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Development and evaluation on a Wireless Multi-Gas-Sensors System for improving traceability and transparency of table grape cold chain

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ABSTRACT: *There is increasing requirement to improve traceability and transparency of table grapes cold chain. Key traceability indicators include temperature, humidity and gas microenvironments (e.g., CO₂, O₂, and SO₂) based on table grape cold chain management need to be monitored and controlled. This paper presents a Wireless Multi-Gas-Sensors System (WGS²) as an effective real-time cold chain monitoring system, which consists of three units: (1) the WMN which applies the 433MHz as the radio frequency to increase the transmission performance and forms a wireless sensor network; (2) the WAN which serves as the intermediary to connect the users and the sensor nodes to keep the sensor data without delay by the GPRS remote transmission module; (3) the signal processing unit which contains a embedded software to drive the hardware to normal operation and shelf life prediction for table grapes. Then the study evaluates the WGS² in a cold chain scenario and analyses the monitoring data. The results show that the WGS² is effective in monitoring quality, and improving transparency and traceability of table grape cold chains. Its deploy ability and efficiency in implantation can enable the establishment of a more efficient, transparent and traceable table grape supply chain.*

Keywords: Table grapes; gas microenvironment monitoring; shelf life prediction; cold chain; traceability and transparency

1. Introduction

The need for traceability and transparency of agro-food chains was driven by numerous recent food safety scandals which triggered growing attentions from governments and consumers. In response, many countries have introduced stricter regulations and smarter industrial development strategies to enable better tracking and tracing of agricultural food products (Aung et al., 2014; Narsimhalu et al, 2015; Gogou et al, 2015; Defraeye et al., 2016). The development of IoT (Internet of Things) and WSN (Wireless Sensor Network) technologies provided more integrated and effective approaches to leverage the huge amount of complex information available nowadays and to enable more effective and easier monitoring of food supply chains (Dehghannya et al., 2010; Pang et al, 2010; Xiao et al, 2016).

Wireless multi-sensors network is a new technology that combines multi-sensors technology and WSN, embedded computing, networking and wireless communication, and distributed

39 processing. It senses and collects information of monitoring objects and sends information to the
40 end-user via wireless and multi-hop network, which has many advantages as low maintenance cost,
41 higher mobility, better flexibility, and fast deployment in special occasions. It is reportedly to
42 benefit quality and safety of products and supply chain optimization and enable quick product
43 recalls of perishable food, which has been adopted in many sectors, such as fruit cold chain (e.g.,
44 Ruiz-Garcia et al, 2008; Guo et al, 2011; Xiao et al, 2015; Wang et al, 2015), aquatic products
45 chain (e.g., Qi et al, 2011 & 2014; Ping-Ho et al, 2013; Xiao et al, 2016), winemaking monitoring
46 (e.g., Di Gennaro et al, 2013; Zhang et al, 2015), greenhouse management (e.g., Gnanavel et al,
47 2016; Jiang et al, 2016), and crops planting (e.g., Garcia-Sanchez et al, 2011; Coates et al, 2013).
48 However, most of these solutions focused on temperature and relative humidity. Few previous
49 research described traceability of gas atmosphere, such as ethylene gas (Jedermann et al, 2006).

50 Given that the cold chain is the key process in the agri-food supply chain to ensure food
51 quality and freshness, key traceability indicators including temperature and other environmental
52 conditions under which the fresh and frozen produces are stored and transported need to be closely
53 monitored and controlled (Bobelyn et al, 2006; Han et al, 2012; Trebar et al, 2015). Unlike other
54 fruits, such as bananas and pears, table grapes deteriorate instead of ripening after harvest. For
55 postharvest decay control and shelf life prolonging, table grapes in the cold chain not only require
56 a temperature-controlled environment, but also some special treatments: for example, fumigated
57 by SO₂ gas or SO₂ generator pads which contain sulfite salt or sodium metabisulphite. As a result,
58 gas atmosphere in the table grape cold chain can be complex: CO₂ and O₂ gases come from the
59 atmosphere and the respiration of table grapes; SO₂ gas slowly released by SO₂ generator pads
60 after reaction with water vapour from humid air.

61 The increased CO₂ concentration or low O₂ concentration in the cold chain environment will
62 slow down the rate of physiological activity by reducing respiration rate of table grapes, which
63 affects the quality of table grapes significantly (Deng et al, 2005; Costa et al, 2011). SO₂ as
64 exogenous gas will prolong table grape storage by significantly retarding the growth of those
65 pathogenic fungi and preserving the fruit's original flavour and nutrients (Youssef et al, 2015;
66 Carter et al, 2015). Therefore, it is important to monitor SO₂, CO₂ and O₂ gases in the cold chain
67 which significantly affect the quality and safety of table grape. The capability of monitoring SO₂,
68 CO₂ and O₂ gases concentration in real-time will improve shelf-life prediction and the traceability
69 and transparency of the table grape cold chains. Extant literature review suggests that there are no
70 previous studies, which developed effective gas concentration monitoring systems in table grape
71 cold chains. This study, therefore, concentrates on developing a Wireless Multi-Gas-Sensors
72 System (WGS²) as an effective real-time table grape cold chain monitoring system.

73 This paper is organized as follows: Section 2 presents system analysis and architecture design
74 of WGS². Multi-gas-sensors development and signal processing for table grape cold chain are
75 demonstrated in Section 3. Section 4 details the WGS² system testing and evaluation in a real cold
76 chain logistics. This paper concludes with the discussions and suggestions for future research.

77 2. WGS² System Analysis and Architecture Design

78 2.1 cold chain example and field study method

79 In this research, two sample table grape cold chains are discussed to illustrate a long distance
80 chain and a short distance chain in China (see Fig.1). One sample table grape cold chain is from
81 Xinjiang province to Guangdong province in China. Another sample table grape cold chain is
82 from Hebei Province to Tianjin city in the North China.



83

84 Fig.1 The mapping for table grape cold chain

85 A systematic literature review, a field observation and interview were conducted to extract
86 the monitoring requirements of the WGS² and the factors that may influence the safety & quality
87 of table grape cold chain. The interviews were conducted face-to-face with 5 cold chain managers
88 and 20 infield cold chain workers from both example cold chains over 7 days. All of the
89 interviewees have over 3 years of working experience in the table grape cold chains. Each
90 interview lasted for around 40 minutes. Interviewees were asked about *their working routine*;
91 *whether they record gas information*; *how they estimate the shelf life of table grapes*; *whether they*
92 *knew about wireless gas monitoring and if so whether they have used it before*; *and what kind of*
93 *information they think are supply chain traceability information.*

94 2.2 Business flow analysis and traceability information requirements of the 95 WGS²

96 The field study also helped to clarify the business flow of the table grape cold chain. The
97 business flow of a typical 'seedless grape' cold chain is shown in Fig. 2. The cold chain process
98 starts from the farm and ends with on-the-shelf retail with the following stages:

- 99 ● Step 1: Grape harvesting. Usually the harvesting happens during a non-rainy cooler times of
100 the day (<25°C) (usually early morning) to prolong the cooling time of the table grapes.
- 101 ● Step 2: Ordinary/Refrigerated transportation. Table grapes are transported immediately via
102 ordinary or refrigerated transport to the refrigeration warehouse for further processing.
103 During this process, table grapes are surrounded by normal CO₂ and O₂ gas in the atmosphere.
104 Some of the table grapes are directly transported to nearby markets for display and sale.

- 105 ● Step 3 & 4: Table grape precooling and cold storage. In the warehouse, table grapes will
 106 firstly be packed in sealed packages fitted with SO₂ generator pad or powder, which reacts
 107 with water vapour from the humid environment and produce a continuous emission of low
 108 SO₂ concentrations within the packages. Then table grapes are precooled for 12-24 hours at
 109 -1~0°C. Finally, table grapes are kept in cold storage until further transportation to the market
 110 for display and sale.
- 111 ● Step 5: Transporting the table grapes to the market or wholesale store. In this process, table
 112 grapes are transported using refrigerated trucks. During this process temperature and the gas
 113 fluctuations, such as SO₂, CO₂ or O₂, may cause safety and quality problems issues such as
 114 brown stain, botrytis cinerea during the cold chain logistics process.
- 115 ● Step 6: Temporary storage for display and sale. The grapes are temporarily stored for display
 116 and sale by wholesalers or retailers.

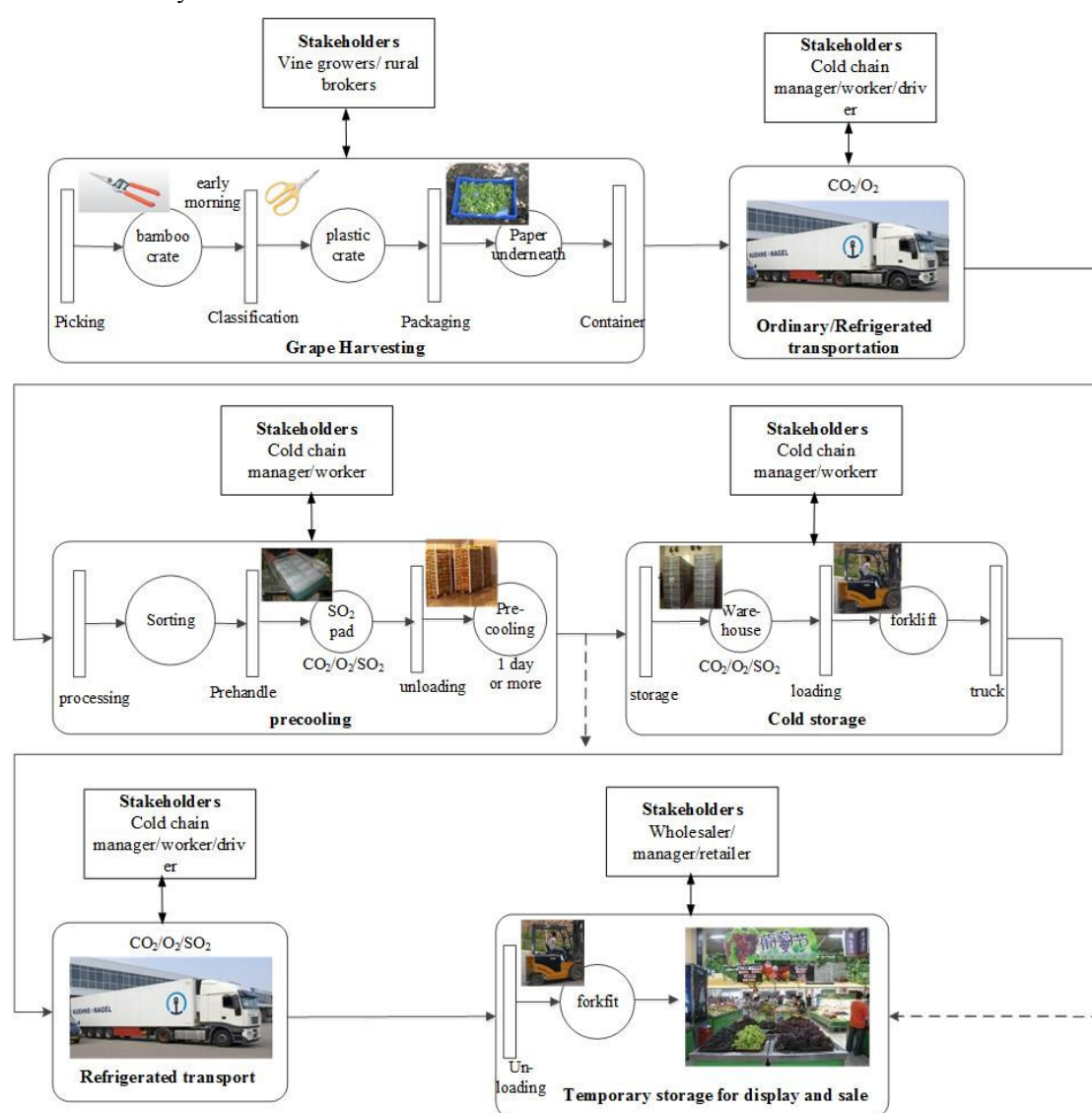


Fig. 2 Process and information flow of table grape cold chain

Multiple steps are involved in table grape cold chain from the farm to display. Changes in temperature, relative humidity and gaseous at any stage can greatly affect the quality of the fruit.

121 Therefore, it is essential to extract the traceability information from the table grape cold chain.
 122 Based on the interview responses and the extant literature review (Zhang et al, 2010; Palou et al,
 123 2010; Ustun et al, 2012; Champa et al, 2015; Thakur et al, 2015; Koutsimanis et al, 2015;
 124 Zubeldia et al, 2016), key traceability indicators and quality indicators are identified. Table 1. lists
 125 traceability information and requirement of the WGS². The critical traceability indicators
 126 including the temperature, the relative humidity, volume fractions of SO₂ gas, CO₂ gas and O₂ gas
 127 in a fixed time. Moreover, other key quality indicators mainly included SSC (Soluble Solids
 128 Content), pH values, brown stain, and shelf life. The WGS² are required to be able to acquire
 129 real-time information on temperature, relative humidity, O₂, CO₂, SO₂ in the cold chain in a
 130 remote centre, to be able to predict the shelf life of the table grapes, to be user-friendly in
 131 operation for quality assurance, and to be implemented at low cost.

132 Table 1. Traceability information and requirement of the WGS²

Steps of cold chain	Key actions	Key environment indicators	Preferred Level Criteria	Stakeholders	Main user	Key quality indicator
Harvesting	Reduce grape ripeness, cooling, no dew, pack only one layer in box	T, RH	T<25°C	Vine growers/rural brokers	Vine growers	Sugar level (sweetness), acid level (acidity taste)
Ordinary/Refrigerated transportation	Fast transportation, less vibration	T, RH, O ₂ , CO ₂	-	Cold chain manager/worker/driver	driver	SSC, PH level, brown stain
Precooling	Fast cooled within 12-24 hours, filled with SO ₂	T, RH, O ₂ , CO ₂ , SO ₂	T: -1~0°C RH: 90-95%	Cold chain manager/worker	Cold chain worker	SSC, PH level, brown stain
Cold storage	Ventilation, low temperature, high humidity	T, RH, O ₂ , CO ₂ , SO ₂	T: -1~0°C RH: 90-95%	Cold chain manager/worker	Cold chain worker	SSC, PH level, brown stain, shelf life
Refrigerated transportation	Fast transportation, less vibration, low temperature	T, RH, O ₂ , CO ₂ , SO ₂	T: -1~0°C RH: 90-95%	Cold chain manager/worker/driver	driver	SSC, PH level, brown stain, shelf life
Temporary storage for display and sale	Cooled storage, handled carefully	T, RH, O ₂ , CO ₂ , SO ₂	T: -1~0°C RH: 85-95%	Wholesaler/manager/retailer	Shop manager/staff	SSC, PH level, brown stain, shelf life

133 Notes: T-temperature, RH-relative humidity

134

2.3 System Architecture Design of WGS²

135

Based on the traceability information requirements identified from the field observation and the field survey, the WGS² structure was developed, which consists of three basic units (see Fig.3):

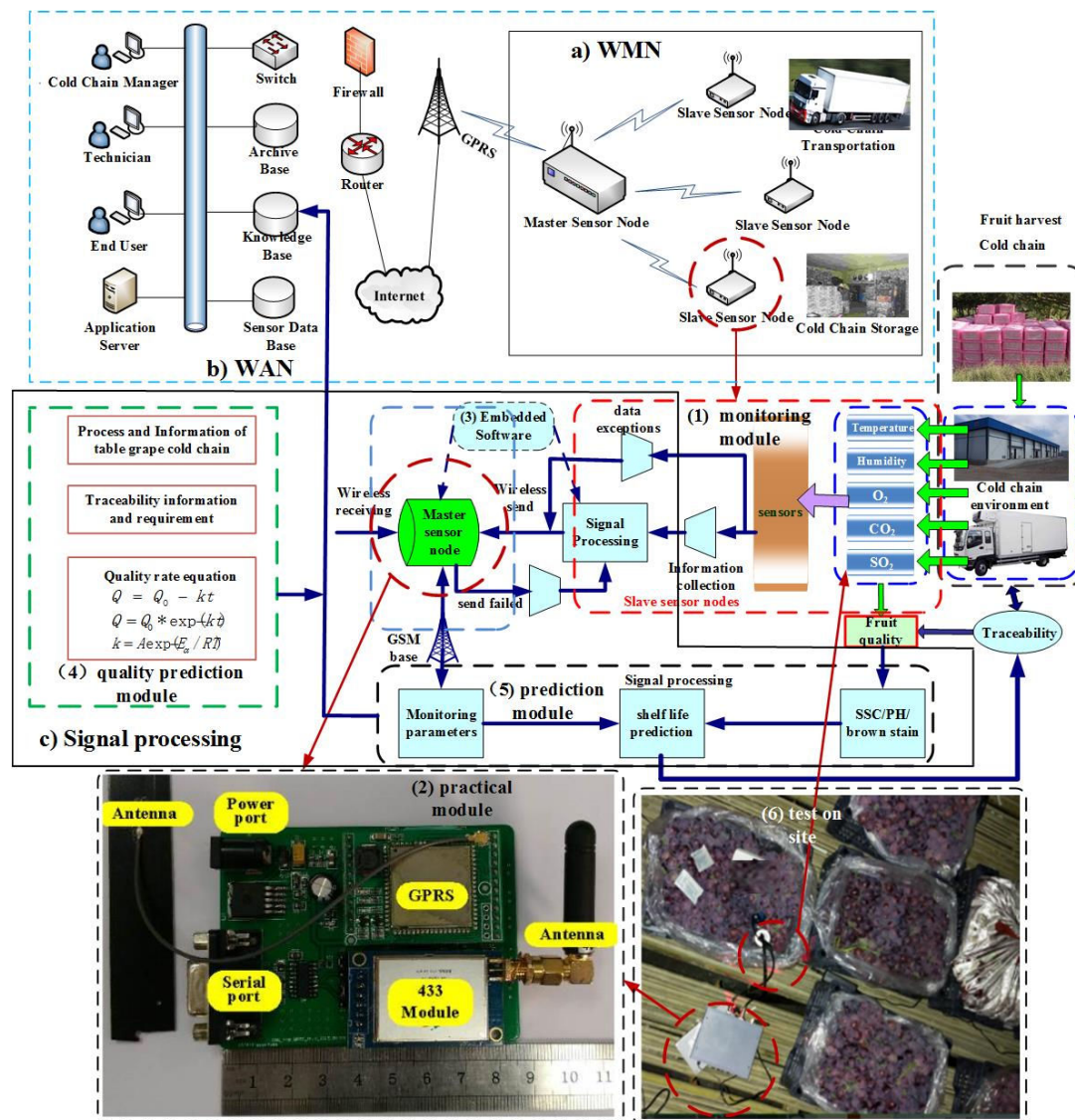
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a) the WMN (Wireless multi-sensors network); b) the WAN (Wide Area Network); and c) the

137

signal processing unit:

138



139

140

Fig. 3. The system architecture of WGS².

141

- The WMN, which combines multi-sensors technology and wireless sensor network technology, is responsible for collecting and transmitting the data in real-time. It consists of a number of SSNs (Slave Sensor Nodes), or optional router nodes and a Master Sensor Node (MSN). The SSN was used as the real-time remote monitoring terminal to monitor the temperature, relative humidity, SO₂, CO₂ and O₂ levels in a periodical mode as shown in (1) monitoring module in Fig.3, while the MSN (see (2) practical module in Fig.3) not only creates and controls the entire network, but also aggregates the sensor data from the sensor nodes. Previous study showed that wave propagation inside a closed container is significantly higher at 433 MHz than at 915 MHz or 2.4 GHz (Ferrer, 2010). Hence, the radio frequency of the WMN unit is set at 433MHz to increase the transmission performance during the wireless

150

151 communication between the SSN and the MSN, which is implemented directly or via the
 152 router node as a relay. The WMN is installed in the container of the vehicle or refrigeration
 153 warehouse.

154 ● The WAN serves as the intermediary to connect the users and the sensor nodes to keep the
 155 sensor data without delay through the GPRS remote transmission module. It provides a
 156 widely accessible interface for the end users to easily obtain the real-time information about
 157 the cold chain via Internet and identify any problems that may lead to decay of grapes.

158 ● Signal processing unit contains an embedded software (see (3) embedded software in Fig. 3)
 159 and the shelf life prediction for table grapes. It carries out signal processing of shelf life
 160 prediction as shown in (5) prediction module in Fig. 3 based on the quality rate equation as
 161 shown in (4) quality prediction module in Fig. 3 as well as signal processing of software
 162 embedded in the system of WGS² which is used to drive the normal operation of the system
 163 hardware. The quality rate equation as shown in (4) quality prediction module in Fig. 3
 164 contains zero-order reaction kinetics model, the first-order reaction kinetics model and
 165 Arrhenius equation.

166 3. Multi-Gas-Sensors development and signal processing for table grape cold 167 chain

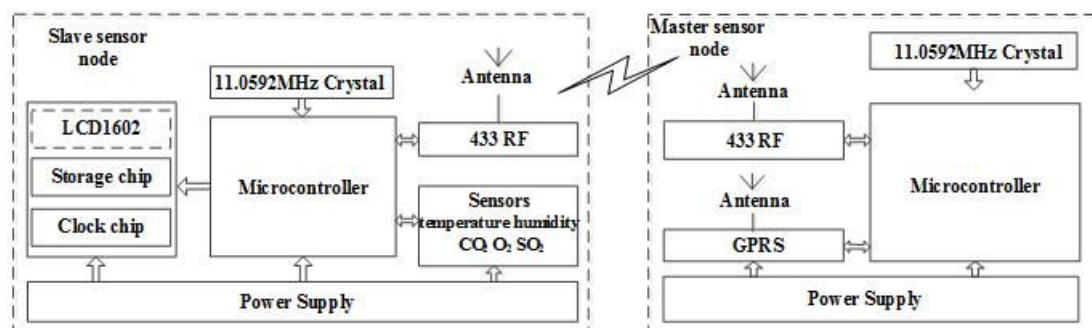
168 3.1 Multi-gas-sensors specification and integration

169 Based on the field study and the extant literature review, sensor requirements are specified in
 170 Table 2. Since the gases composition in the cold chain are very complex and dynamic due to the
 171 mixture of SO₂ gas, CO₂ and O₂, the gas sensors were tested and specified during the cold chain
 172 monitoring process. Literature shows that there are many gas sensors available in the market, but
 173 not all of them can satisfy the monitoring requirement of table grape cold chain (Aiello et al, 2012;
 174 Wang et al, 2016; Xiao et al, 2013; Xiao et al, 2015). Therefore, it is necessary to develop
 175 multi-gas-sensors to improve the traceability and transparency of table grape cold chain. The
 176 theoretical range of gas sensors are not common to develop in actual market, which need to be
 177 customized and calibrated. This is especially important for the SO₂ sensor, since volume of SO₂ is
 178 only 0-20 ppm in the table grapes cold chain, which is very small in range compared to the SO₂
 179 volume in the industry. For this reason, the sensor resolution was required to be 1 ppm and the
 180 sensor range was required to be 0-150ppm, which improve the accuracy of monitoring data for
 181 table grape chain.

182 Table 2. Monitoring parameters for table grapes cold-chains

Parameter	Temperature range	Humidity range	Volume of O ₂	Volume of CO ₂	Volume of SO ₂
Theoretical range	-2°C-36°C	50%-95%	1%-21%	0%-15%	0-20 ppm
Sensor module	AM2322	AM2322	AP-M	ATI	MF-20
Sensor range	-40°C-80°C	0%-99.9%	0%-30%	0%-15%	0-150 ppm
Sensor accuracy	<±0.3°C	±2% RH	±2% FS	±2% FS	±1 ppm
Response time	5s	5s	<15s	<30s	<30s
power Consumption	<0.1 mW	<0.1 mW	<100 mW	<25 mW	<100 mW

183 The multi-gas-sensors are integrated into the SSN as shown in Fig. 4. Both the SSN and the
 184 MSN apply the radio frequency of 433MHz to increase the transmission distance, which form a
 185 wireless sensor network. A GPRS module in the MSN is used to communicate between the MSN
 186 in the vehicle and the remote server via the RS232 bus.



187
 188 Fig. 4. Block diagram of the SSN and WSN hardware

189 The development environment and the design of the prototype and the PCB board followed
 190 Altium Designer (2004):

- 191 ➤ In order to improve processing speed and improve the capacity of disturbance resistance, the
 192 STC12LE5A60S2 is used as the microcontroller to realize system functionality of the SSN
 193 and the MSN. It has four 16-bit timers, two full duplex asynchronous serial ports and an
 194 advanced instruction set architecture.
- 195 ➤ Storage chip is used to save sensor information when signals are cut off in long international
 196 transport. Clock chip is used to control the time when data collected will be saved and
 197 produce timing pulse to wake up the CPU. LCD1602 is optional, but it can be used to display
 198 information when the sensor nodes are tested.
- 199 ➤ Multiple sensors are used to measure levels of the temperature, the humidity, the volume of
 200 SO₂, CO₂ and O₂ gases. The output type of temperature and humidity is digital signal, and the
 201 output type of gas sensors is voltage which is measured using an ADC on the microprocessor
 202 in cycled time.

203 3.2 Multi-gas-sensors calibration

204 The sensors' specification (e.g. point zero) can be adjusted to be consistent with the
 205 calibration source when the sensors' specification deviates from the calibration source. The
 206 calibration criteria follow the principle of minimizing the square error in the concentration (Feng
 207 et al, 2010; Romanak et al, 2010; Medina-Rodríguez, 2015). In order to measure gas concentration,
 208 the gas sensors also need the function to respond to different values of the concentration. In our
 209 calibration experiment, the sensor response is measured by SO₂ of 0, 19.6, 50.2 and 98.3 ppm,
 210 where the SO₂ is produced by a gas automatic control device manufactured by China Agriculture
 211 University. Fig. 5 shows how the response (in voltage) of the sensor increases with the increase of
 212 SO₂, which is proportional to its voltage signal. The regression of the relationship between voltage
 213 signal and SO₂ concentration is given in equation (4), where the coefficient of determination R² is
 214 0.9958. Hence, for any given level of SO₂ concentration, the voltage signal corresponds to a
 215 certain concentration level. The regression of the relationships between voltage signal and CO₂

216 and O₂ concentrations are given in equations (5) and (6), respectively.

217
$$y = 60.39x - 23.87 \tag{4}$$

218 where x is the voltage signal (V) and y is the volume fraction of SO₂ (ppm).

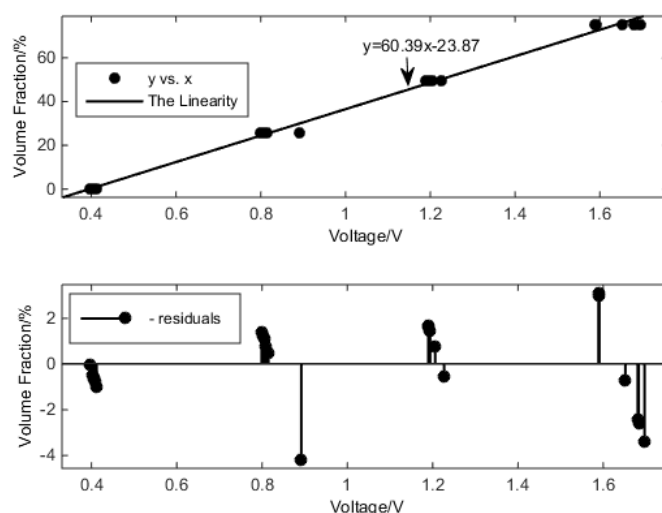
219
$$y = 9.36\%x - 3.84\% \tag{5}$$

220 where x is the voltage signal (V) and y is the volume fraction of CO₂ (%).

221

222
$$y = 18.75\%x - 7.5\% \tag{6}$$

223 where x is the voltage signal (V) and y is the volume fraction of O₂ (%).



224

225 Fig. 5. Linear Regression of SO₂ Sensors' Response

226 **3.3 Multi-Gas sensing signal processing**

227 Multi-Gas sensing signal processing includes two parts: signal processing of software
 228 embedded in the WGS² system and shelf life prediction. The signal processing of embedded
 229 software is responsible for sensor data acquisition and driving the hardware to normal operation.
 230 Shelf life prediction is to count the length of time grapes can be stored before becoming unsuitable
 231 for consumption. The shelf life prediction model was based on the theory of zero or first-order
 232 reaction kinetics model and the Arrhenius equation (Chen et al, 2016). The quality monitoring
 233 indexes include SSC, pH values, and brown stain levels, which are indicators of postharvest
 234 ripening for table grapes (Villa-Rojas et al, 2011). The situations with different concentrations of
 235 SO₂ was considered when modelling the evolution of SSC, pH values and brown stain levels,
 236 respectively.

237 Following steps are shown in the flow chart (see Fig. 6.):

238 Step 1: Initialization of the SSN and the MSN, such as the initialization of the clock,
 239 EEPROM (Electrically Erasable Programmable Read-Only Memory), UART (Universal
 240 Asynchronous Receiver/Transmitter) interrupt and the network.

241 Step 2: The MSN starts a network and waits for the network joining requests from the SSN.
 242 Then the system starts the timeout event through checking whether time is counted.

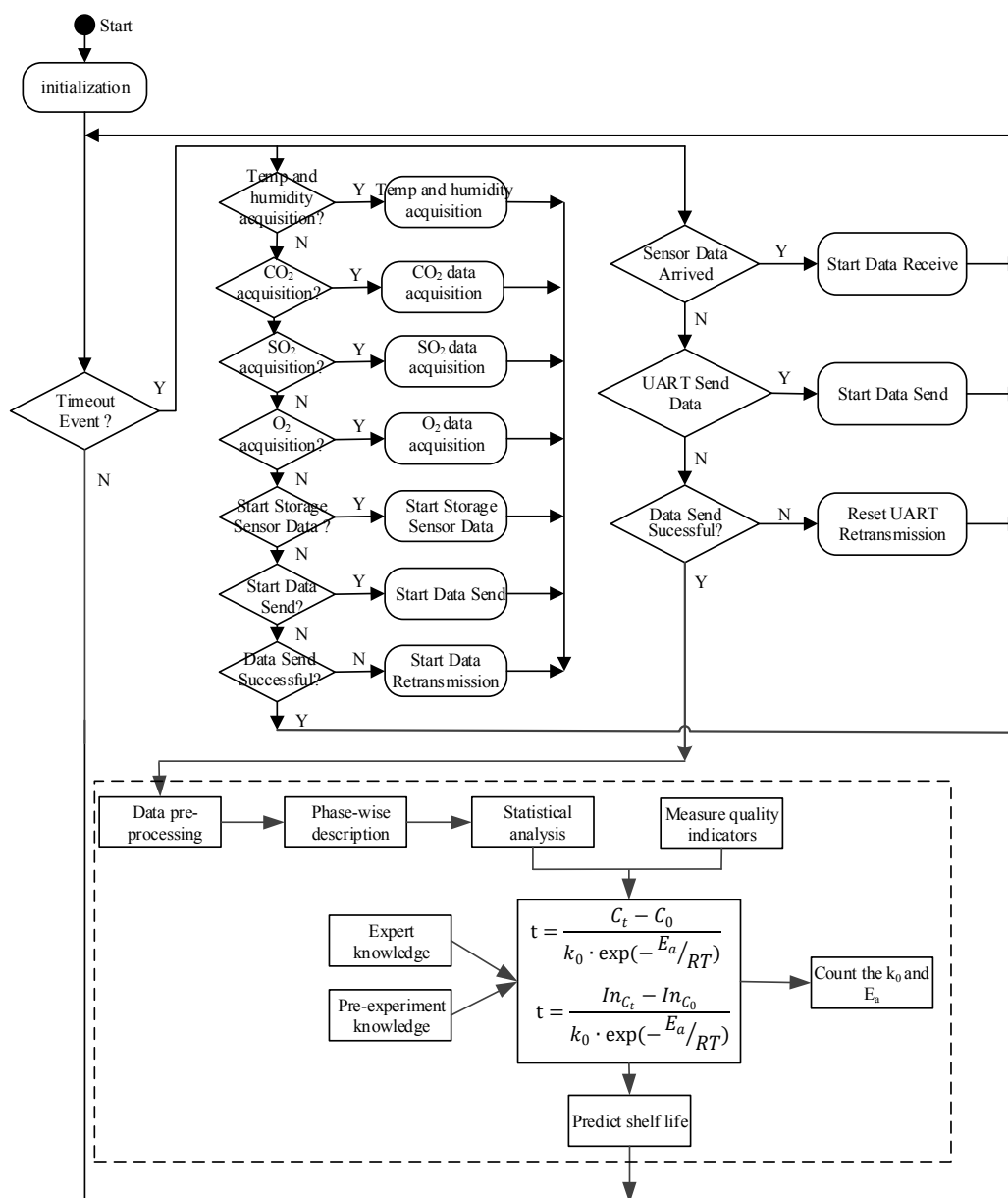
243 Step 3: Then the interrupt event occurs when slave sensor node first starts collecting the
 244 sensor data of temperature, humidity, CO₂, SO₂ and O₂ gas.

245 Step 4: After the sensor data collection, the system starts to check if EEPROM stores the
 246 sensor data and prepares to save the sensor data and time.

247 Step 5: After that, the system requests function which belongs to the 433 module of the SSN
 248 to send the data. Then the MSN starts receiving the data and storing them into a buffer array, and
 249 then waits for the UART transmission to carry out transmission to the remote control terminal via
 250 the GPRS module.

251 Step 6: The sensor node will sleep until the next timeout event after the successful data
 252 transmission. If it fails to send the data, the system will retransmit the sensor data.

253 Step 7: The system will predict the shelf life of table grape according the model which
 254 developed and evolved by reaction kinetics model and the Arrhenius equation.



255
 256

Fig. 6. Flow chart of multi-gas sensing signal processing

257 **4. WGS² Testing and Evaluation**

258 **4.1 Experiment scenario and design**

259 The WGS² system was implemented and tested in two table grape chains from Hebei to
260 Tianjin and from Xinjiang to Guangdong. There were 10 tons of Kyoho grape were transported in
261 a refrigerated truck from Hebei to Tianjin, China, and 10 tons of seedless grape were transport in a
262 refrigerated truck from Xinjiang to Guangdong, China. The length, width and height of the
263 refrigerated container are 12.032m×2.352m×2.385m. A MSN and 10 SSNs were installed in both
264 trucks. Fig.1 indicates the nodes deployment in the refrigerated truck during transportation. The
265 MSN was installed in the driver's cabin and the data-receiving terminal was installed in a remote
266 control centre.

267 The data sample interval of the sensor nodes was set to 1 second, and the data sending
268 interval of the MSN was set to 1 minute. The length of data sending was 19 Bytes, which included
269 the SSN ID (1 Byte), the temperature data (3 Byte), the humidity data (3 Byte), the SO₂ gas data
270 (4 Byte), the CO₂ data (4 Byte) and the O₂ gas data (4 Byte). The MSN aggregates the data
271 acquired from the 10 SSN with every sample interval (1 s) and transmits the sampled data to the
272 WAN layer, and then send the quality prediction via the GPRS module for every data-sending
273 interval (1 min).

274 Four experiments were conducted for analyzing the performance of the WGS² system:

- 275 ● The first experiment aimed to analyze the monitoring data of WGS² in the table grape cold
276 chain according to the implementation scenario.
- 277 ● The second experiment was to build shelf-life prediction model which link the quality
278 indicators to the temperature and SO₂ level.
- 279 ● The third experiment was to check the battery status of each sensor node.
- 280 ● The last experiment was a system evaluation of the WGS² for improving the temperature and
281 gas transparency of the cold chain.

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283 **4.2 Monitoring data analysis of WGS² in the table grape cold chain**

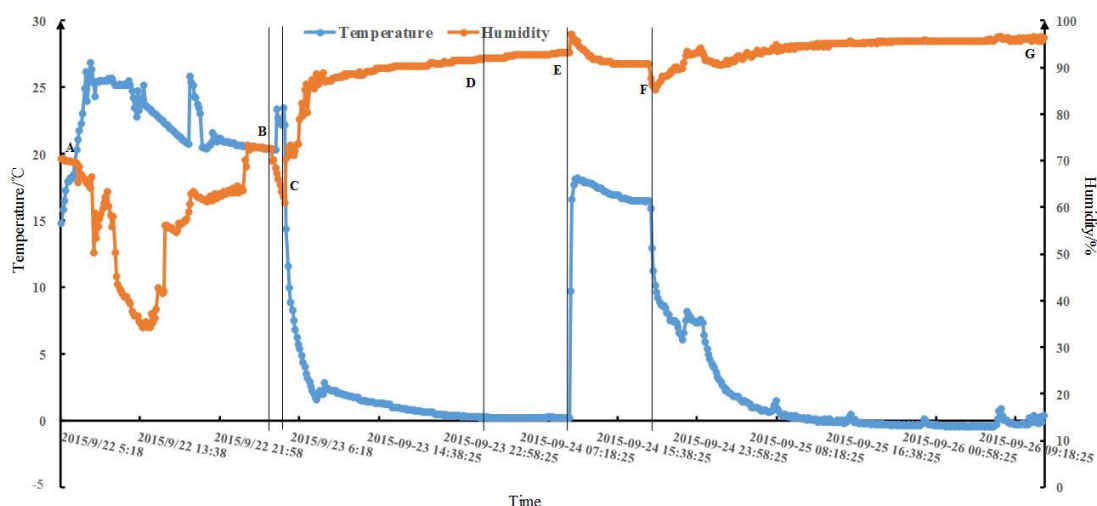
284 **4.2.1 Table grape chain from Hebei to Tianjin**

285 The plot of the temperature and relative humidity in the table grape cold chain from Hebei to
286 Tianjin is shown in Fig 7.

- 287 ● The AB segment is the table grape harvesting process at the farm, where the temperature and
288 relative humidity vary with the ambient temperature and relative humidity. The average
289 temperature is 22.77°C and average relative humidity is 54.83% in this process.
- 290 ● The BC segment is the ordinary transportation process from the farm to cold storage by the
291 ordinary truck.

- 292 ● The CD segment is the pre-cooling process, where the temperature is about -2°C in the cold
 293 storage after the ordinary transportation.
- 294 ● The DE segment is the cold storage process to wait for wholesalers to purchase, during which
 295 the temperature is stable at about 0°C . The E point is when table grapes are loaded onto
 296 the truck, and the ambient temperature in this process rises to about 16°C .
- 297 ● The EF segment is the refrigerated transportation process. The F point is when table grapes
 298 are unloaded from the truck, and the temperature in this process is about 14°C .
- 299 ● The temperature then reduces to about 8°C rapidly, before the table grapes are packed in the
 300 refrigerated storage, when the temperature decreases rapidly from the normal temperature to
 301 the refrigerated temperature at about -1°C in the FG segment, which stands by temporary
 302 storage for display and sale. The results show that WGS² system worked well and reflects the
 303 temperature and humidity information of table grape cold chain logistics.

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Fig. 7. The plot of the temperature and relative humidity in the table grape cold chain

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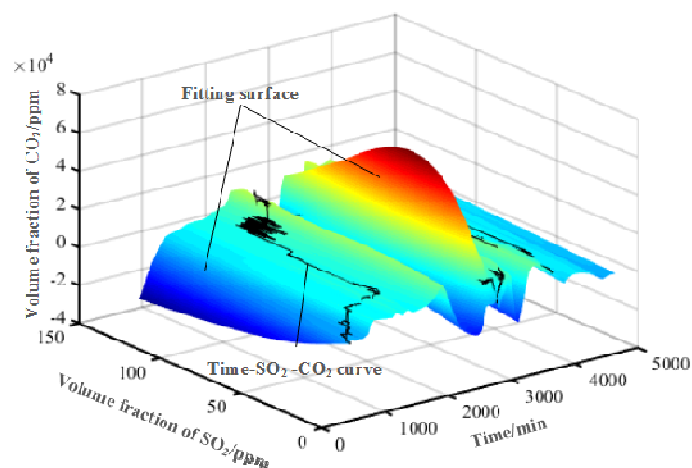
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The plot of the volume fraction of SO_2 and CO_2 in the table grapes cold chain from Hebei to Tianjin is demonstrated in Fig. 8. Before the SO_2 generator pads are placed in table grape packages, the volume fraction of SO_2 is 0 ppm and the volume fraction of CO_2 varies with the natural gas atmosphere. In the table grapes' precooling and cold storage process, the SO_2 gas was released slowly and the level was below 10 ppm. In contrast, the volume fraction of CO_2 was increased gradually. During the table grapes' refrigerated transportation process, the average volume fraction of SO_2 and CO_2 are about 5.86 ppm and 1,202.98 ppm, respectively. After the transportation process, table grapes are stored in the refrigerated warehouse in Tianjin. The volume fraction of SO_2 increases quickly when SO_2 is quickly released by SO_2 generator pads, which reacts with the high relative humidity in the refrigerated warehouse. The average volume fraction of SO_2 and CO_2 are about 58.76 ppm and 9,488.41 ppm, during this time the volume fraction of CO_2 increases quickly due to the respiration of table grapes, then remains stable with the low respiration rate of table grapes at 0°C .



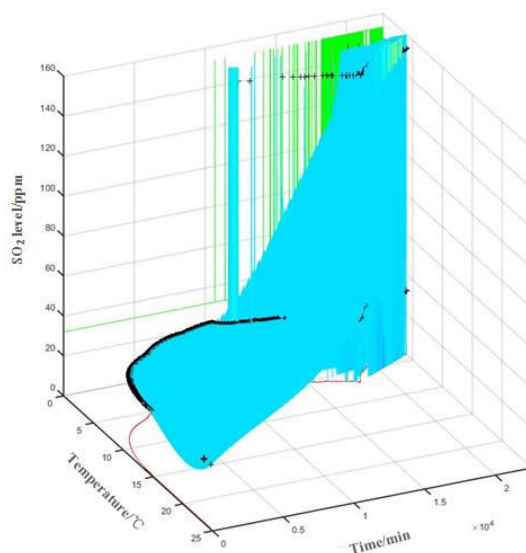
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321

Fig.8. The volume fraction of SO₂ and CO₂ in the table grape cold chain

322 4.2.2 Table grape chain from Xinjiang to Guangdong

323 The change of key traceability indicators for table grape chain from Xinjiang to Guangdong
 324 is shown in Fig.9. Compare with monitoring data analysis of WGS² in the table grape cold chain
 325 from Hebei to Tianjin, the changed trend of temperature and SO₂ level are almost the same in the
 326 table grape harvesting process at the farm, pre-cooling process, preservation storage process and
 327 transportation process. The change of SO₂ level varied quickly in the process of temporary storage
 328 for display and sale. The temperature difference and high relative humidity improve the SO₂ gas
 329 release rate of SO₂ generator pad or powder in the process of temporary storage for display and
 330 sale.



331

332 Fig.9 the change of key traceability indicators for table grape chain from Xinjiang to Guangdong

333 The temperature and relative humidity changes because of the influence of the ambient
 334 temperature and the energy released by the life activities of table grape, which changes the CO₂
 335 level by affecting the respiration rate of fruit and SO₂ level by effecting the release rate of SO₂
 336 generator pad or powder. Moreover, the SO₂ level changes the CO₂ level by retarding the

337 respiration rate of table grape. The monitoring data results reflect the atmosphere of table grape
 338 cold chain logistics, which could be monitored in real-time via the sensor nodes installed. The
 339 results show that WGS² system could provide complete and accurate temperature, humidity and
 340 gas monitoring information in cold chain, which provide the more effective safety and quality
 341 assurance for table grapes in the cold chain.

342 4.2.3 The comparisons between two cold chain

343 The comparison between Xinjiang- Guangdong cold chain and Hebei-Tianjin cold chain is
 344 shown in Table 3. The distance of two cold chains are 4,300 km and 300 km, respectively. The
 345 durations of table grape precooling and grape weight are almost the same for two cold chains.
 346 Table grape cold storage duration for Xinjiang- Guangdong cold chain is longer than table grape
 347 cold storage duration for Hebei-Tianjin cold chain.

348 Table 3. The comparisons between two cold chains

Type	Distance	Grape weight	Grape varieties	Grape harvesting duration	Ordinary transportation duration	Table grape precooling duration	Table grape cold storage duration	Transporting the table grapes to retail stores duration	Temporary storage for display and sale
Xinjiang-Guangdong cold chain	4,300 km	10 tons	Seedless grape	Depends on preparation	About 1.5 hours	Approximately 1 day	About 2.5 days	About 5.5 days	Depends on sales
Hebei-Tianjin cold chain	300 km	10 tons	Kyoho grape	speed of cargo	About 1 hours	Approximately 1 day	About 9 hours	About 8 hours	

349

350 4.3 Shelf-life prediction model considering SO₂

351 Considering influences of postharvest ripening and constant concentrations of SO₂, the shelf
 352 life of table grapes was predicted according the determination quality indicators which including
 353 SSC, pH and brown stain and the results of fitted curve. The SSC was determined by a handheld
 354 Japanese digital refractometer (Atago PAL-1, Atago Co. Ltd., Tokyo, Japan); the pH value was
 355 measured using a Shanghai pH meter (PHS-3C, Jingke Co. Ltd., Shanghai, China); and the brown
 356 stain was determined according to a grading of 6 levels: 0 - fresh light green, 1 - green, 2 - dark
 357 green, 3 - green to light brown, 4 - brown, 5 - brown to dark grey and dried (Harvey et al, 1988).

358 The 10 bunches of Kyoho grapes were put into constant temperature incubators with 0 °C,
 359 10 °C, 20 °C, 25 °C, and the constant SO₂ level with 0 ppm, 10 ppm, 20 ppm. And every bunch
 360 of grapes was almost the same weight and size about 1.2 kg. They were picked from a vineyard in
 361 Hebei province, China, and were transported on the same day to the laboratory for precooling at 0
 362 °C. The quality indicators were measured from the samples at same intervals in the same
 363 treatment.

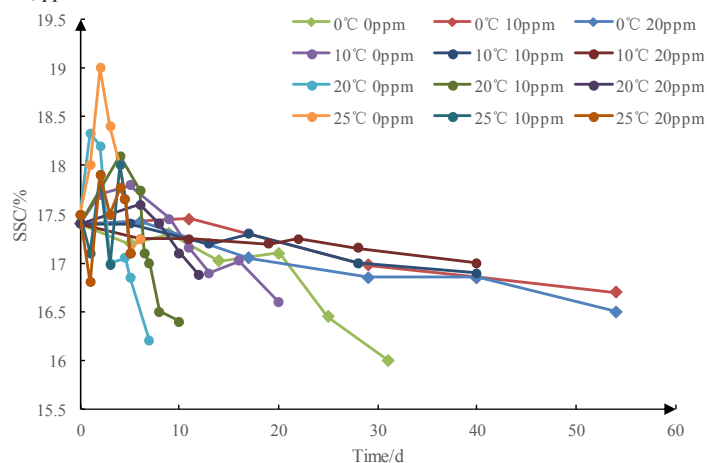


Fig.10. The evolution of SSC at various temperature and constant SO₂ level

364
365

366 The evolution of SSC at various temperature and SO₂ levels is shown in Fig.10. The
 367 evolution of SSC in the grapes showed a trend of rising followed by falling at the temperatures
 368 higher than 10 °C, and the peak time at 10 °C was obviously latter than the situations at 20 and
 369 25 °C, while no rising stage for SSC at 0 °C was observed. The addition of SO₂ showed effects
 370 of inhibition and delay on the accumulating and consuming of SSC in postharvest table grapes,
 371 and the effects were enhanced with the increase of SO₂ concentration within a range of 0~20ppm.
 372 Then, using the fitted curve to get the model which links the quality indicators to the temperature
 373 and SO₂ level. Fig.11. shows the fitted curve of SSC at 0 °C and 0 ppm and the fitted coefficients
 374 of determination is 0.8219. At last, the shelf life prediction for evolution of pH, brown stain and
 375 SSC at various temperature and constant SO₂ level will be get through fitted curve, zero or
 376 first-order reaction kinetics model and the Arrhenius equation.

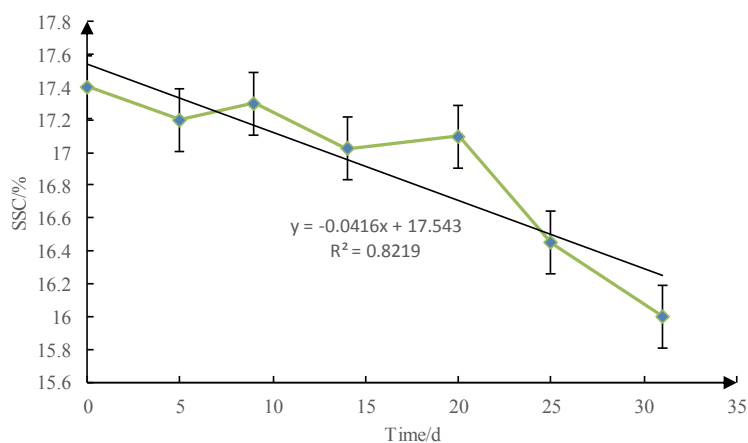


Fig.11. The fitted curve of SSC at 0 °C and 0 ppm

377
378

379 Therefore, the shelf life model of table grapes at fluctuant temperature and constant
 380 concentrations of SO₂ could be modelled, as shown in Table 4. Table 4 also shows the shelf life
 381 prediction model considering SO₂ embedded in the WGS² system. The interface of shelf life
 382 prediction for table grapes is shown in Fig.12. It consists four parts of indices: the first part
 383 displays time; the second part has “check”, “SSC”, “PH” and “brown stain” buttons; the third part
 384 displays the monitoring data; the fourth part displays the results of the fitted curve. The evaluation

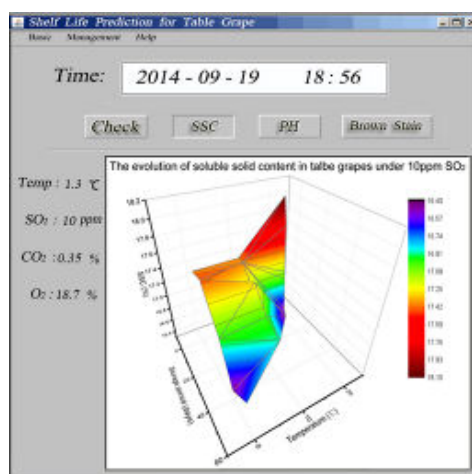
385 results show that grapes shelf-life prediction model built on the WGS² could be used to predict the
 386 remaining shelf-life of the grapes during cold chain logistics and provide the effective decision
 387 support for the grapes managers in cold chain.

388 Table 4 Shelf life prediction for table grape

Indexes	SO ₂ (ppm)	Shelf life prediction	R ²
brown stain	0	$y = -7479.6 * x + 24.521$	0.9336
	10	$y = -9854.6 * x + 32.633$	0.9759
	20	$y = -9037.8 * x + 29.846$	0.986
SSC	0	$y = -9241.2 * x + 27.466$	0.9531
	10	$y = 17.4 * \exp(-0.006 * x)$	0.8663
	20	$y = 17.4 * \exp(-0.006 * x)$	0.8256
PH	0	$y = 3.76 * \exp(-0.006 * x)$	0.8615
	10	$y = 3.76 * \exp(-0.004 * x)$	0.8663
	20	$y = 3.76 * \exp(-0.003 * x)$	0.8256

389 x-Celsius degree/°C, y-shelf life/days

390



391

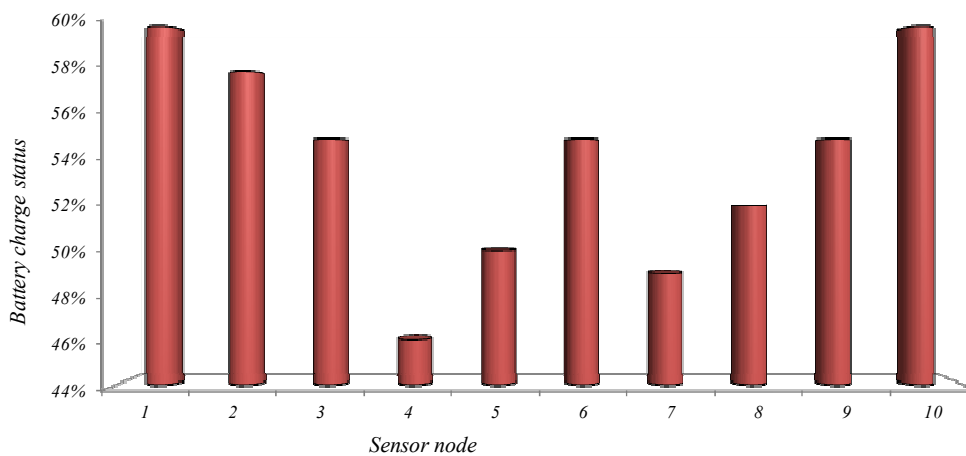
392 Fig. 12. The interface of shelf life prediction for table grapes.

393

394 4.4 Sensor nodes power evaluation

395 Each sensor node is supplied with a 5V, 30Ah lithium battery. The node power management
 396 circuit ensures the sensor node operation is stable until the total voltage drops to 3V (0% battery
 397 charge). More power is required to establish the communication link with the low signal link
 398 between the SSN and MSN (Xiao et al, 2014). Fig. 13 presents the battery charge status of each
 399 sensor node after approximately half month from September 1, 2014 to September 16, 2014. The
 400 battery charge status varies from 46% to 60% for all nodes. The batteries of sensor node No.4,
 401 No.5 and No.7 were quickly depleted because of the low signal between those nodes and the
 402 network MSN, hence more power being required to establish the communication. Based on the
 403 results of the experiment, it was predicted that the network can be in normal operation for

404 approximately one month. For table grape chain, it's largely enough for tracing the environmental
405 information by WGS² system online.



406

Fig. 13. Battery charge status of the sensor nodes in the network

407

408 4.5 System evaluation of the WGS²

409 Managers and workers, who have over 3 years of working experience of the table grape
410 production, transportation, cold storage, or sale, who are considered as main stakeholders of the
411 table grape cold chain (as **classified in detail in Fig.2 and page 5**), were invited to take part in a
412 group interview to evaluate the system and discuss the system performance and to feedback on the
413 improvement that the system has enabled to ensure management efficiency of table grape cold
414 chain. It was indicated that the reduced the quality loss and the raised market price of table grapes
415 were resulted from the use of the WGS² system's real-time monitoring and shelf life prediction.
416 Table 5 shows the efficiency and performance analysis for the WGS² implementation. As can be
417 seen, the implementation of WGS² has improved the cold chain gas environment monitoring
418 greatly, which improves the traceability of the table grapes and enables better table grape cold
419 chain management.

Table 5. Cold chain monitoring performance analysis for WGS² implementation

System performance indicators	Cold chain temperature and humidity monitoring	Cold chain SO ₂ gas monitoring	Cold chain CO ₂ gas monitoring	Cold chain O ₂ gas monitoring	Cold chain shelf life prediction	Data signal analysis method	Quality loss	Market price (RMB)
Traditional work	Recorders or radio frequency identification technology, high cost and offline	Null	Null	Null	Only based on temperature	Null	25%~30%	<8yuan/kg
Previous work in our team	Range:-40 to -124°C Accuracy:±0.4°C	Range:0-20ppm Accuracy:±5%FS Power:0.5w	Null	Null	Only based on temperature	Null	<19%	<10yuan/kg
WGS ² system	Range:-40 to -80°C Accuracy:±0.3°C	Range:0-150ppm Accuracy:±2%FS Power<0.25w	Real-time	Real-time	Based on temperature and SO ₂ gas	Embedded	<10%	>16yuan/kg
Advantage	Better accuracy of temperature monitoring and traceability	Better accuracy and power of the SO ₂ monitoring and traceability	Capability of CO ₂ monitoring and traceability	Capability of O ₂ monitoring and traceability	Capable of capturing and defining the link between grape quality and SO ₂ gas	Improving traceability and transparency of table grape cold chain	Reduce the quality loss for table grape cold chain	heightening benefit for table grape cold chain

422

Table 6. Cased by SO₂ sensors in WGS² system performance analyzed in detail

Class	Industrial	Cold chain (online)	E-nose/E-tongue
Scale range	>2000 ppm	<100ppm	small
Accuracy	±20ppm	±1ppm	low
Power supply	High Supporting	Low Self-supporting	High Supporting
Signal processing	Data & early warning	Quality coupling	Quality coupling
Online	Online	Online accumulative	Offline/fast

423 Table 6 lists the cased by SO₂ gas sensors in WGS² system performance analyzed in detail.
 424 Scale range of industrial SO₂ gas sensor is normally above 2000 ppm and the accuracy is above
 425 ±20ppm; Industrial sensors have fixed power supply. On the other hand, E-nose or E-tongue is
 426 widely used to detect specifications of mixed gas offline and roughly calculate the amount of gas.
 427 In comparison, table grape cold chain sensors in WGS² have high accuracy, small size, capable of
 428 online and low power consumption which be self-supported by portable power supply from field
 429 observation.

430 5. Conclusions

431 This paper presents a novel system of the WGS², which is developed and implemented in two
 432 table grape cold chains from Hebei to Tianjin, China and Xinjiang to Guangdong, China. This
 433 WGS² technology enables a real-time sensor data acquisition, offers high accuracy and efficiency
 434 without the need of complicated infrastructure. The WGS² system can help the cold chain
 435 managers to carry out real-time monitoring of the key traceability indicators, so that to control the
 436 safety and quality of table grapes cold chain more effectively.

437 The system test and evaluation show that WGS² can monitor the state of the cold chain by
 438 acquiring and transmitting the real-time temperature, humidity, SO₂, CO₂, and O₂ in the cold chain,
 439 helping managers and workers monitor the cold chain in a timely manner and resolve any
 440 problems that may cause unexpected quality loss. The grape shelf-life prediction results indicate
 441 that the grapes shelf-life prediction model built in the WGS² can be used to predict the SSC, pH
 442 and brown stain change and the remaining shelf-life of table grapes cold chain.

443 The WGS² can transmit the sensed gas data to the remote monitoring centre in real-time via
 444 the wireless network and the GPRS remote transmission module from the spot and reflect the
 445 environmental information accurately. Moreover, the wireless network has a relatively reliable
 446 signal in the cold chain scenario and can display reliable transmission of the sensor data in the
 447 cold chain.

448 The network was estimated to be able to operate successfully for approximately one month
 449 with sufficient the battery charge status of each sensor node. The signal quality of GPRS in the
 450 container may be influenced by the environmental changes, such as temperature or humidity
 451 changes, and windy or rainy weather. Moreover, the signal quality of WSN in the container may

452 be affected by the materials and thickness of the container. Therefore, the on-site resistance and
453 stability of the WGS² can be improved. Moreover, it is necessary to integrate low energy
454 consumption sensors into the SSN to meet the demands of actual application.

455 Although the WGS² is developed to monitor the table grape cold chain, the system
456 architecture and the system models can be exploited by future researchers or practitioners to
457 develop monitoring systems to for much wider cold chain monitoring tasks.

458

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