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Effect of cooking conditions on iron release from pots and development of kinetic models for iron supplementation in NIPs

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ABSTRACT

The World Health Organization (WHO) has identified the use of iron cookware as a potential strategy for alleviating iron deficiency anaemia (IDA) and emphasises the need for action-oriented research in this area. In response to this need, our study systematically investigated the patterns of iron release from various types of cookware under different cooking conditions. Among these, nitrided iron pots (NIPs), the most widely used cookware, were selected for the development of kinetic models to predict iron release efficiently across a range of cooking temperatures and pH levels in food materials. Our results demonstrated that iron release from the pots was significantly influenced by cooking conditions such as the type of cookware, cooking temperatures, cooking times, types of acidic substances, and the pH of the cooking environment. Specifically, higher temperatures, longer cooking times, lower pH levels, and the presence of acetic acid were found to maximise iron release into food. We developed a series of kinetic models—Iron Release-Temperature Models (I, II, and III) and Iron Release-pH Models (IV, V, and VI)—to predict iron release from NIPs. The temperature models are applicable for cooking food with a pH of 5.00–6.00 within a temperature range of 50–100 °C, while the pH models are designed for food with a pH of 3.00–6.00 at boiling temperatures. Validation experiments confirmed the relative accuracy of these models. Additionally, when comparing the predicted iron release with the Recommended Nutrient Intake (RNI) guidelines, the findings support the efficacy of iron pots as a viable method for iron supplementation.

1. Introduction

Iron is the most abundant essential trace element in the human body and plays a crucial role in maintaining normal bodily functions (Charlebois and Pantopoulos, 2023; McClung, 2019). Normally, the body maintains a balance between iron absorption and metabolism. Inadequate iron intake can disrupt this balance, leading to diseases such as iron deficiency anaemia (IDA). IDA is a widespread nutritional deficiency that affecting many populations globally, particularly in low-income areas, such as impoverished regions in Africa, China, and Southeast Asia. In 2019, the World Health Organization (WHO) estimated that the prevalence of anaemia in children aged 6–59 months was 39.8%, with an additional 29.9% of women aged 15–49 also affected (WHO, 2021).

The primary cause of this high prevalence of IDA is inadequate dietary iron intake. The WHO (2014) recommends improving dietary diversity, consuming iron-fortified foods, or taking iron-containing supplements. In line with this guidance, the government of China attempted to implement iron-fortified meals for underprivileged students. Surprisingly, the rate of anaemia rose from 6.7% in 2016 to 10.0% in 2021 (China Food Newspaper, 2022). This unexpected increase may be due to the high cost and limited availability of the meal, suggesting that methods requiring significant financial investment may not be suitable for low-income populations where IDA is most prevalent. Exploring methods of to introduce low-cost iron sources might be an effective intervention strategy to combat IDA. Among these methods, using iron cooking pots is considered potentially effective, and falls under the category of action-oriented research needs as indicated by the WHO (2001). During the cooking process, iron in pots may become ionised by hydrogen ions donated by proton donors such as acetic acid, citric acid, and lactic acid. The released Fe^{2+} and Fe^{3+} can be effectively absorbed and utilised, providing a theoretical basis for the claim that

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"iron pots are effective for iron supplementation."

Empirical evidence from cooking experiments also supports this claim. Xing et al. (2018) compared the iron content of pea paste cooked in iron pots with that cooked in clay pots. They found that the iron content in pea paste cooked in iron pots was 21.4 ± 1.0 mg/100 g, which was 3.3 times higher than that in clay pots. Kröger-Ohlsen et al. (2002) reported that the iron content in maize porridge cooked in iron pots increased by 2–9 times, and the addition of citric acid to the porridge resulted in approximately twice the iron content compared to samples with lactic acid. However, other studies have reported conflicting results. Charles et al. (2011) conducted a randomised controlled intervention using a fish-shaped iron ingot to cook food, aiming to address iron deficiency among rural women in Cambodia. They found that iron supplementation through food cooked with iron ingots was effective in the short term for IDA, but the long-term results were less favourable. Sharieff et al. (2008) determined the effectiveness of iron supplementation through cooking in cast iron pots, blue steel pots, and with oral iron supplements, concluding that iron pots did not effectively control the development of IDA. Thus, the claim that "iron pots are effective for iron supplementation" remains controversial.

Actually, the release of iron from pots is influenced by various factors, such as the type of iron pots, the pH of the food materials, cooking temperature, and cooking time. However, these factors are rarely investigated comprehensively, which may account for the conflicting results mentioned above. Therefore, further studies are necessary to address the action-oriented research needs highlighted by the WHO and to either support or refute the claim that "iron pots are effective for iron supplementation."

In addition, the release of iron from pots is likely to follow principles of chemical reaction kinetics. Although kinetic models specifically for the release of iron from pots have not been reported to date, related studies show that metal release behaviour in acidic food packaging materials typically adheres to zero or first-order chemical reaction kinetics, and that the relationship between reaction rate constants and temperatures aligns the Arrhenius model (Koontz et al., 2020; Li, 2020). Developing kinetic models for the most commonly used cooking conditions could significantly reduce the financial expenditure associated with experimental procedures could be significantly reduced if kinetic models could be developed for the most commonly used cooking conditions pertaining to the release of iron from pots. Given that widely used nitrided iron pots (NIPs) are highly wear-resistant, corrosion-resistant, and do not rust easily, they are considered suitable subjects for research into the development of kinetic models for the iron release process.

The objectives of this study are threefold: (1) to investigate the effect of cooking conditions on the release of iron from pots, addressing the action-oriented research needs recommended by the WHO; (2) to develop kinetic models for predicting iron release in NIPs, and validate the accuracy of these models; and (3) to predict the release of iron from NIPs during the cooking of various acidic foods and compare these results with the Recommended Nutrient Intake (RNI) to evaluate the validity of the claim that "iron pots are effective for iron supplementation."

2. Materials and methods

2.1. Materials

Cast iron pots (CIPs), refined iron pots (RIPs), NIPs, and stainless steel pots (SSPs), as along with vinegar, tomatoes, and pickled vegetables, were purchased from local supermarkets (Guiyang, Guizhou, China). The glass pot used in the control group was obtained from Hejian BH Glass Products Co., Ltd (Cangzhou, Hebei, China). Chemical reagents, including acetic acid, citric acid monohydrate, and lactic acid, were sourced from Jinshan Chemical Reagent Co., Ltd (Chengdu, Sichuan, China).

2.2. Methods for simulating acidic cooking environments

Most foods contain a complex mixture of acids, including acetic acid, citric acid, and lactic acid. Therefore, these acids were selected to study iron release under different cooking conditions. To further ensure pH stability, acetate, citrate, and lactate buffers were employed to simulate various acidic cooking environments and pH levels.

2.3. Cooking conditions affecting the release of iron from pots

2.3.1. Cooking temperatures

To ensure relatively stable iron release results, all pots were soaked in 10% acetic acid for 1 h in advance. The CIPs, RIPs, NIPs, and SSPs were then preheated in a thermostatic water bath (HH.S21-4, Boxun Medical Biological Instrument Co., Ltd., Shanghai, China) to the specified temperatures of 50, 60, 70, 80, 90, and 97 °C (the boiling point of water in Guiyang, Guizhou, China), respectively. Given that the pH of commonly cooked food materials ranges from 4.50 to 6.50 (Featherstone, 2015), the acetate, citrate, and lactate buffers were calibrated to a pH of 5.50 using a pH meter (PHS-3C, INASE Scientific Instrument Co., Ltd., Shanghai, China) and then maintained in a constant temperature sink (DK-8D, Bluepard Experimental Instrument Co., Ltd., Shanghai, China) (Featherstone, 2015). A total of 1 L of each buffer was added to each pot, and the release of iron was measured after 1 h.

2.3.2. Cooking times

The NIPs and SSPs were preheated to the specified temperatures mentioned above. Then, 1 L of acidic buffer, at the same temperature and with a pH of 5.50, was added to each pot. Samples were taken at 10-min intervals to determine the release of iron during the cooking process. The buffer was replenished immediately after each sample was collected. This entire procedure was repeated to study the effect of cooking time on the release of iron from pots under different acidic cooking environments.

2.3.3. Types of acidic substances

Sample treatment methods were similar to those described in section 2.3.2 except that the NIPs and SSPs were preheated to 97 °C. The procedure was repeated to investigate the effect of acidic cooking environments, simulated by acetate, citrate, and lactate buffers, on the release of iron from the pots.

2.3.4. pH of acidic cooking environments

Sample treatment methods were similar to those described in section 2.3.2 except that the NIPs and SSPs were preheated to 97 °C, and 1 L of buffer with a specific pH preheated to the same temperature was added to each pot. The entire procedure was repeated to study the effect of different pH levels (3.00, 4.00, 5.00, and 6.00) on the release of iron from the pots under various acidic cooking environments.

2.4. Determination of iron release from pots

The release of iron from the pots was analysed using the 1,10-phenanthroline method, as described by Gutiérrez et al. (2016) with slight modifications. A standard curve was first established to determine the total iron release (including Fe^{2+} and Fe^{3+}) from the pots using a series of standard solutions with Fe^{2+} concentrations ranging from 0.00 to 0.20 mg/L. The absorbance of $[Fe(phen)_3]^{2+}$, an orange-coloured iron complex formed after the addition of 1,10-phenanthroline, was measured at 510 nm with a visible spectrophotometer (722N, INESA Instrument Co., Ltd, Shanghai, China). The standard curve used to determine iron release is illustrated in Fig. 1, with a linear regression equation of $y = 0.2012x + 0.0002$ and a coefficient of determination (R^2) of 0.9994. Fe^{3+} in the samples was reduced to Fe^{2+} using hydroxylamine hydrochloride. The absorbance of these samples was then measured similarly, and the iron release from the pots was calculated using the standard curve. For

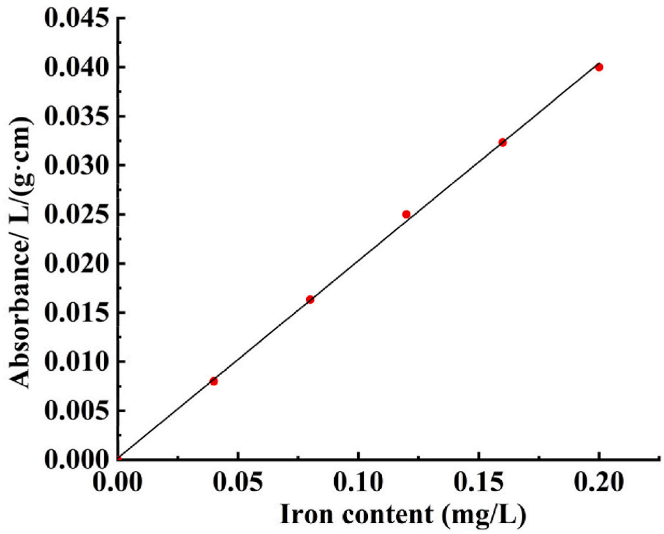

Fig. 1. Standard curve used to determine iron release from pots.

samples with precipitation, a filtration step was performed prior to measurement.

2.5. Development of kinetic models for iron supplementation in NIPs

Typically, metal release follows either zero or first-order reaction kinetics (Koontz et al., 2020; Sander et al., 2018). The linear equation for the zero-order reaction kinetics model of iron release from pots is expressed as Eq. (1):

$$C_A = C_0 - k_0 t \tag{1}$$

where C_A and C_0 represent the iron release from the pots during the cooking process and the corresponding initial values (mg/L), respectively; t denotes the reaction time (min); k_0 is the zero-order reaction rate constant.

The linear equation for the first-order reaction kinetics model of iron release from pots is expressed as Eq. (2):

$$\ln C_A = \ln C_0 - k_1 t \tag{2}$$

where k_1 is the first-order reaction rate constant.

The relationship between cooking temperature (T) and the chemical reaction rate constants (k) is described by the Arrhenius equation, as given in Eq. (3) (Forouzesh et al., 2023):

$$\ln k = -\frac{E_a}{RT} + \ln A \tag{3}$$

where Ea is the reaction activation energy (kJ/mol), R is the gas constant (8.314 J/mol·K), and A is the pre-exponential factor.

These equations can be used to establish a correlation between C_A and C_0, facilitating the calculation of k_0 or k_1 at a given temperature. By integrating these chemical reaction kinetics equations with Eq. (3), correlations between C_A, T, and can be derived, enabling the development of kinetic models to predict iron release from NIPs at different cooking temperatures. Additionally, correlations between C_A, pH, and t can be established to create kinetic models for predicting iron release from NIPs when cooking food materials at various pH levels.

2.6. Validation of kinetic models for iron supplementation in NIPs

Commonly used food materials, including diluted vinegar, tomatoes, and pickled vegetables, which are rich in acetic, citric, and lactic acids, respectively, were employed to test the reliability of the kinetic models. Since most foods are cooked at the boiling point when using water as a heat transfer medium, validation conditions were set at the local boiling point of water (97 °C). To align with the application conditions of the iron release kinetic models, 200 g of food materials were mixed with a specific amount of deionised water to achieve a total cooking pH of 5.50. For the kinetic model validation, diluted vinegar, tomato soup, and pickled vegetable soup were prepared by adding 800 g of deionised water to 200 g of food materials, and their actual pH values were recorded. A glass pot was used in the control test to eliminate the influence of iron present in the food materials themselves. The iron release results predicted by the kinetic models were compared with the corresponding experimental data, and the relative error was analysed to assess the reliability of the models. To maintain consistency with weight units, the mg/L unit used in the model development was converted to mg/kg starting for this section. The conditions to for validating the kinetic models for iron supplementation in NIPs are shown in Table 1.

2.7. Statistical analysis

Each experiment was conducted in triplicate. Data were processed using Microsoft Excel 2021 (Microsoft Corp, Redmond, WA, USA). Graphs were obtained using Origin 2022 software (OriginLab Corp., Northampton, MA, USA).

3. Results

3.1. Analysis of iron release from pots under different cooking conditions

3.1.1. Cooking temperatures

As illustrated in Fig. 2, the release of iron from the pots in the acidic buffer increased with temperature, as the elevated temperature accelerated the movement of iron, thus enhancing the chemical reaction rate of iron release from the pots. The highest iron release in all pots occurred in acidic cooking environments simulated by citrate buffer (Fig. 2b), with iron release values of 7.68, 6.85, and 6.42 mg/L in the CIPs, RIPs, and NIPs, respectively. In contrast, the corresponding result for the SSPs was 2.84 mg/L, significantly lower than the iron release observed in the other pots. This discrepancy is attributed to the electrochemical reaction induced by the “iron-carbon” galvanic couples, which enhances the corrosion of iron in the pots. Generally, iron pots with higher carbon content tend to have more “iron-carbon” galvanic couples, thereby increasing the electrochemical reaction (Konovalova, 2021). The carbon content of CIPs ranges from 2.5% to 4%, while that of RIPs is less than 0.02%. The carbon content of NIPs is similar to that of RIPs. However, the thin nitriding layer on the surface of NIPs inhibits the formation of “iron-carbon” galvanic couples, leading to relatively low iron release from NIPs. The SSPs contain only 60%–70% iron, whereas the other iron pots mentioned contain more than 90% iron. Additionally, a film of iron and chromium oxides is present on the inner surface of SSPs (Lodhi et al., 2018). The results indicate that this film was not conducive to the corrosion release of iron, resulting in the lowest maximum iron release from the SSPs.

Table 1
Conditions to validate kinetic models for iron supplementation in NIPs.

Food materials	Iron release-temperature kinetic models		Iron release-pH kinetic models	
	Cooking temperatures (°C)	pH levels	Cooking temperatures(°C)	pH levels
Diluted vinegar	97	5.50	97	3.00
Tomato soup	97	5.50	97	4.60
Pickled cabbage soup	97	5.50	97	3.90

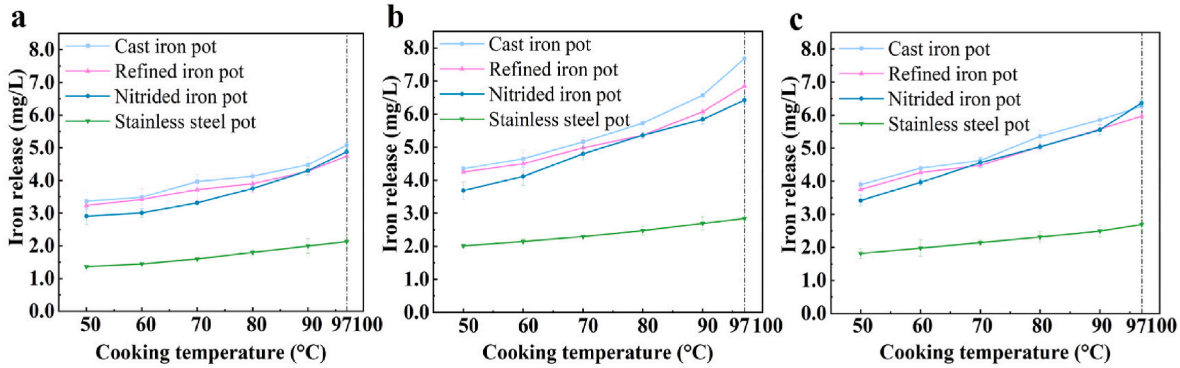

Fig. 2. Iron release from pots at different cooking temperatures in simulated acidic cooking environments: acetate buffer (a), citrate buffer (b), and lactate buffer (c).

3.1.2. Cooking times

A linear relationship was observed between cooking times and iron release from both NIPs and SSPs (Fig. 3). According to Kahyarian et al. (2017), the presence of an adequate concentration of hydrogen ions led to the formation of numerous minute conductive structures on the surface of the pot in contact with the buffer. These structures enhanced the reaction rate on the pot surface, allowing hydrogen ions to intercept free electrons from the iron and facilitate subsequent iron oxidation. As the cooking duration increased, the reaction with hydrogen ions on the pot surface continued, resulting in the detachment of a greater quantity of iron from the metal phase and an increased release of iron. Notably, after cooking at 97 °C for 60 min, the iron release from NIPs in acetate buffer, citrate buffer, and lactate buffer increased to 4.91, 6.07, and 5.82 mg/L, respectively, which were 2.13–2.30 times higher than that from SSPs under the same conditions.

3.1.3. Types of acidic substances

The highest cumulative release of iron in NIPs occurred in the acidic environment simulated by citrate buffer, followed by lactate buffer and acetate buffer, as shown in Fig. 4. A similar trend was observed in SSPs as well. Generally, organic acids with oxygen-containing functional groups, such as -OH and -COOH, are capable of forming complexes with metal ions (Geng et al., 2020; Liu et al., 2017). Citric acid, a polyacid with a higher number of hydroxyl and carboxyl groups, formed more organic acid-metal ion complexes compared to lactic acid and acetic acid. Additionally, the stability constants of citric acid-metal ion complexes were found to be higher than those of lactic or acetic acid-metal ion complexes (Zhang et al., 2022).

3.1.4. pH of acidic cooking environments

The release of iron from NIPs and SSPs at different pH levels is depicted in Fig. 5. Iron release was observed to increase as the pH of the acidic buffers decreased, due to the higher concentration of hydrogen ions, which readily react with iron to facilitate its release (Demont et al., 2012). After 60 min of boiling in a highly acidic environment simulated by a citrate buffer at pH 3.00, the iron release from NIPs and SSPs reached levels of 7.64 mg/L and 3.73 mg/L, respectively. This indicates that the buffer system can ionise more hydrogen ions in a highly acidic environment.

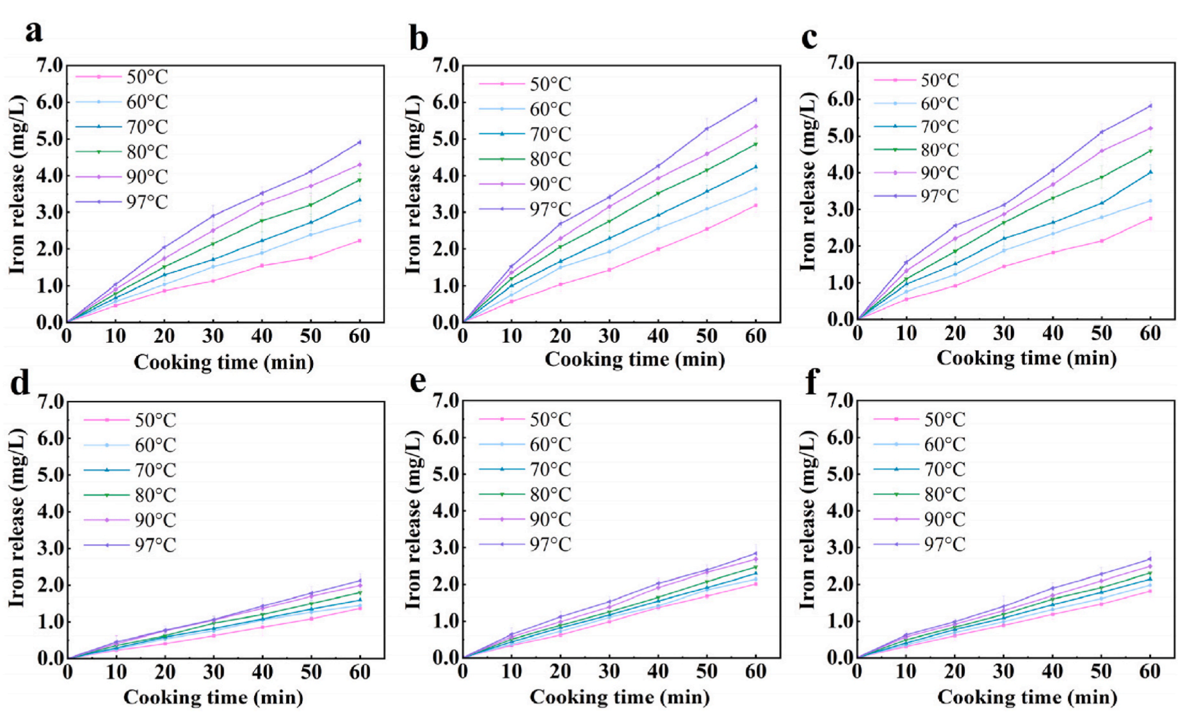

Fig. 3. Iron release from NIPs and SSPs at different cooking times in simulated acidic environments: acetate buffer (a, d), citrate buffer (b, e), and lactate buffer (c, f).

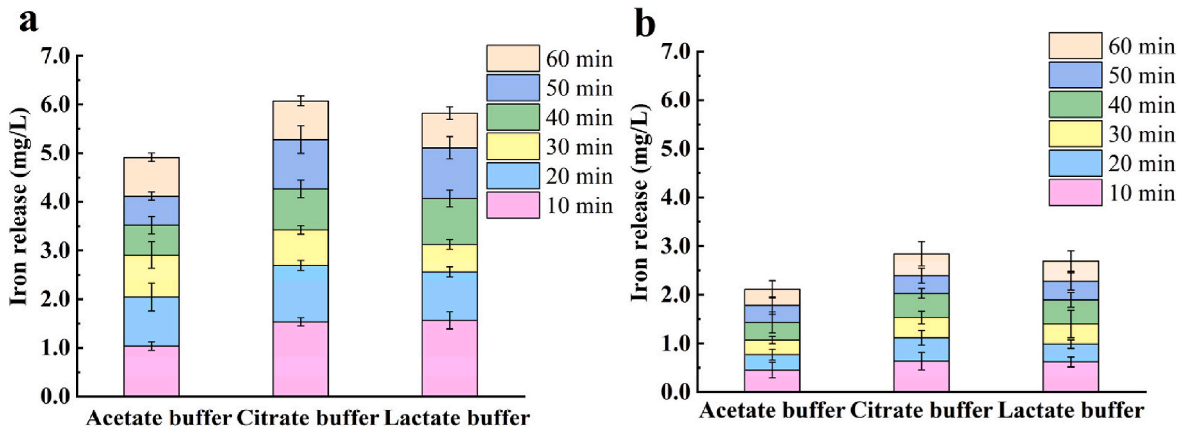

Fig. 4. Cumulative release of iron in NIPs (a) and SSPs (b) in acidic cooking environments simulated by different buffer types.

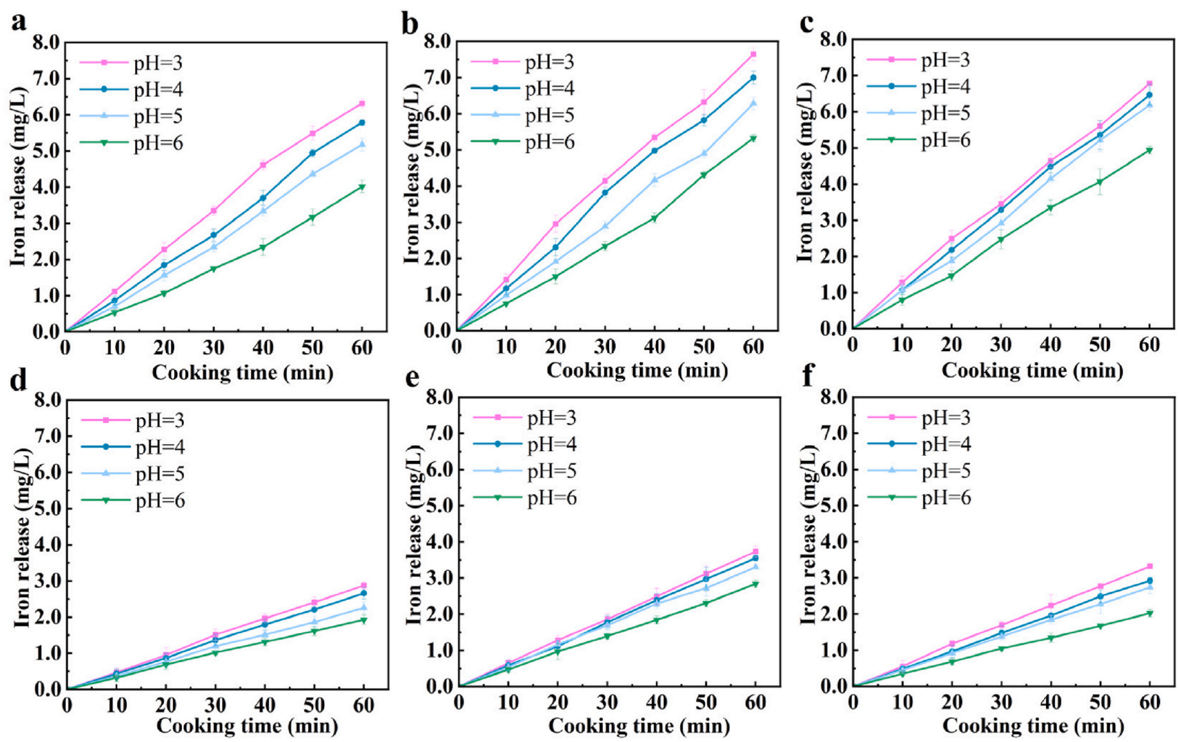

Fig. 5. Iron release from NIPs and the SSPs at different pH levels in simulated acidic cooking environments: acetate buffer (a, d), citrate buffer (b, e), and lactate buffer (c, f).

3.2. The kinetic models for iron supplementation in NIPs

3.2.1. The iron release-temperature kinetic models

Table 2 presents the kinetic parameters for the release of iron from NIPs under different acidic cooking environments at various temperatures. A comparison of the coefficients for the zero-order and first-order reaction kinetic models revealed that the release of iron from NIPs during the cooking process was consistent with the zero-order reaction kinetic model.

Fig. 6 presents a comparison of the rate constants under buffer-simulated acidic cooking environments in NIPs. As the cooking temperature increased, the concentration of iron in the solution also rose, indicating that higher temperatures positively affect the release of iron from the pots.

Fig. 7 illustrates the Arrhenius plots for iron release from NIPs in different acidic cooking environments. The Arrhenius activation energy (*Ea*) for iron release was calculated to be 17.12, 15.03, and 16.48 kJ/mol for acetate buffer, citrate buffer, and lactate buffer, respectively. The corresponding pre-exponential factor (*A*) was computed as 22.45, 14.06, and 21.48, respectively.

The iron release-temperature kinetic models, which characterise iron release from NIPs based on the acidic cooking environments simulated by acetate buffer, citrate buffer, and lactate buffer are denoted as Model (I), Model (II), and Model (III), respectively. These models can be used to predict the iron release from NIPs when cooking food materials with a pH ranging from 5.00 to 6.00 at temperatures between 50 °C and 100 °C.

$$C_{A,T} = t \times 22.45 \times \exp\left(\frac{-2059.39}{T}\right) \quad \text{(I)}$$

$$C_{C,T} = t \times 14.06 \times \exp\left(\frac{-1808.16}{T}\right) \quad \text{(II)}$$

Table 2
Kinetic parameters of iron release from NIPs under different acidic cooking environments at various temperatures.

Buffer types	Temperatures (°C)	Zero-order		First-order	
		k_0	R^2	k_1	R^2
Acetate buffer	50	0.0373	0.9972	0.0297	0.9364
	60	0.0477	0.9986	0.0304	0.9396
	70	0.0560	0.9982	0.0300	0.9388
	80	0.0667	0.9973	0.0300	0.9215
	90	0.0761	0.9955	0.0295	0.9066
	97	0.0857	0.9949	0.0288	0.9031
Citrate buffer	50	0.0514	0.9987	0.0333	0.9678
	60	0.0627	0.9973	0.0295	0.9254
	70	0.0727	0.9968	0.0278	0.9569
	80	0.0852	0.9943	0.0267	0.9413
	90	0.0947	0.9928	0.0261	0.9366
	97	0.1066	0.9934	0.0261	0.9420
Lactate buffer	50	0.0457	0.9987	0.0309	0.9521
	60	0.0567	0.9960	0.0282	0.9427
	70	0.0672	0.9953	0.0272	0.9622
	80	0.0803	0.9950	0.0272	0.9421
	90	0.0916	0.9946	0.0265	0.9555
	97	0.1020	0.9931	0.0255	0.9628

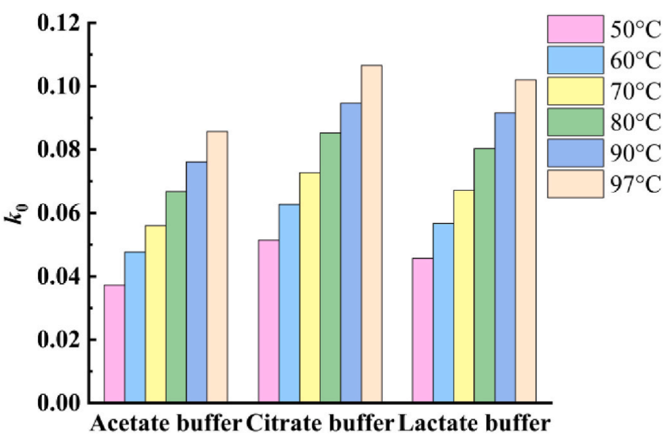

Fig. 6. Chemical reaction rate constants under buffer-simulated acidic cooking environments in NIPs.

$$C_{L,T} = t \times 21.48 \times \exp\left(\frac{-1981.79}{T}\right) \tag{III}$$

3.2.2. *The iron release-pH kinetic models*

Table 3 presents the kinetic parameters for the release of iron from NIPs under different acidic cooking environments simulated by buffers with various pH levels. The coefficient for zero-order reaction kinetics was greater than that for first-order reaction kinetics, indicating that the iron release from NIPs during cooking follows the zero-order reaction kinetic model.

Fig. 8 illustrates the relationship between k_0 and pH in different acidic cooking environments. The corresponding coefficients of determination (R^2) were all greater than 0.9910. The iron release rate constant (k_0) in the NIPs tended to increase gradually as the buffer pH decreased.

The iron release-pH kinetic models, which characterise iron release from NIPs based on the acidic cooking environments simulated by acetate buffer, citrate buffer, and lactate buffer, are denoted as Model (IV), Model (V), and Model (VI), respectively. These models can be used to predict the release of iron from NIPs when cooking food materials with a pH between 3.00 and 6.00 at boiling temperatures.

$$C_{A,pH} = (-0.0019pH^2 + 0.0025pH + 0.1186)t \tag{IV}$$

$$C_{C,pH} = (-0.0014pH^2 - 0.0029pH + 0.1520)t \tag{V}$$

$$C_{L,pH} = (-0.0020pH^2 + 0.0044pH + 0.1260)t \tag{VI}$$

The iron release-pH kinetic models illustrate the interactions between iron release, the pH of food materials, and cooking times, as depicted in Fig. 9. The results demonstrated that the iron release from NIPs was significantly enhanced by lower pH levels and longer cooking times.

Table 3
Kinetic parameters of iron release from NIPs under acidic cooking environments simulated by acidic buffers with various pH levels.

Buffer types	pH levels	Zero-order		First-order	
		k_0	R^2	k_1	R^2
Acetate buffer	3.00	0.1094	0.9988	0.0332	0.9173
	4.00	0.0954	0.9989	0.0365	0.9409
	5.00	0.0847	0.9984	0.0383	0.9352
	6.00	0.0629	0.9957	0.0389	0.9574
Citrate buffer	3.00	0.1303	0.9982	0.0313	0.9121
	4.00	0.1189	0.9988	0.0343	0.9147
	5.00	0.1014	0.9987	0.0356	0.9471
	6.00	0.0844	0.9966	0.0378	0.9578
Lactate buffer	3.00	0.1217	0.9983	0.0313	0.9186
	4.00	0.1109	0.9986	0.0361	0.9105
	5.00	0.995	0.9982	0.0372	0.9297
	6.00	0.0808	0.9983	0.0362	0.9463

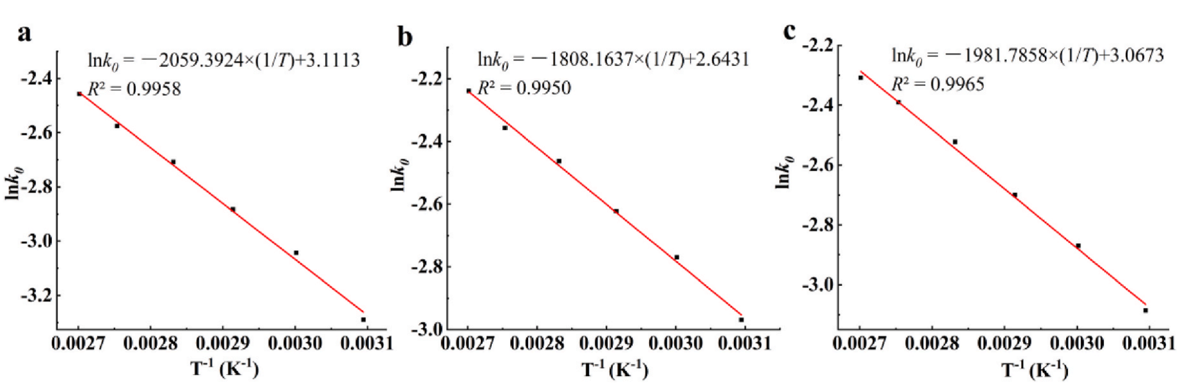

Fig. 7. Arrhenius plots illustrating the changes in the release of iron from NIPs under acidic cooking environments simulated by acetate buffer (a), citrate buffer (b), and lactate buffer (c), respectively.

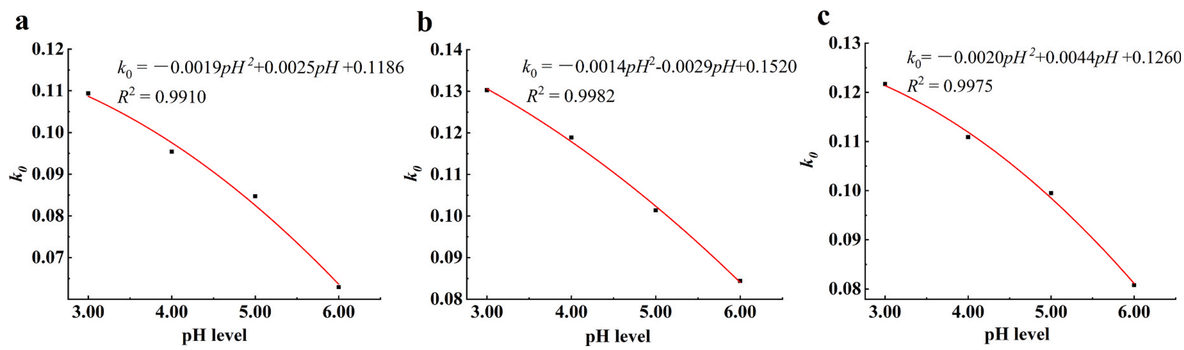

Fig. 8. Linear fit between the iron release rate constant (k_0) and the pH of different acidic cooking environments simulated by different buffers: acetate buffer (a), citrate buffer (b), and lactate buffer (c).

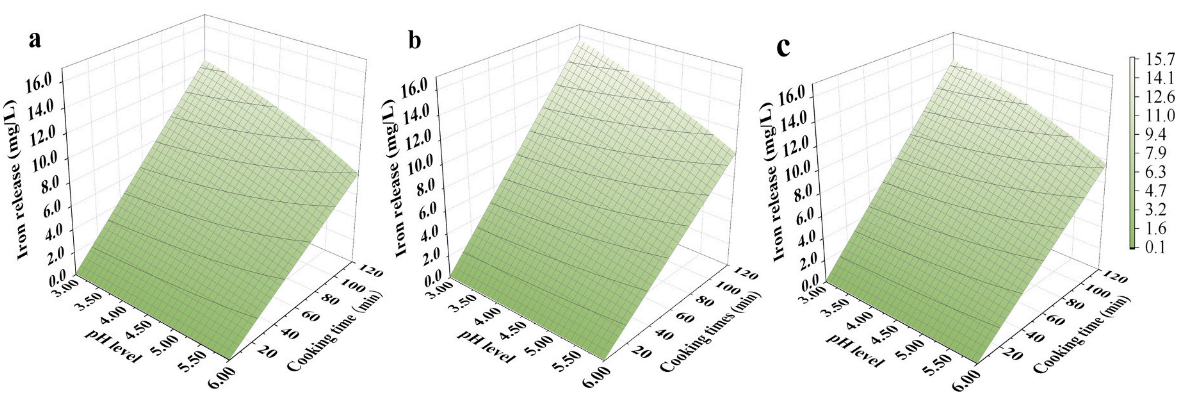

Fig. 9. Visual representation of the interactions between the release of iron, the pH of food materials, and cooking times in acidic cooking environments simulated by acetate buffer (a), citrate buffer (b), and lactate buffer (c), respectively.

3.3. Reliability of the kinetic models for iron supplementation in NIPs

3.3.1. The iron release-temperature kinetic models

The comparison between the predicted and measured results for iron release from NIPs is presented in Table 4. The discrepancy between the predicted and measured results for iron release in NIPs while cooking diluted vinegar, tomato soup, and pickled cabbage soup ranged from −3.49% to −16.77%, 3.11% to −22.01%, and −9.10% to −24.54%, respectively. Overall, these errors fall within an acceptable range, indicating that the iron release-temperature kinetic models are reliable.

3.3.2. The iron release-pH kinetic models

The comparison between the predicted and measured results for iron release from NIPs is shown in Table 5. The relative errors between the predicted and measured results for iron release while cooking diluted vinegar, tomato soup, and pickled cabbage soup ranged from 0.91% to −21.31%, 0.58% to −21.73%, and −2.38% to −24.71%, respectively. Overall, these errors fall within an acceptable range, suggesting that the iron release-pH kinetic models are reliable.

For all kinetic models, the discrepancy between the predicted and measured results of iron release increased significantly when the

Table 4
Comparison of the predicted and measured results of iron release from NIPs based on the iron release-temperature kinetic models.

Foods	Cooking temperatures (°C)	Major acid components	Application models	pH levels	Cooking times (min)	Predicted results (mg/kg)	Measured results (mg/kg)	Relative errors (%)
Diluted vinegar	97	Acetic acid	I	5.50	10	0.86	0.79	−9.37
					20	1.72	1.51	−13.45
					30	2.58	2.28	−13.20
					40	3.44	3.32	−3.49
					50	4.29	3.70	−16.04
					60	5.15	4.41	−16.77
Tomato Soup	97	Citric acid	II	5.50	10	1.06	1.28	17.13
					20	2.12	2.19	3.11
					30	3.18	3.07	−3.78
					40	4.24	3.78	−12.32
					50	5.30	4.46	−19.04
					60	6.37	5.23	−22.01
Pickled cabbage soup	97	Lactic acid	III	5.50	10	1.02	0.92	−10.67
					20	2.03	1.86	−9.10
					30	3.05	2.66	−14.67
					40	4.06	3.39	−19.99
					50	5.08	4.08	−23.42
					60	6.09	4.81	−24.54

Table 5
Comparison of the predicted and measured results of iron release from NIPs based on the iron release-pH kinetic models.

Foods	Cooking temperatures (°C)	Major acid components	Application models	pH levels	Cooking times (min)	Predicted results (mg/kg)	Measured results (mg/kg)	Relative errors (%)
Diluted vinegar	97	Acetic acid	IV	3.00	10	1.09	1.10	0.91
					20	2.18	1.86	−17.07
					30	3.27	2.74	−19.33
					40	4.36	3.77	−15.73
					50	5.45	4.74	−14.86
					60	6.54	5.39	−21.31
Tomato soup	97	Citric acid	V	4.60	10	1.09	1.05	−3.81
					20	2.18	2.19	0.58
					30	3.27	3.07	−6.49
					40	4.36	3.85	−13.27
					50	5.45	4.61	−18.20
					60	6.54	5.37	−21.73
Pickled cabbage Soup	97	Lactic acid	VI	3.90	10	1.13	1.27	10.93
					20	2.25	2.51	10.11
					30	3.38	3.30	−2.38
					40	4.51	4.21	−6.99
					50	5.64	4.83	−16.76
					60	6.76	5.42	−24.71

cooking time exceeded 50 min. This phenomenon may be attributed to the formation of a passivation film on the surface of NIPs during the prolonged cooking. In typical home cooking processes, the cooking time for most foods is usually less than 30 min. During this period, the kinetic models developed in this study can provide reasonably accurate predictions of iron release from NIPs.

4. Discussion

4.1. Prediction of iron release in NIPs according to the kinetics models

The WHO (2004) has established the RNI for iron, which varies according to sex, age group, and iron bioavailability. For adult males, adult females, and males and females aged 11–17 years, the RNI ranges is 9.1–27.4, 19.6–58.8, 9.7–37.6, and 20.7–65.4 mg/d, respectively. The kinetic models encompassing a range of cooking temperatures (Models I, II, and III) and pH levels (Models IV, V, and VI) were employed to predict the release of iron from NIPs during specific cooking processes. Iron intake was calculated based on the quantity of cooked food consumed per person per day. By comparing the predicted iron intake with the RNI data provided by the WHO, it is possible to determine whether cooking food in NIPs at specific temperatures or with food materials at certain pH levels can meet the human body's iron intake requirements.

4.1.1. Cooking temperatures

Our research demonstrated that elevated cooking temperatures facilitate the release of iron from pots. It was hypothesised that acidic foods, with a pH range of 5.00–6.00, comprising various organic acids were subjected to temperatures of 80, 90, and 100 °C in NIPs, with cooking periods ranging from 10 to 120 min. The predicted ranges of iron intake for the human body, based on the consumption of 300 g of these foods cooked in NIPs, are presented in Table 6.

According to the data presented in Table 6, assuming a daily consumption of 300 g each of diluted vinegar, potatoes, and cheese, the total iron supplementation from both the food materials and NIPs ranged from 10.28 to 17.82, 10.39–19.16, and 10.52–20.64 mg/d, respectively, with cooking temperatures set at 80 °C, 90 °C, and 100 °C, and cooking times ranging from 10 to 120 min. The lowest iron release within these ranges exceeded the minimum iron requirements for adult males and males aged 11–17 years, as indicated by the RNI data. A greater release of iron from pots is likely because most cooking processes occur at or above the boiling point of water. For adult females and females aged 11–17 years, the total iron intake from the food system can be sufficient to meet the minimum RNI requirement when the cooking temperature is 100 °C and the cooking time exceeds 100 min. This could help alleviate and ameliorate the issue of IDA to some extent.

4.1.2. Food materials

The iron release-pH kinetic models developed in section 3.2.2 should be applied when the pH of the cooking environment ranges from 3.00 to 6.00. Within this range, a pH of 4.60 serves as the boundary between low-acid and acidic foods. Foods with a pH below 4.60 are classified as acidic and typically contain high levels of organic acids, such as those found in most fruits, vegetables, and fermented foods. Foods with a pH above 4.60 are classified as low-acid and include high-protein and starchy foods (Balestrini et al., 2022). Based on this classification, various types of food materials were used to calculate the final iron intake per person per day. It was assumed that common food materials with a pH ranging from 3.00 to 6.00 were cooked in NIPs at 100 °C, with the cooking time controlled within a range of 10–120 min. The predicted

Table 6
Predicted iron intake after consumption of food cooked in NIPs at various temperatures.

Consumption regions	Food materials	Main acids	pH levels	Iron content in food materials (mg/100 g)	Predictive models	Predicted results of iron release from NIPs (mg/kg)			Iron supplementation with 300 g of the corresponding food(mg/300 g)		
						80 °C	90 °C	100 °C	80 °C	90 °C	100 °C
Global	Vinegar	Acetic acid	5.00–5.60	0.00	I	0.66–7.90	0.77–9.28	0.90–10.80	0.20–2.37	0.23–2.78	0.27–3.24
Global	Potato	Citric acid	5.40–5.90	0.80	II	0.84–10.08	0.96–11.61	1.11–13.27	2.65–5.42	2.69–5.88	2.73–6.38
Global	Cheese	Lactic acid	5.00–5.30	2.40	III	0.78–9.42	0.91–10.99	1.06–12.73	7.43–10.03	7.47–10.50	7.52–11.02

* The pH and iron content data shown in Tables 6 and 7 are both obtained from the references (FDA/CFSAN, 2003; Zhejiang University, 2022).

ranges of iron intake for the human body when consuming 300 g of foods cooked in NIPs under various pH environments are presented in Table 7.

The data presented in Table 7 enables us to discuss the specific daily intake of food cooked in NIPs under two scenarios. In the first scenario, where an individual consumes a mixture of 900 g of various food materials, the intake of low-acid foods containing citric acid, such as millet grain (300 g), sweet potato (300 g), and plantain (300 g), results in a total iron release of 19.45–28.76 mg/d. Alternatively, if the food materials are replaced with acidic foods containing lactic acid, such as lafun, bamboo shoots, and pickled cabbage, the total iron release ranges from 29.38 to 40.41 mg/d. In the second scenario, assuming the consumption of 900 g of a single food item like kocho, an acidic food with a pH of 4.50, the total iron release is 48.51–57.57 mg/d. For Jinhua ham, a low-acid food with a pH of 5.54, the total iron release ranges from 20.61 to 29.40 mg/d. Compared to the RNI established by the WHO, the lowest iron release within these ranges exceeds the minimum iron requirements for adult males, adult females, and males and females aged 11–17 years. Therefore, regular consumption of acidic foods cooked in NIPs can adequately meet the daily iron supplementation needs of these groups. In daily life, individuals can choose various acidic foods cooked in NIPs according to their specific iron requirements. For example, individuals with IDA are recommended to consume acidic foods with high iron content, such as lafun, gowe, and chili sauce. Conversely, those who have already received sufficient iron supplementation can opt for low-acid foods cooked in NIPs.

4.2. *Assessment of the claim: "iron pots are effective for iron supplementation."*

As shown in section 4.1, the total amount of iron that can be supplied by NIPs and 300 g of lafun, as predicted by the kinetic models, ranges from 22.40 to 25.97 mg/300 g. This indicates that consuming a single type of food material can meet the minimum RNI iron requirements for adult males, adult females, and males and females aged 11–17 years. Additionally, when the cooking temperature is 100 °C and the cooking time is 120 min, using a nitrided cast iron pot to cook 300 g each of diluted vinegar, potatoes, and cheese can provide a maximum total iron amount of 20.64 mg per day, which is sufficient to meet the minimum RNI iron requirements for adult males and males aged 11–17 years. Thus, for individuals with mild iron deficiency or those seeking to meet their daily iron requirements, regular consumption of acidic foods cooked in NIPs can be effective. Therefore, the claim that "iron pots are effective for iron supplementation" is reasonable. This conclusion is also supported by other authoritative literature (Adish et al., 1999; Alves et al., 2019; Armstrong, 2017; Kulkarni et al., 2013).

Nevertheless, our study and previous research have indicated that relying solely on foods cooked in NIPs may not be sufficient to meet the iron needs of all individuals, particularly pregnant women, children, and those with severe iron deficiency (Borigato and Martinez, 1998; Charles et al., 2011; Sharieff et al., 2008). For these groups, additional iron supplements are still necessary. This presents a significant challenge for low-income populations where IDA is most prevalent. For instance, in Cambodia, approximately 50% of children and women are affected by IDA, and many can only afford one meal a day. In Ethiopia, children's basic nutritional requirements remain unmet. Despite these challenging circumstances, regular consumption of food cooked in NIPs still offers positive effects.

5. Conclusions

Our study effectively addressed the action-oriented research needs identified by the WHO by examining the iron release patterns from various types of pots under different cooking conditions. Iron release was significantly influenced by factors such as the types of cookware, cooking temperatures, cooking times, types of acidic substances, and the pH of the cooking environment. Specifically, higher temperatures, longer cooking times, lower pH levels, and the presence of acetic acid were found to maximise iron release into food.

The kinetic models developed for iron supplementation in NIPs adhered to zero-order reaction kinetics. Models I, II, and III can predict

Table 7
Predicted iron intake after consumption of food cooked in NIPs under various pH environments.

Consumption regions	Food materials	Main acids	pH levels	Iron content in food materials (mg/100 g)	Predictive models	Predicted results of iron release from NIPs (mg/kg)	Iron supplementation with 300 g of the corresponding food(mg/300 g)
Global	Millet grain	Citric acid	5.90	5.10	V	0.86–10.34	15.56–18.40
Global	Carrot	Citric acid	5.60	0.50	V	0.92–11.02	1.78–4.81
China	Jinhua ham	Lactic acid	5.54	2.20	VI	0.89–10.68	6.87–9.80
Global	Sweet potato	Citric acid	5.50	0.50	V	0.94–11.24	1.78–4.87
Global	Pumpkin	Citric acid	5.30	0.40	V	0.97–11.68	1.49–4.70
East Africa	Plantain	Citric acid	5.00	0.60	V	1.02–12.3	2.11–5.49
Global	Fermented sausage	Lactic acid	4.80	5.80	VI	1.01–12.12	17.70–21.04
Ethiopia	Kocho	Acetic acid	4.50	5.30	IV	0.91–10.97	16.17–19.19
Global	Tomato	Citric acid	4.40	0.40	V	1.12–13.46	1.54–5.24
West Africa	Lafun	Lactic acid	4.30	7.36	VI	1.08–12.95	22.40–25.97
China	Preserved bamboo shoots	Lactic acid	4.20	0.50	VI	1.09–13.10	1.83–5.43
West Africa	Gowe	Lactic acid	4.00	6.30	VI	1.12–13.39	19.24–22.92
Global	Honey	Citric acid	4.00	1.00	V	1.18–14.16	3.35–7.25
East Asia	Acidified chili sauce	Lactic acid	3.70	3.80	VI	1.15–13.79	11.75–15.54
Global	Pickled cabbage	Lactic acid	3.50	1.60	VI	1.17–14.03	5.15–9.01

iron release from NIPs when cooking food materials with a pH of 5.00–6.00 at temperatures ranging from 50 to 100 °C. Conversely, Models IV, V, and VI, were designed to predict iron release from NIPs when cooking food materials with a pH between 3.00 and 6.00 at the boiling point temperature. Validation experiments indicated that the predictions made by these models were relatively accurate.

Compared with the RNI data, the predicted total iron release from food cooked in NIPs can readily exceed the minimum iron requirements for adult males and males aged 11–17 years. It can also provide significant support for adult females and females aged 11–17 years. These findings confirm that the claim "iron pots are effective for iron supplementation" is reasonable. However, in case of high iron demand, it is advisable to regularly consume acidic foods cooked in NIPs while also taking additional iron supplements.

CRediT authorship contribution statement

Cuizhu Shi: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Guangrong Zhe:** Formal analysis, Investigation. **Xiang Ding:** Data curation, Visualization. **Qian Meng:** Methodology, Validation. **Jingpeng Li:** Conceptualization, Resources, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Li Deng:** Conceptualization, Resources, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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