dough by confocal laser scanning microscopy (CLSM): Formation of ice and changes in the gluten network. *Journal of Cereal Science*. **42** (2):255-260.

Baldwin, E. A., Bai, J., Plotto, A., and Dea, S. (2011). Electronic noses and tongues: applications for the food and pharmaceutical industries. *Sensors (Basel)*. **11** (5):4744-4766.

Barbin, D. F., Sun, D.-W., and Su, C. (2013). NIR hyperspectral imaging as non-destructive evaluation tool for the recognition of fresh and frozen–thawed porcine longissimus dorsi muscles. *Innovative Food Science & Emerging Technologies*. **18**:226-236.

Barresi, A. A., Velardi, S. A., Pisano, R., Rasetto, V., Vallan, A., and Galan, M. (2009). In-line control of the lyophilization process. A gentle PAT approach using software sensors. *International Journal of Refrigeration*. **32** (5):1003-1014.

Bosca, S., Barresi, A. A., and Fissore, D. (2013). Use of a soft sensor for the fast estimation of dried cake resistance during a freeze-drying cycle. *Int J Pharm*. **451** (1-2):23-33.

Campanone, L. A., Roche, L. A., Salvadori, V. O., and Mascheroni, R. H. (2002). Monitoring of Weight Losses in Meat Products during Freezing and Frozen Storage. *Food Science and Technology International*. **8** (4):229-238.

Carcione, J. M., Campanella, O. H., and Santos, J. E. (2007). A poroelastic model for wave propagation in partially frozen orange juice. *Journal of Food Engineering*. **80** (1):11-17.

Cheng, J.-H., Qu, J.-H., Sun, D.-W., and Zeng, X.-A. (2014). Visible/near-infrared hyperspectral imaging prediction of textural firmness of grass carp (Ctenopharyngodon idella) as affected by frozen storage. *Food Research International*. **56**:190-198.

Chong, V., Kondo, N., Ninomiya, K., Nishi, T., Monta, M., Namba, K., and Zhang, Q. (2008). Features extraction for eggplant fruit grading system using machine vision. *Applied engineering in agriculture*. **24** (5):675-684.

Cuibus, L., Castro-Giráldez, M., Fito, P. J., and Fabbri, A. (2014). Application of infrared thermography and dielectric spectroscopy for controlling freezing process of raw potato. *Innovative Food Science & Emerging Technologies*. **24**:80-87.

Davies, E. R. (2009). The application of machine vision to food and agriculture: a review. *The Imaging Science Journal*. **57** (4):197-217.

De Beer, T., Allesø, M., Goethals, F., Coppens, A., Vander Heyden, Y., Lopez De Diego, H., Rantanen, J., Verpoort, F., Vervaet, C., and Remon, J. P. (2007). Implementation of a process analytical technology system in a freeze-drying process using Raman spectroscopy for in-line process monitoring. *Analytical chemistry*. **79** (21):7992-8003.

De Beer, T. R., Vercruysse, P., Burggraeve, A., Quinten, T., Ouyang, J., Zhang, X., Vervaet, C., Remon, J. P., and Baeyens, W. R. (2009). In-line and real-time process monitoring of a freeze drying process using Raman and NIR spectroscopy as complementary process analytical technology (PAT) tools. *J Pharm Sci*. **98** (9):3430-3446.

Du, C.-J., and Sun, D.-W. (2006). Learning techniques used in computer vision for food quality evaluation: a review. *Journal of Food Engineering*. **72** (1):39-55.

El Barbri, N., Llobet, E., El Bari, N., Correig, X., and Bouchikhi, B. (2008). Application of a portable electronic nose system to assess the freshness of Moroccan sardines. *Materials Science and Engineering: C*. **28** (5-6):666-670.

Escuder-Gilabert, L., and Peris, M. (2010). Review: highlights in recent applications of electronic tongues in food analysis. *Anal Chim Acta*. **665** (1):15-25.

FAO (2013) Food Wastage Footprint: Impacts on Natural Resources. http://reliefweb.int/report/world/food-wastage-footprint-impacts-natural-resources.

Gülseren, İ., and Coupland, J. N. (2007). Ultrasonic velocity measurements in frozen model food solutions. *Journal of Food Engineering*. **79** (3):1071-1078.

Gülseren, İ., and Coupland, J. N. (2008). Ultrasonic properties of partially frozen sucrose solutions. *Journal of Food Engineering*. **89** (3):330-335.

 ACCEPTED MANUSCRIPT

Geidobler, R., and Winter, G. (2013). Controlled ice nucleation in the field of freeze-drying: fundamentals and technology review. *Eur J Pharm Biopharm*. **85** (2):214-222.

Giannakourou, M., and Taoukis, P. (2002). Systematic application of time temperature integrators as tools for control of frozen vegetable quality. *Journal of food science*. **67** (6):2221-2228.

Gieseler, H., Kramer, T., and Pikal, M. J. (2007). Use of manometric temperature measurement (MTM) and SMART freeze dryer technology for development of an optimized freeze-drying cycle. *J Pharm Sci*. **96** (12):3402-3418.

Gil, L., Barat, J. M., Garcia-Breijo, E., Ibañez, J., Martínez-Máñez, R., Soto, J., Llobet, E., Brezmes, J., Aristoy, M. C., and Toldrá, F. (2008). Fish freshness analysis using metallic potentiometric electrodes. *Sensors and Actuators B: Chemical*. **131** (2):362-370.

Hamm, T. B. E., Zanuzo, M. R., Lucchetta, L., Ferri, V. C., Antunes, P. L., Girardi, C. L., Fachinello, J. C., Silva, J. A., Hooko, V., and Rombaldi, C. V. (2008). Cold storage and classification management in peach decay cv granada. *Revista Brasileira de Fruticultura*. **30** (4):885-891.

Han, F., Huang, X., Teye, E., Gu, F., and Gu, H. (2014). Nondestructive detection of fish freshness during its preservation by combining electronic nose and electronic tongue techniques in conjunction with chemometric analysis. *Anal Methods*. **6** (2):529-536.

Hernández-Hierro, J. M., Esquerre, C., Valverde, J., Villacreces, S., Reilly, K., Gaffney, M., González-Miret, M. L., Heredia, F. J., O'Donnell, C. P., and Downey, G. (2014). Preliminary study on the use of near infrared hyperspectral imaging for quantitation and localisation of total glucosinolates in freeze-dried broccoli. *Journal of Food Engineering*. **126**:107-112.

Hills, B., Goncalves, O., Harrison, M., and Godward, J. (1997). Real time investigation of the freezing of raw potato by NMR microimaging. *Magnetic resonance in chemistry*. **35** (13):S29-S36.

Hong, X., Wang, J., and Hai, Z. (2012). Discrimination and prediction of multiple beef freshness indexes based on electronic nose. *Sensors and Actuators B: Chemical*. **161** (1):381-389.

Huan, Z., He, S., and Ma, Y. (2003). Numerical simulation and analysis for quick-frozen food processing. *Journal of Food Engineering*. **60** (3):267-273.

Iliev, B., Lindquist, M., Robertsson, L., and Wide, P. (2006). A fuzzy technique for food- and water quality assessment with an electronic tongue. *Fuzzy Sets and Systems*. **157** (9):1155-1168.

Ishiguro, H., and Horimizu, T. (2008). Three-dimensional microscopic freezing and thawing behavior of biological tissues revealed by real-time imaging using confocal laser scanning microscopy. *International Journal of Heat and Mass Transfer*. **51** (23-24):5642-5649.

James, C., Purnell, G., and James, S. J. (2015). A Review of Novel and Innovative Food Freezing Technologies. *Food and Bioprocess Technology*. DOI 10.1007/s11947-015-1542-8

Jannot, Y., Batsale, J.-C., and Chausi, B. t. (2004). Study of a simple transient non-intrusive sensor for internal temperature estimation during food product freezing. *International Journal of Refrigeration*. **27** (6):612-620.

Jedermann, R., Potsch, T., and Lloyd, C. (2014). Communication techniques and challenges for wireless food quality monitoring. *Philos Trans A Math Phys Eng Sci*. **372** (2017):20130304.

Jiang, H., Zhang, M., Mujumdar, A. S., and Lim, R. X. (2014). Comparison of drying characteristic and uniformity of banana cubes dried by pulse-spouted microwave vacuum drying, freeze drying and microwave freeze drying. *J Sci Food Agric*. **94** (9):1827-1834.

Karlsdottir, M. G., Arason, S., Kristinsson, H. G., and Sveinsdottir, K. (2014). The application of near infrared spectroscopy to study lipid characteristics and deterioration of frozen lean fish muscles. *Food Chem*. **159**:420-427.

Kiani, H., and Sun, D.-W. (2011). Water crystallization and its importance to freezing of foods: A review. *Trends in Food Science & Technology*. **22** (8):407-426.

Kim, W. R., Aung, M. M., Chang, Y. S., and Makatsoris, C. (2015). Freshness Gauge based cold storage management: A method for adjusting temperature and humidity levels for food quality. *Food Control*. **47**:510-519.

Kuo, J.-C., and Chen, M.-C. (2010). Developing an advanced Multi-Temperature Joint Distribution System for the food cold chain. *Food Control*. **21** (4):559-566.

Laguerre, O., Hoang, H. M., and Flick, D. (2013). Experimental investigation and modelling in the food cold chain: Thermal and quality evolution. *Trends in Food Science & Technology*. **29** (2):87-97.

Lee, S., Cornillon, P., and Kim, Y. (2002). Spatial Investigation of the Non- frozen Water Distribution in Frozen Foods using NMR SPRITE. *Journal of food science*. **67** (6):2251-2255.

ACCEPTED MANUSCRIPT

Lemus-Mondaca, R. A., Vega-Gálvez, A., and Moraga, N. O. (2011). Computational Simulation and Developments Applied to Food Thermal Processing. *Food Engineering Reviews*. **3** (3-4):121-135.

Li, B., and Sun, D.-W. (2002). Novel methods for rapid freezing and thawing of foods–a review. *Journal of Food Engineering*. **54** (3):175-182.

Li, H. (2013). Application Research of Food Quality Detection Based on Computer Vision. *Journal of Computers*. **8** (7)):1758-1762.

Li, H., Chen, Q., Zhao, J., and Ouyang, Q. (2014). Non-destructive evaluation of pork freshness using a portable electronic nose (E-nose) based on a colorimetric sensor array. *Analytical Methods*. **6** (16):62-71.

Liang, Y.-T., and Chiou, Y.-C. (2009) Machine vision-based automatic raw fish handling and weighing system of Taiwan Tilapia. In: Next-Generation Applied Intelligence. *Springer*, pp 711-720.

Liao, W.-J., Lien, T.-W., Hsiao, B.-R., Wang, H.-S., Yang, C.-F., Tarng, J.-H., Nien, C.-C., and Chiu, T.-C. (2015). Sensor Integrated Antenna Design for Applications in Cold Chain Logistic Services. *IEEE Transactions on Antennas and Propagation*. **63** (2) :727-735.

Lu, L., Zheng, W., Lv, Z., and Tang, Y. (2013). Development and Application of Time-temperature Indicators Used on Food during the Cold Chain Logistics. *Packaging Technology and Science*. **26**:80-90.

Moraga, N. O., Vega-Gálvez, A., and Lemus-Mondaca, R. (2012). Numerical Simulation of Experimental Freezing Process of Ground Meat Cylinders. *International Journal of Food Engineering*. 7 (6) :1-20.

Morsy, N., and Sun, D. W. (2013). Robust linear and non-linear models of NIR spectroscopy for detection and quantification of adulterants in fresh and frozen-thawed minced beef. *Meat Sci*. **93** (2):292-302.

Musatov, V. Y., Sysoev, V. V., Sommer, M., and Kiselev, I. (2010). Assessment of meat freshness with metal oxide sensor microarray electronic nose: A practical approach. *Sensors and Actuators B: Chemical*. **144** (1):99-103.

Oró, E., Miró, L., Farid, M. M., Martin, V., and Cabeza, L. F. (2014). Energy management and CO2 mitigation using phase change materials (PCM) for thermal energy storage (TES) in cold storage and transport. *International Journal of Refrigeration*. **42**:26-35.

Patel, K. K., Kar, A., Jha, S. N., and Khan, M. A. (2012). Machine vision system: a tool for quality inspection of food and agricultural products. *J Food Sci Technol*. **49** (2):123-141.

Pearce, T. C., Schiffman, S. S., Nagle, H. T., and Gardner, J. W. (2006) Handbook of machine olfaction: electronic nose technology. *John Wiley & Sons*, http://www.le.ac.uk/engineering/tcp1/book/content.htm

Petzold, G., and Aguilera, J. M. (2009). Ice Morphology: Fundamentals and Technological Applications in Foods. *Food Biophysics*. **4** (4):378-396.

Piras, C., Scano, P., Locci, E., Sanna, R., and Marincola, F. C. (2014). Analysing the effects of frozen storage and processing on the metabolite profile of raw mullet roes using (1)H NMR spectroscopy. *Food Chem*. **159**:71-79.

Ramakrishnan, S., Wysk, R. A., and Prabhu, V. V. Prediction of process parameters for intelligent control of freezing tunnels using simulation. In: Simulation Conference, 2001. Proceedings of the Winter, 2001. IEEE, pp 888-895

Rodríguez-Pulido, F. J., Gordillo, B., Lourdes González-Miret, M., and Heredia, F. J. (2013). Analysis of food appearance properties by computer vision applying ellipsoids to colour data. *Computers and Electronics in Agriculture*. **99**:108-115.

Rudnitskaya, A. L. A., Seleznev, B., and Vlasov, Y. (2002). Recognition of liquid and flesh food using anelectronic tongue'. *International Journal of Food Science & Technology*. **37** (4):375-385.

Saad, Z., and Scott, E. P. (1997). Analysis of accuracy in the numerical simulation of the freezing process in food materials. *Journal of Food Engineering*. **31** (1):95-111.

Sanchez-Alonso, I., Martinez, I., Sanchez-Valencia, J., and Careche, M. (2012). Estimation of freezing storage time and quality changes in hake (Merluccius merluccius, L.) by low field NMR. *Food Chem*. **135** (3):1626-1634.

Sanchez-Alonso, I., Moreno, P., and Careche, M. (2014). Low field nuclear magnetic resonance (LF-NMR) relaxometry in hake (Merluccius merluccius, L.) muscle after different freezing and storage conditions. *Food Chem*. **153**:250-257.

Santos, M. V., Vampa, V., Califano, A., and Zaritzky, N. (2010). Numerical simulations of chilling and freezing processes applied to bakery products in irregularly 3D geometries. *Journal of Food Engineering*. **100** (1):32-42.

Sigfusson, H., Ziegler, G. R., and Coupland, J. N. (2004). Ultrasonic monitoring of food freezing. *Journal of Food Engineering*. **62** (3):263-269.

Simpson, R., Teixeira, A., and Almonacid, S. (2007). Advances with intelligent on-line retort control and automation in thermal processing of canned foods. *Food Control*. **18** (7):821-833.

 ACCEPTED MANUSCRIPT

Starfrost (2009) Exposing the myths of mehanical freezing. http://www.starfrost.com/case-studies/43-case-studies/160-cryogenic-v-mechanical-freezing-case-study-32.html.

Sun, D.-W. (2004). Computer vision—an objective, rapid and non-contact quality evaluation tool for the food industry. *Journal of Food Engineering*. **61** (1):1-2.

Sun, Y. (2012). Intelligent Operation and Control of Refrigeration Craft in Cold Storage. *Advanced Materials Research*. **468-471**:1827-1830.

Suppakul, P. (2012). Intelligent packaging. *Handbook of frozen food processing and packaging CRC Press, Boca Raton*. **5**:835-857.

Søgersen, G., Arnesen, J., Nilsen, B., and Hildrum, K. (2003). On-line prediction of chemical composition of semi-frozen ground beef by non-invasive NIR spectroscopy. *Meat Sci*. **63** (4):515-523.

Tan, Y. B., and Zhang, Q. Y. (2014). Food Cold Chain Transportation Management Based on Grid Technology. *Applied Mechanics and Materials*. **543-547**:4540-4542.

Tian, X. Y., Cai, Q., and Zhang, Y. M. (2012). Rapid classification of hairtail fish and pork freshness using an electronic nose based on the PCA method. *Sensors (Basel)*. **12** (1):260-277.

Trebar, M. (2015). RFID Logistic Management with Cold Chain Monitoring–Cold Store Case Study. *International Scholarly and Scientific Research & Innovation*. **9** (3):643-646.

Uddin, M., Okazaki, E., Turza, S., Yumiko, Y., Tanaka, M., and Fukuda, Y. (2005). Non- destructive Visible/NIR Spectroscopy for Differentiation of Fresh and Frozen- thawed Fish. *Journal of food science*. **70** (8):c506-c510.

ACCEPTED MANUSCRIPT

Vijayarekha, K. (2012). Machine vision application for food quality: a review. *Res J Appl Sci, Eng Technol*. **4** (24):5453-5458.

Wilson, A. D., and Baietto, M. (2009). Applications and advances in electronic-nose technologies. *Sensors (Basel)*. **9** (7):5099-5148.

Wilson, A. D., and Baietto, M. (2011). Advances in electronic-nose technologies developed for biomedical applications. *Sensors (Basel)*. **11** (1):1105-1176.

Wu, D., and Sun, D.-W. (2013). Colour measurements by computer vision for food quality control – A review. *Trends in Food Science & Technology*. **29** (1):5-20.

Wu, L. Z., and Zhao, Y. (2013). Cold Chain Logistics Temperature Monitoring System Based on Internet of Things Technology. *Applied Mechanics and Materials*. **416-417**:1969-1973.

Zutphen, H. v. (2014) Specialists in artificial olfaction. http://www.enose.nl/rd/technology/.

Table 1 Intelligent analysis technologies used in the pretreatment of frozen foods

Methods	**Function**	**Advantages**	**Limitations**	**Ref.**
Computer vision	Automation grading and quality assessment of tilapias and eggplants	Non-destructive, cost-effective and high efficiency	Needs large computational resource for image processing	Liang et al. (2009) Chong et al. (2008)
Electronic nose	Evaluation of freshness of fish meat	Non-destructive, cost-effective and high efficiency	Large number of previously measured data is required for calibration (learning) and modeling	Musatov et al. (2010) El Barbri et al. (2008)
Electronic tongue	Evaluation of freshness of sea (Sparus aurata) bream fish	Conveniently, cost-effective and high efficiency	Large number of previously measured data is required for calibration	Gil et al. (2008) Han et al. (2014)

 ACCEPTED MANUSCRIPT

			(learning) and modeling	

 ACCEPTED MANUSCRIPT

Table 2 Intelligent analysis technologies used in the production of frozen foods

Technologies	**Function**	**Advantages**	**Limitations**	**Ref.**
Digital simulation	Simulation and prediction of complex quick-freezing process	Reduces analysis times, shortens the development cycle of new products, and decreases the development costs of new products	Very limited industry application	Moraga et al. (2012) Santos et al. (2010)
Confocal laser scanning spectroscopy	Monitoring of frozen process in real time	Produces 3D optical tomograms of biological materials with high spatial-resolution in real time	Technically complex and expensive	Baier-Schenk et al. (2005) Tøgersen et al. (2003)
Near infrared	On-line analysis of the chemical composition	Efficient, low cost, and no	Only the surface moisture of material	Tøgersen et al. (2003)

 ACCEPTED MANUSCRIPT

spectroscopy	of food raw materials	pollution	can be determined due to its short wavelength, not affected by impurities	De Beer et al. (2009)
Nuclear magnetic resonance	Monitoring movement of moisture and the distribution information in the sample	Fast, non-destructive, and non-invasive	Technically complex and expensive	Hills et al. (1997) Sanchez-Alonso et al. (2012)
Ultrasound	Calculation ice content of the sample on-line	Cheap, robust, rapid and easy to automate measurements	The relationship between ultrasound signals and the quality parameters of freezing food is indirect	Gülseren et al. (2007, 2008)

ACCEPTED MANUSCRIPT

Table 3 The key elements of intelligent warehouse management system

Key elements	**Key features**	**Example**
Intelligent cooling system	Automatic monitoring of cooling operation, and control of cold storage temperature	Automatic air defrost technology
Intelligent security systems	Automatic protection of refrigeration system. Automatic fault tips, alarm and measurement	Automatic sprinkler
Intelligent information systems	Purchase management, shipping management, and cold storage management	First-in, first out. Priority shipping of goods produced in earlier date
Intelligent transport systems	Automatic transfer of goods	Automatic rejection of goods not meeting system requirements in terms of size and weight

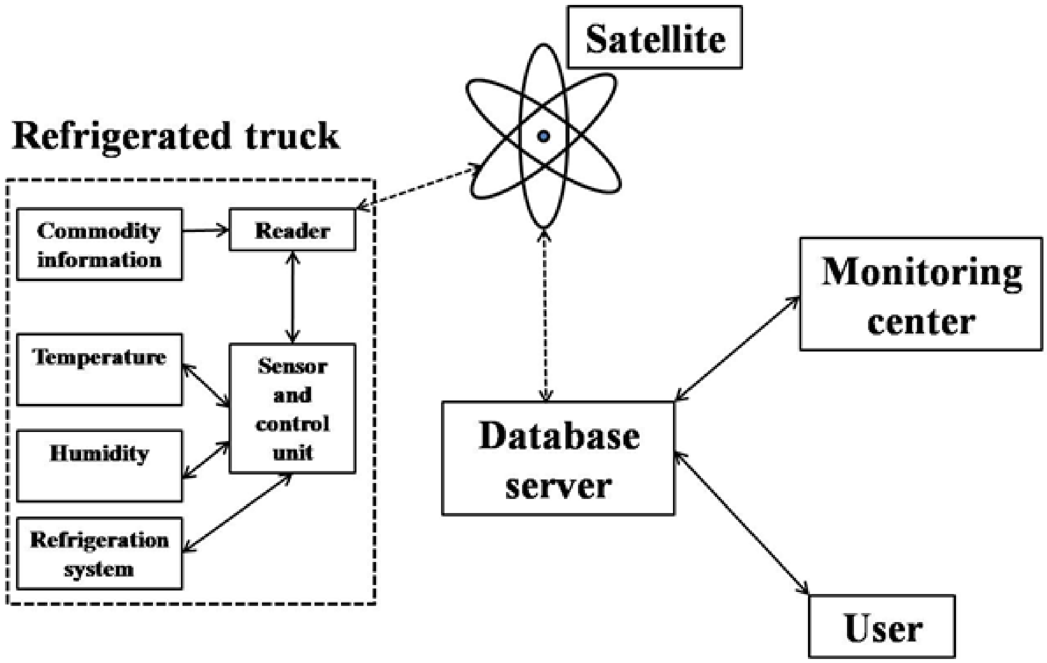

Fig.1. Schematic diagram of an intelligent cold chain logistics system

ACCEPTED MANUSCRIPT