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Effects of different cooling methods on the carbon footprint of cooked rice

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A B S T R A C T

Global warming has become a serious problem facing the international community. All countries strive to reduce greenhouse gas (GHG) emissions. The food system produces a large amount of GHGs, and thus study of the carbon footprint (CF) in the food industry has attracted the attention of researchers. Based on the lifecycle assessment (LCA) method, the present study calculated CFs of cooling of cooked rice, as a unit operation under different operational conditions. The results showed that the carbon footprints for cooling 200 g cooked rice were 54.36 ± 1.07 gCO_2eq for refrigerator cooling at 0 °C, 66.05 ± 2.00 g CO_2eq for refrigerator cooling at 8 °C, 741.55 ± 27.26 g CO_2eq for vacuum cooling, 1914.10 ± 141.24 g CO_2eq for air blast cooling at 0 °C, 2463.61 ± 221.21 g CO_2eq for air blast cooling at 3 °C, and 3916.54 ± 202.28 g CO_2eq for air blast cooling at 8 °C. In addition, the CF for the cooling process was positively correlated with the output power of equipment and the cooling time. The carbon emissions arising from electricity consumption contributed to most of the CF for the cooling process. Sensitivity analysis of the parameters for the CF for the cooling process revealed that the CF of cooling process was stable for the applied equipment emission factor, but sensitive to the efficiency of electricity use and the extent of load. Improving the efficiency of electricity use and increasing cooling load could reduce the final CF of a product.

1. Introduction

Global economic activity now generates a large volume of greenhouse gases (GHG) leading to a global temperature rise, a global greenhouse effect and a resultant threat to the human environment. An effective response to climate change requires international collaboration (Thøgersen and Nielsen, 2016). The Paris Agreement 2015 is a step in the right direction (Hohne et al., 2017).

Carbon emissions are a general term for GHG emissions, which include carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). With the increasing awareness of climate change, measurement of the carbon footprint (CF) has become a powerful tool to combat global warming (Cellura et al., 2012; Pandey et al., 2011). CF expressed in carbon dioxide equivalent (CO_2eq), equates to the amount of GHG emissions over the life stages of a product, and the methodologies to calculate the product CF are based on the principle of LCA (Wiedmann and Minx, 2008). CF has been used for measuring the influence of GHG emissions on climate and human activity (Minx et al., 2009).

The global food system is responsible for 33% of anthropogenic carbon emissions (Audsley et al., 2010). Hence, total carbon emissions could be reduced by limiting GHG emissions from the food

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industry. The Chinese food industry is of low efficiency, emitting a large volume of GHG. The pressure to reduce emissions requires the Chinese food industry to establish food systems with low carbon emissions. Monitoring carbon emissions and tracking CF in all aspects of food production can identify the manufacturing sections that must target carbon emission reduction. However, the complexity of the food systems render calculation of the overall carbon emissions extremely difficult. As a result studies of food CF mainly focus on food processes (Mungkung et al., 2006; Thrane, 2006; Xu et al., 2013; Ziegler et al., 2003) and their whole life cycle assessment (Biswas and Naude, 2016; Pirlo et al., 2014; Xu et al., 2013). However, for the CF of whole lifecycles, it is difficult to compare existing food systems due to the differences in processes, sources of raw materials, and boundary conditions. Food production consists of many unit operations. A unit operation, even for different food production systems, follows the same basic principles, and can be performed using the same or similar equipment. The food system includes a number of major unit operations, such as drying (Arikan et al., 2012; Uribe et al., 2013; Cui et al., 2008; Yang et al., 2017; Pu and Sun, 2016), freezing (Pu et al., 2014; Kiani et al., 2011; Ma et al., 2015; Xie et al., 2015; Cheng et al., 2016; Pu et al., 2015; Cheng et al., 2017; Xie et al., 2016), cooling (Cheng et al., 2014; Li et al., 2014; Stangierski & Baranowska, 2015; Sun and Hu, 2003; Wang and Sun, 2002a; Wang and Sun, 2002b; Sun and Wang, 2000; Sun, 1997; McDonald et al., 2000; Sun and Brosnan, 1999; Zheng and Sun, 2004; Wang and Sun, 2004), etc. Thus, researching the carbon emissions of various unit operations can supply emission data for the whole lifecycle. This reduces the work load during a lifecycle carbon emission study, thus enhancing the effectiveness and accuracy of the results, while supplying further guidance to optimize food processing technology, leading to development of a low-carbon emission industry. For example, Xu et al. (2016) compared the CFs of two freezing processes, immersion freezing and a novel ultrasonic-assisted freezing. They concluded that the ultrasonic-assisted freezing is more environmentally friendly than the traditional freezing method.

In modern Chinese life, fast food and the fast food meal box (FFMB), has become popular, in which cooked rice is an important component (Jiao et al., 2017; Ma and Sun, 2009). Chinese fast food can be supplied by hot chain and cold-chain distribution. The cold chain system is more often employed for cooked rice. Its production procedure includes cooking, then rapid cooling to below 10 °C, followed by storage below 10 °C during transportation and sales. Cooling of cooked rice is a necessary step in the manufacturing of FFMB if cold chain is used. Rapid cooling of cooked rice to below 10 °C is desired so as to reduce growth and reproduction of any surviving bacteria. In addition, rapid cooling could reduce manufacturing time and hence improve production efficiency (Zhang and Sun, 2006a). The methods of cooling normally include air blast cooling, forced air cooling, plate cooling, and vacuum cooling method (Ma and Sun, 2009; Yu et al., 2010), and Zhang and Sun (2006a,b) have shown that their cooling rates are different, but no research was carried out to investigate their CF. Therefore, the present research aimed to compare CFs of the cooling processes, namely, refrigerator cooling (RC), vacuum cooling (VC) and air blast cooling (AB), as unit operations, during cooling of cooked rice in box. We hoped to identify more environmentally friendly cooling processes as well as supplying data to reduce carbon emissions from the food system.

2. Material and methods

CF assessment is generally based on life cycle assessment (LCA) as a methodology to evaluate the entire lifecycle of a product, from its raw materials, through manufacturing, to final waste disposal. The current study used PAS2050:2011 (BSI, 2011) and ISO14067 (2011) regulations to calculate the CF of different cooling modes.

2.1. Definition of goal and scope

In the present study, the CF of cooling cooked rice was calculated based on the cooling method. In order to follow the health and nutrition guideline for chilled FFMB, the staple food and other components in the box should be reduced to below 10 °C within 2 h after cooking. That temperature should be maintained during packing, storage, and transportation, until reheating before consumption. Based on the standard method of cooling cooked rice (Chen et al., 2014), the center temperature should drop to 10 °C. In the present study, the core temperature of cooked rice in box spanned from 50 °C to 10 °C.

2.1.1. Function unit

The current study calculated the carbon emissions only during the unit operation of cooling, not during the whole life cycle of a product. The function unit of this study was the cooling of 0.02 kg cooked rice in a plastic meal box (14.5 × 9 × 7 cm) from its core temperature of 50 °C–10 °C.

2.1.2. System boundary

The specification of system boundaries can benefit the calculation of CFs of a specific product or process, clearly define the evaluated object, specify the scope of the experiment, and clarify the input and output sources in the experiment. Specifying the system boundary aims to determine the scope of a product and process for calculating CF and specifying the necessary stages and processes of the lifecycle for its evaluation.

In the present study, the carbon emission during the cooling of cooked rice, its preparation, setup of equipment, and cooling were measured. The environmental impact caused only by the cooling was, i.e., the system boundary in the experiment covered only the cooling process. The system inputs during the cooling process included the equipment, electric power, refrigerant, and plastic products.

2.1.2.1. Preparation of cooked rice. Pearl rice (0.80 kg) was washed twice with water, and excess water was drained. The rice was then placed in an electric rice cooker (FB2127, SKG, Foshan, China) by adding 1.04 L water (about 1.3 times of rice volume), soaked at room temperature for 30 min and then cooked using the “cooking” operation mode (Zhang and Sun, 2006b). After cooking, the rice was loosened, and placed into plastic meal boxes (14.5 × 9 × 7 cm), with 0.20 kg cooked rice per box (Table 1).

2.1.2.2. Cooling processes. For refrigerator cooling (RC), a refrigerator (BCD-370WGPVA, Vandelo Series, Midea Group, China) was used (Table 1). The power consumption of the refrigerator is 0.085 kWh per hour during cooling as measured with a wireless power meter (JNX-2000, Shenzhen Jingxinda Co., Shenzhen, China).

For vacuum cooling (VC), a vacuum cooler (VC-1601, ColdmaxCo., Dongguan, China) was used (Table 1.) Refrigerant R22 was used even though it has already been phased out in most Western countries while use in China is allowed until 2030. The unit energy consumption was 5.5 kW per hour as measured by a digital power meter (UT200A, UNI-T, Dongguan, China) under vacuum condition.

For air blast cooling (AB), a rapid cooling unit (CET-SE7510-05F, China-Scicooling (Beijing) Co., Ltd, Beijing, China) was used (Table 1). The supplier confirmed that a refrigerant without GHG effect was used in their equipment. Thus the carbon emissions from this refrigerant was not considered. The chamber temperature may vary between −75 °C and 80 °C. The experimental equipment

Table 1
The main parameters of the equipment.

Equipment	Cooker	Refrigerator cooling	Vacuum cooling	Air blast cooling
Model	FB2127	BCD-370WGPVA	VC-1601	CET-SE7510-05F
Weight/kg	3.5	100	400	230
Price/US $	28.78	1439	14,390	14,390
Effective volume/L	4	218	18	100
R404A/kg	–	0.21	0	0
R22/kg	–	0	0.25	0

requires that the load must not be higher than 1/5 of the inner chamber size. In the present study, the chamber temperature was set at 0 °C and 8 °C. Besides, a temperature of 3 °C was also chosen in order to investigate the effect of ambient temperature on the CF of cooling process. The energy consumption of the equipment was 5.60 kW per hour under cooling conditions of AB-1 (0 °C), 5.67 kW per hour under cooling conditions of AB-2 (3 °C), and 5.75 kW per hour under cooling conditions of AB-3 (8 °C), as measured by a digital power meter (UT200A, UNI-T, Dongguan, China).

2.1.2.3. Rice cooling process. For refrigerator cooling, the cooling method was used according to McDonald et al. (2000) and Zhang and Sun (2006a,b). During cooling, a portion of boxed cooked rice was transferred into the refrigerator without sealing with the refrigerator set at 0 °C and 8 °C, respectively. The boxed cooked rice was placed at the center of the middle tray. A K-type thermocouple connected to a temperature data logger (TC-08, Pico Technology, Cambridge shire, UK) was inserted into the rice to record the temperature in the geometric core of the sample. The cooling process continued until the temperature reached 10 °C. Three replicates were performed. This experiment investigated the effect of cooling temperatures on carbon emissions during the refrigerator cooling process. The conditions for the refrigerator cooling are shown in Table 2.

For vacuum cooling and air blast cooling, the process was similar to the refrigerator cooling process, i.e., a portion of boxed cooked rice was cooled until the sample core temperature reached 10 °C. The experiment was performed in three replicates. However, for air blast cooling, the air temperature was set at 0 °C, 3 °C, and 8 °C, respectively. For vacuum cooling, the pressure in the chamber was gradually reduced while the sample core temperature was decreased simultaneously. Table 2 also shows the cooling conditions for these cooling experiments.

2.2. Inventory analysis

Inventory analysis requires the collection of detailed information of the input and output of the product CF as well as the processing and classification of the information. Inventory analysis is the most time-consuming stage in LCA (Xu et al., 2016). The accuracy and effectiveness of the collected data have a significant impact on the calculation of carbon emissions (Reap et al., 2008). It is necessary to follow requirements specified in ISO 14067 (2011), like time, geography, techniques, etc., during data collection in order to obtain detailed and accurate data.

LCA data can be obtained from the published literature, experimental data and even assumptions. The data can be obtained by direct and indirect collection. Direct collection gathers raw data in experiments or by interviews with experimenters. Indirect collection obtains carbon emissions from literature, by interviewing experts and using auxiliary software. In this experiment, the input resource included equipment, energy, refrigerants, and plastic boxes. At the same time, the carbon emissions of equipment can be estimated by sectoral emissions in in-put and out-put life cycle assessment.

In the cooling process, manufacturing, maintenance, and dismantling of fixed equipment should be included in the system boundaries according to ISO14040 (2006). In the cooling process, the equipment, temperature recorders, and computers were regarded as input resources, and their carbon emissions during the cooling should be calculated. In this experiment, the input of cooling cooked rice included equipment (the refrigerator, vacuum cooler, air blast cooler, temperature data acquisition, and computer), electricity, refrigerant, and plastic boxes. The product CF can be calculated using the following equations:

$$EF_i = \frac{GHG_i}{t_i} \tag{1}$$

$$CF_{\text{total}} = \sum_{i=1}^{n} (Q_i \times EF_i) \tag{2}$$

$$CF_{\text{unit}} = \frac{CF_{\text{total}} + (N_i - 1)CF_e + (N_i - 1)CF_p}{N_i} \tag{3}$$

$$N_i = \frac{V_e}{V_p} \tag{4}$$

where EF_i is the carbon emission factor of the ith input (g CO_2eq/min), GHG_i is the lifecycle carbon emission of the ith input (g CO_2eq), t_i is lifecycle of the ith input (min), Q_i the cooling time for the sample (min), CF_e is the CF of electricity (g CO_2eq), CF_p is the CF of used plastic box (g CO_2eq), CF_{unit} is the CF of cooling process (g CO_2eq), N_i is the number of samples that could be carried out simultaneously for each equipment, V_e is the effective volume of each equipment (L), and V_p is the volume of used plastic box (L).

Table 3 shows the total GHG data and working life for each input. According to input-output analysis, the equipment emission factor was 76.44 kg CO_2eq per thousand US $ (11 kg CO_2eq per thousand RMB) (Xu and Hu, 2011) for estimating equipment life cycle emissions. The working life of the equipment was provided by the equipment manufacturers. The cooling process also involved other materials. For carrying cooked rice, the mass of each box was 28 g. Each kilogram of plastic produced 2.0 kg of CO_2eq as the emission factor of the plastic meal box (Rotz et al., 2010). In addition, one plastic box could be used 18 times during the cooling process.

As the refrigerant leakage in the experiment was difficult to detect, the industrial average data were used in the calculation. For

Table 2
Cooling conditions for different cooling procedures.

Cooling method	Refrigerator cooling		Vacuum cooling	Air blast cooling		
Sample	RC-1	RC-2	VC	AB-1	AB-2	AB-3
Ambient temperature	0 °C	8 °C	–	0 °C	3 °C	8 °C

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Table 3
The total working time and GHG data of the inputs.

Inputs	Working life	Total greenhouse gas emission
Rapid temperature change equipment	1.15×10^6min	1100 kg CO_2eq
Vacuum cooling machine	1.15×10^6min	1100 kg CO_2eq
R404A	1.15×10^6min	295.6 kgCO_2eq (BSI, 2011)
Temperature data acquisition	7.2×10^5 min	22 kg CO_2eq
Computer	1.15×10^6min	370 kgCO_2eq (Stutz, 2010)
Refrigerator	1.15×10^6min	110 kg CO_2eq
R22	1.15×10^6min	108.6 kgCO_2eq (BSI, 2011)
Electricity	–	1.03 kgCO_2/kWh(Hou et al., 2012)
Plastic box	–	2.0 kgCO_2eq/kg (Rotz et al., 2010)

smaller cooling equipment, the simple screening method is often used to calculate the GHG emissions from the refrigerant used (DEFRA, 2012; EPA, 2008). The screening method to estimate emissions from refrigeration is based on the types of equipment used and emissions factors. For the refrigerant R404A and R22, losses during installation, losses caused by leakage, and losses in final disposal contributed almost their CFs (DEFRA, 2012). For the refrigerator, the three losses for the employed refrigerant R404A were 0.6%, 0.3% and 35%, respectively (DECC, 2011; DEFRA, 2012; EPA, 2008). Refrigerant charging capacity was 0.21 kg, and for 100 years scope, R404A global warming potential was 3921.6 times the CO_2 equivalent. By adding up the GHG emissions from each fraction (installation, leakage, and disposal), the carbon emission of R404A was 295.6 kg CO_2eq. In the case of the vacuum cooling machine, it could be regarded as a small industrial system, and the three losses for R22 were 1%, 8%, and 15%, respectively (DECC, 2011; DEFRA, 2012; EPA, 2008). The charging capacity of the refrigerant in the vacuum cooling machine was 0.25 kg, which was 1810 times the CO_2 equivalent for a 100-year global warming potential. By adding up the GHG emissions from each fraction stated above, the R22 carbon emission was 108.6 kg CO_2eq.

2.3. Impact assessment

In the present study, only the lifecycle carbon emissions during the cooling of cooked rice were studied. According to the Intergovernmental Panel on Climate Change (IPCC) (2007), a 100-year time horizon is used for global warming potential.

2.4. Statistical analysis

Data of cooling time and final CF of different cooling conditions were analyzed using one-way ANOVA statistical software (SPSS, Chicago, IL, USA, version 11.5, 2002).

3. Results and discussion

3.1. Comparison of cooling times

Table 4 shows the results of cooling times. The cooling time were 95.30 ± 1.93 min for refrigerator cooling at 0 °C, 116.47 ± 3.62 min for refrigerator cooling at 8 °C, 7.83 ± 0.29 min for vacuum cooling, 19.88 ± 1.49 min for air blast cooling at 0 °C, 25.28 ± 2.27 min for air blast cooling at 3 °C, and 39.61 ± 2.05 min for air blast cooling at 8 °C. Previous studies (McDonald et al., 2000; Zhang et al., 2013; Zhang and Sun, 2006b) showed that cooling cooked food by vacuum cooling is feasible. Table 4 also shows that vacuum cooling causes a reduction of cooling time compared with other cooling methods ($p < 0.001$). The differences in cooling time was due to different cooling mechanisms. Air blast cooling or refrigerator cooling process only involves convective and conductive heat transfer. However, vacuum cooling process comprises mass transfer and heat transfer accompanied by phase change (McCabe et al., 1993). As the pressure decreases, the evaporation temperature of water is lowered correspondingly. When the inside pressure of chamber decreases to the saturation pressure, which is correspondent to the initial temperature of the food, water in the product starts to evaporate (Zheng and Sun, 2004). The vacuum cooling could be regarded as a rapid cooling method with even cooling in a product. In addition, the results showed that at the same temperature level, air blast cooling generally has a higher cooling rate compared to refrigerator cooling ($p < 0.001$), as the forced air around the samples accelerates the cooling procedure. For example, when the ambient temperature was 0 °C, the cooling time of AB-1 (19.88 ± 1.49 min) was reduced significantly ($p < 0.001$) compared to the RC-1 (95.30 ± 1.93 min). Besides, for the air blast cooling and refrigerator cooling, the heat exchange driving force is the temperature difference between the air and the rice. Therefore, the lower the air temperature, the faster the cooling, and thus the shorter the cooling time of air blast and refrigerator cooling was. For example, the cooling time of RC-1 (95.30 ± 1.93 min) was reduced significantly ($p < 0.001$) compared to the RC-2 (116.47 ± 3.62 min). Because the air temperature difference between air blast cooling at 0 °C and 3 °C was small, there was no significant difference of the cooling time ($p > 0.001$).

Table 4
Cooling time of 0.02 kg cooked rice from 50 °C to 10 °C.

Cooling conditions	RC-1	RC-2	VC	AB-1	AB-2	AB-3
Cooling time/min	95.30[d]	116.47[e]	7.83[a]	19.88[b]	25.28[b]	39.61[c]
Standard deviation	1.93	3.62	0.29	1.47	2.27	2.05

Note: Means with different letters indicate significant difference ($p < 0.001$). RC-1 represents refrigerator cooling at 0 °C (RC-1), RC-2 represents refrigerator cooling at 8 °C, VC represents vacuum cooling, AB-1 represents air blast cooling at 0 °C, AB-2 represents air blast cooling at 3 °C, and AB-3 represents air blast cooling at 8 °C.

3.2. CF of different cooling methods

The CF of cooling one box of cooked rice from 50 °C to 10 °C was calculated by Eqs. (1)–(4). As the inputs were equipment (computer, data logger, and coolers), refrigerants (R22 and R404a), electricity, and plastic box, by multiplying these inputs with their respective emission factors, the total GHG emission of cooling one box of cooked rice under conditions RC-1 (0 °C), RC-2 (8 °C), VC, AB-1 (0 °C), AB-2 (3 °C), and AB-3 (8 °C) could be obtained.

The CF for cooling one box of cooked rice (Table 5), indicates 54.36 ± 1.07 gCO_2eq for refrigerator cooling at 0 °C (RC-1), 66.05 ± 2.00 g CO_2eq for refrigerator cooling at 8 °C (RC-2), 741.55 ± 27.26 g CO_2eq for vacuum cooling (VC), 1914.10 ± 141.24 g CO_2eq for air blast cooling at 0 °C (AB-1), 2463.61 ± 221.21 g CO_2eq for air blast cooling at 3 °C (AB-2), and 3916.54 ± 202.28 g CO_2eq for

Table 5
The carbon footprint of cooling 0.20 kg cooked rice from 50 °C to 10 °C.

Conditions	RC-1	RC-2	VC	AB-1	AB-2	AB-3
CF from Refrigerant/gCO_2eq	0.10 ± 0.00	0.13 ± 0.00	0.01 ± 0.00	0	0	0
CF from Equipment/gCO_2eq	0.04 ± 0.00	0.05 ± 0.00	0.15 ± 0.01	0.91 ± 0.07	1.15 ± 0.10	1.80 ± 0.09
CF from Data logger/gCO_2eq	0.01 ± 0.00	0.01 ± 0.00	0.00 ± 0.00	0.03 ± 0.00	0.03 ± 0.00	0.06 ± 0.00
CF from Computer/gCO_2eq	0.13 ± 0.00	0.16 ± 0.00	0.05 ± 0.00	0.30 ± 0.02	0.39 ± 0.03	0.61 ± 0.03
CF from Plastic product/gCO_2eq	1.73 ± 0.00	1.73 ± 0.00	1.73 ± 0.00	1.73 ± 0.00	1.73 ± 0.00	1.73 ± 0.00
CF from Electricity/gCO_2eq	52.35 ± 1.06	63.98 ± 1.99	739.60 ± 27.26	1911.13 ± 141.15	2460.63 ± 221.07	3912.01 ± 202.15
CF of cooling process/gCO_2eq	54.36 ± 1.07	66.05 ± 2.00	741.55 ± 27.26	1914.10 ± 141.24	2463.61 ± 221.21	3916.54 ± 202.28

Note: RC-1 represents refrigerator cooling at 0 °C (RC-1), RC-2 represents refrigerator cooling at 8 °C, VC represents vacuum cooling, AB-1 represents air blast cooling at 0 °C, AB-2 represents air blast cooling at 3 °C, and AB-3 represents air blast cooling at 8 °C.

air blast cooling at 8 °C (AB-3). For the inputs of the cooling unit, the electricity consumption dominated most of the carbon footprint, accounting for about 96.30% for refrigerator cooling at 0 °C (RC-1), 96.86% for refrigerator cooling at 8 °C (RC-2), 99.74% for vacuum cooling (VC), 99.84% for air blast cooling at 0 °C (AB-1), 99.87% for air blast cooling at 3 °C (AB-2), and 99.89% for air blast cooling at 8 °C (AB-3).

The minimal carbon footprint of the cooling process was produced by refrigerator cooling. Although vacuum cooling is the most rapid method, its carbon footprint was not the lowest while air blast cooling accounted for the greatest carbon footprint. The results also showed that with increasing cooling time, the CF of refrigerator cooling and air blast cooling method increased. Therefore, reducing the temperature of these cooling methods could decrease the carbon footprint of cooling one box of cooked rice. Although the cooling time of refrigerator cooling at 0 °C was longer than that of air blast cooling at 8 °C, the CF of refrigerator cooling at 0 °C was smaller than that of air blast cooling at 8 °C. This was related to the smaller output power of the refrigerator. On the other hand, the results showed that the difference of the carbon footprint of cooling between AB-1 and AB-3 processes was larger than the difference of that between RC-1 and RC-2, even though the cooling temperature difference was the same. This was also related to the difference of output power.

3.3. Sensitivity analysis

An important part of LCA is sensitivity analysis. Therefore, some factors not considered in the previous sections were analyzed here.

3.3.1. Carbon emission factor of equipment

The carbon emission of equipment had been assumed based on economic data. In this section, the carbon emission factors were changed into a mass emission factor for calculating the CF of cooling process. This was 3.54 kgCO_2eq/kg per kg of machinery mass, and the emission factor was also 2.0 kgCO_2eq/kg for the production of plastic (Rotz et al., 2010). The results Table 6 showed that the CF of the cooling process was stable for the equipment emission factors. This was mainly due to the small proportion of carbon emissions generated by equipment in the final CF of the product.

3.3.2. Electricity use efficiency

The electrical efficiency of the equipment varies for different types of equipment and remaining service life. In this study, electrical efficiencies of 30% higher and lower than the original value were used for the sensitivity analysis (Table 7). The resultant CFs for all the cooling methods varied by nearly 30% due to the change of the efficiency. This was mainly because the carbon emissions generated by electricity accounted for a large proportion of the final CF, i.e., the final carbon emissions were highly sensitive to electrical use efficiency.

3.3.3. Cooling load quantity

With the same equipment for a cooling process, different load quality could change the CF of the cooling process. Sensitivity analysis was carried out for the cooling process by changing the cooling loads to 9 boxes. Table 8 shows that the CF of the cooling process was reduced by 88.66% under conditions of RC-1 (0 °C), 86.10% under conditions of RC-2 (8 °C), 88.90% under conditions of VC, 94.11% under conditions of AB-1 (0 °C), 93.10% under conditions of AB-2 (3 °C), and 92.47% under conditions of AB -3 (8 °C). This occurred because electricity consumption was mainly related to the volume of the load. The cooling chambers could hold and chill many samples at the same time. When the load was only one box of cooked rice, the electricity consumption, which generated carbon emissions, accounted for more than 95% of the CF of cooling process, causing a considerable waste of electricity. As the load

Table 6
Sensitivity analysis for the emission factors of equipment.

Cooling conditions	Emission factor	CF of cooling process/g CO_2eq	Percentage of CF from equipment
RC-1	Based on economic data	54.36 ± 1.07	0.07%
	Based on mass data	54.31 ± 1.07	0.23%
RC-2	Based on economic data	66.05 ± 2.00	0.07%
	Based on mass data	65.99 ± 2.00	0.23%
VC	Based on economic data	741.55 ± 27.26	0.02%
	Based on mass data	741.53 ± 27.26	0.03%
AB-1	Based on economic data	1914.10 ± 141.24	0.05%
	Based on mass data	1913.54 ± 141.20	0.04%
AB-2	Based on economic data	2463.61 ± 221.21	0.05%
	Based on mass data	2462.87 ± 221.15	0.03%
AB-3	Based on economic data	3916.54 ± 202.28	0.05%
	Based on mass data	3915.42 ± 202.22	0.03%

Note: RC-1 represents refrigerator cooling at 0 °C (RC-1), RC-2 represents refrigerator cooling at 8 °C, VC represents vacuum cooling, AB-1 represents air blast cooling at 0 °C, AB-2 represents air blast cooling at 3 °C, and AB-3 represents air blast cooling at 8 °C.

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Table 7
Sensitivity analysis for the electrical use efficiency.

Cooling conditions	Electricity use efficiency	CF/g CO_2eq	Variation percentage
RC-1	+30%	38.66 ± 0.75	28.89%
	Original	54.36 ± 1.07	
	−30%	70.07 ± 1.39	
RC-2	+30%	46.86 ± 1.40	29.06%
	Original	66.05 ± 2.00	
	−30%	85.25 ± 2.60	
VC	+30%	519.62 ± 19.09	29.91%
	Original	741.55 ± 27.26	
	−30%	963.38 ± 35.44	
AB-1	+30%	1340.76 ± 98.90	29.95%
	Original	1914.10 ± 141.24	
	−30%	2487.44 ± 183.59	
AB-2	+30%	1725.52 ± 154.89	29.96%
	Original	2463.61 ± 221.21	
	−30%	3201.70 ± 287.53	
AB-3	+30%	2742.84 ± 141.64	29.97%
	Original	3916.54 ± 202.28	
	−30%	5090.24 ± 262.93	

Note: RC-1 represents refrigerator cooling at 0 °C (RC-1), RC-2 represents refrigerator cooling at 8 °C, VC represents vacuum cooling, AB-1 represents air blast cooling at 0 °C, AB-2 represents air blast cooling at 3 °C, and AB-3 represents air blast cooling at 8 °C.

Table 8
Sensitivity analysis for the amount of load.

Cooling conditions	Plastic box	CF/g CO_2eq	Variation percentage
RC-1	1 box	54.36 ± 1.07	88.66%
	9 boxes	6.16 ± 0.35	
RC-2	1 box	66.05 ± 2.00	86.10%
	9 boxes	9.18 ± 0.23	
VC	1 box	741.55 ± 27.26	88.90%
	9 boxes	82.31 ± 3.03	
AB-1	1 box	1914.10 ± 141.24	94.11%
	9 boxes	112.75 ± 1.77	
AB-2	1 box	2463.61 ± 221.21	93.10%
	9 boxes	170.04 ± 11.52	
AB-3	1 box	3916.54 ± 202.28	92.47%
	9 boxes	294.77 ± 23.99	

Note: RC-1 represents refrigerator cooling at 0 °C (RC-1), RC-2 represents refrigerator cooling at 8 °C, VC represents vacuum cooling, AB-1 represents air blast cooling at 0 °C, AB-2 represents air blast cooling at 3 °C, and AB-3 represents air blast cooling at 8 °C.

quantity increased, the percentage of electrical carbon emission in the CF per product decreased, resulting in a reduction of carbon emissions of the cooling process. This study showed that the CF of the cooling process was sensitive to cooling load quantity. The results of the sensitivity analysis demonstrated that an optimal load capacity could reduce energy consumption per unit load and resultant reduction of carbon emissions. Furthermore, repeated use of the pack box could also reduce the carbon emissions of the cooling process.

4. Conclusions

In this paper, the CF of cooling cooked rice was studied from the viewpoint of a unit operation. The required cooling times were 95.03 ± 1.93 for refrigerator cooling at 0 °C (RC-1), 116.47 ± 3.62 for refrigerator cooling at 8 °C (RC-2), 7.83 ± 0.29 for vacuum cooling (VC), 19.88 ± 1.47 for air blast cooling at 0 °C (AB-1), 25.28 ± 2.27 for air blast cooling at 3 °C (AB-2), and 39.61 ± 2.05 min for air blast cooling at 8 °C (AB-3). This study confirmed that vacuum cooling is an efficient method and is suitable for chilling cooked rice. The time of vacuum cooling was much shorter than the other cooling methods.

The CF of cooling one box of cooked rice were 54.36 ± 1.07 gCO_2eq for refrigerator cooling at 0 °C (RC-1), 66.05 ± 2.00 g CO_2eq for refrigerator cooling at 8 °C (RC-2), 741.55 ± 27.26 g CO_2eq for vacuum cooling (VC), 1914.10 ± 141.24 g CO_2eq for air blast cooling at 0 °C (AB-1), 2463.61 ± 221.21 g CO_2eq for air blast cooling at 3 °C (AB-2), and 3916.54 ± 202.28 g CO_2eq for air blast cooling at 8 °C (AB-3). In addition, the CF of cooling process was positively correlated with the output power of equipment and the cooling time. The CF of refrigerator cooling process was the minimum, because of the low output power of the refrigerator. Besides, the CF of air blast cooling process had the greatest CF compared with the other cooling processes. The carbon emissions from electrical consumption contributed to the majority of the CF of cooling process. In addition, the sensitivity of the parameters for the cooling process were examined including the carbon emission factors of equipment, electricity use efficiency, and the amount of load in the cooling process. The results showed that the carbon emission was highly sensitive to electricity use efficiency and load quantity, but it was stable for the originally applied equipment emission factors. Reducing equipment output power and increasing load quantity could significantly reduce the CF of the cooling processes.

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