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Effect of Iron Fortification on the Physicochemical and Sensory Properties of Functional Yoghurt

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ABSTRACT

This research examined the effects of iron fortification on the functional yoghurt's chemical, physical, and sensory characteristics. At a concentration of 12% weight/volume, two distinct forms of advantageous iron salts ferrous sulfate T2 and ferrous bis-glycinate T3 were introduced. To provide a comparison, raw milk T1 was used as the control treatment. Tests including chemistry, physics, and rheology were conducted to evaluate the product's sensory qualities immediately after manufacturing and after it had been stored at 4°C for 3, 7, and 10 days. Following storage, the moisture contents of T1, T2, and T3 decreased, reaching 87.06%, 87.00%, and 87.7%, respectively. Meanwhile, the solids percentage increased to 10.98%, 11.70%, and 11.60%. There was an increase in the proportion of protein, fat, and ash after storage. Furthermore, it was observed that the peroxide value had a positive correlation with the advancement of the process. The storage periods were initially calculated to be 1.8, 1.88, and 1.87 MeqO2/kg immediately after production. Subsequently, these values rose to 2.01, 2.16, and 2.15 MeqO2/kg. Additionally, it was observed that the population of lactic acid bacteria progressively grew with the duration of storage, reaching 45×10^6, 50×10^6,55×10^6 CFU/ml at the start of storage. which increased to 75×10^6, 90×10^6, and 95×10^6 CFU/ml after 10 days. T2 had the greatest values for viscosity, hardness, and whey separation, measuring 2890 cp, 99.80 g, and 6.8%, respectively. Following storage, the values show a rise, with T1 exhibiting the greatest overall sensory acceptance in comparison to treatments T2 and T3. The iron content had a substantial decline during the storage periods.

1-INTROUCTION

Iron deficiency anemia (IDA) remains one of the most prevalent nutritional disorders globally, affecting a significant portion of the population, particularly women of reproductive age, children, and adolescents in both developing and developed countries [1]. The consequences of IDA are profound, leading to impaired cognitive development, reduced work capacity, compromised immune function, and increased morbidity. While various strategies exist to combat this issue, including supplementation and dietary diversification, food fortification has emerged as a sustainable, cost effective, and population wide approach to increase iron intake [2].

Dairy products, especially yoghurt, present an ideal vehicle for iron fortification. Yoghurt is widely consumed across diverse demographic groups, possesses a positive health image, and has a consistent texture that can potentially mask the addition of micronutrients. The development of "functional yoghurt" with enhanced health benefits, such as improved iron status, aligns with the growing consumer demand for foods that offer more than basic nutrition [3]. Consequently, fortifying yoghurt with iron has the potential to make a substantial public health impact. However, the incorporation of iron into a complex food matrix like yoghurt is fraught with significant technological challenges. Iron, particularly in its more bioavailable ferrous (Fe^{2+}) form, is a potent pro-oxidant. When added to yoghurt, it can catalyze lipid oxidation of milk fats and accelerate protein oxidation, leading to the development of undesirable rancid and off flavors [4]. Furthermore, iron can interact with the casein micelles that form the yoghurt gel network, potentially destabilizing it and resulting in a weaker texture, increased syneresis, and a gritty mouthfeel [5]. Aesthetically, iron fortification can induce color changes, often producing unappealing grey, green, or brownish hues due to the formation of iron complexes and Maillard reaction products, making the product visually unacceptable to consumers [6].

The extent of these adverse effects is highly dependent on the chemical form of the iron compound used. While highly soluble salts like ferrous sulfate offer excellent bioavailability, they are most reactive and cause the most severe sensory and physicochemical defects. In contrast, less soluble compounds such as ferric pyrophosphate or microencapsulated iron salts are more inert but may have lower bioavailability [7]. This creates a critical tradeoff between nutritional efficacy and product quality. Therefore, selecting an appropriate iron source and optimizing the fortification process is paramount to the successful development of a functional iron fortified yoghurt. The present study investigates the sensory and physicochemical aspects of iron-fortified yogurt during production and storage to improve its nutritional value and meet the daily iron requirement while treating iron deficiency in dairy products.

2-MATERIAL AND METHODS

Milk Source

Raw cow's milk was prepared from the agricultural research station at the College of Agriculture / University of Basra.

Yoghurt Manufacturing

Yoghurt was made according to the method mentioned by Panesar and Shinde (2011) with some modifications for three milk samples [8]. The first sample was supplemented with 63mg/kg ferrous bis-glycinate T2. The second sample contained 83 mg/kg ferrous sulphate T3 at a rate of 12% w/v, while the control sample was free of T1 additives. Heat the milk to 60°C and double homogenize it at 2000 and 500 psi. Then, the milk was heated to 85°C for 5 minutes, then cooled to 42°C, inoculated with the activated starter in the quantity indicated by the producing company at a rate of 0.02%, and incubated at 42°C for 4 hours until coagulation [9]. The yoghurt was stored in the refrigerator at 4°C. Physicochemical, rheological, and peroxide number tests were conducted, and the samples were evaluated sensory after 0, 3, 7, and 10 days.

Physicochemical and Rheological Tests

Chemical composition

Using an Eko milk analyser, we were able to measure the percentages of fat, protein, solids, moisture, and ash in both the dry milk and the yoghurt (Dutch origin) [10].

Estimation of pH and Total Acidity

Estimate the pH using a German-made Sartorius pH meter. The total acidity was estimated by titration with a 0.1 N sodium hydroxide solution in the presence of evidence of phenolphthalein [10].

Microbiological Tests

Estimation of the Number of Lactic Acid Bacteria

The method mentioned by Dave and Shah (1996) was followed to estimate the number of lactic acid bacteria using an M.R.S. agar medium with a pH of 4.5. The plates were incubated under anaerobic conditions at a temperature of 37°C for 48 hours [11].

Estimation of Peroxide Value

The peroxide value was estimated according to what was stated in (A.O.A.C. 2008) [12].

Rheological Tests for Yoghurt

The viscosity of the samples was estimated according to the method mentioned by Liptak (2003) using a DVII viscometer produced by Brookfield Engineering Lab Inc., Stough, and Mass. Hardness was estimated using a Test metric M350-10CT Texture Analyzer (Panesar and Shinde, 2011). Whey purity was estimated according to the method described by Panesar and Shinde (2011) by placing 20 g of the treatments in a plastic tube, centrifuging it at a speed of 1000 rpm for 15 minutes, and weighing the filtrate [8].

Estimating the Amount of Iron

Atomic absorption spectrophotometer was used to measure Iron in parameters at a wavelength of 213.9 nm [13].

Sensory Evaluation

Using a form that included the qualities of look, texture, flavour, aroma, and overall acceptability, ten specialized evaluators from the Department of Food Sciences/College of Agriculture/University of Basra assessed the samples' sensory qualities Soad et al., (2014) with some modifications [14].

Statistical Analysis

Applying C.R.D. to the data, we used GenStat's version 12.1's ANOVA analysis table and L.S.D. test to determine, at the 0.05 level of probability, if there were statistically significant differences between the averages of the coefficients [15].

3-RESULTS AND DISSCUSION

Chemical composition

Table (1) shows the percentages of moisture, solids, protein, fat, and ash for the control treatment T1 and the yoghurt treatments fortified with iron T2 ferrous sulfate and ferrous diglycines T3 after 0, 3, 7, and 10 days. It is noted that there are significant differences between the treatments for the percentages of moisture, solids, protein, and fat. There are no significant differences in the ash content at the probability level of $p<0.05$, as the reinforcement or type of Iron used did not affect the chemical content between the treatments. The moisture percentage for treatments T1, T2, and T3, respectively, was 88.13, 87.87, and 88.16%. The percentages decreased during storage, reaching 87.06, 87.0, and 87.7% after 10 days.

The percentage of solids for the treatments increased after consolidation, as the values after manufacturing reached 10.80, 11.50, and 11.20%. The values also increased after storage, and after 10 days, they reached 10.98, 11.70, and 11.60%, respectively, for all treatments. Protein levels were 3.50%, 3.45%, and 3.50% after manufacturing. Increased to 3.60%, 3.55%, and 3.58% after 10 days of storage.

Iron did not affect fat content, with percentages of 3.70%, 3.66%, and 3.72% post-processing. After ten days, these percentages rose to 3.76%, 3.71%, and 3.77%, respectively. After adding iron salts, ash concentration rose to 0.80%, 0.83%, and 0.84% at manufacture.

Table 1: Chemical composition of unfortified and iron-fortified yoghurt samples for four storage periods.

Treatments	٪	1 st	3th	7th	10^{th}
T1	٪Moisture	88.13^{a}	87.98^{b}	87.53^{c}	87.06^{d}
	Total solids	10.80^{d}	10.90^{c}	10.95^{b}	10.98^{a}
	٪Protein	3.50^{b}	3.58^{a}	3.59^{a}	3.60^{a}
	٪ Fat	3.70^{b}	3.73^{a}	3.75^{a}	3.76^{a}
	٪Ash	0.80^{a}	0.82^{a}	0.83^{a}	0.84^{a}

T2	٪Moisture	87.87^{a}	87.55^{b}	87.13^{c}	87.00^{d}
	Total solids	11.50^{c}	11.60^{b}	11.60^{b}	11.70^{a}
	٪Protein	3.45^{c}	3.46^{b}	3.50^{b}	3.55^{a}
	٪ Fat	3.66^{b}	3.69^{a}	3.70^{a}	3.71^{a}
	٪Ash	0.83^{a}	0.85^{a}	0.86^{a}	0.88^{a}
T3	٪Moisture	88.16^{a}	87.86^{b}	78.10^{c}	87.7^{d}
	Total solids	11.20^{d}	11.30^{c}	11.50^{b}	11.60^{a}
	٪Protein	3.50^{c}	3.51^{c}	3.53^{b}	3.58^{a}
	٪ Fat	3.72^{b}	3.72^{b}	3.76^{a}	3.77^{a}
	٪Ash	0.84^{a}	0.84^{a}	0.85^{a}	0.86^{a}

*Different letters within column indicating of significant differences ($p<0.05$)

Al-shaikh and Doosh (2018) attributed the decrease in moisture content as the storage period increased to the rate of water evaporation [16].

The reason for the increase in the percentage of solids after fortification with iron compounds is the increase in the percentage of solids added and their increase after storage due to a decrease in moisture content [16].

Protein levels may have risen owing to a reduction in moisture and an increase in percentage, including protein [4]. demonstrating that fat content stays consistent with Iron addition but varies due to humidity decrease [16]. These values increased during storage for all treatments to approximately, about, and around. The findings aligned with the research conducted by Zina and Nasser (2019) and El Kholy (2011) suggested that the increased ash content was attributed to the incorporation of iron salts during the consolidation process [9,17].

Estimation of pH and Total titratable acidity

When held for 0, 3, 7, and 10 days, Figure (1) displays the pH, and Figure (2) the total acidity for T1, T2, and T3. At a probability threshold of $p<0.05$, the statistical analysis revealed that the treatments differed significantly in terms of both total acidity and pH. The capacity of the starting bacteria to transform the sugar lactose into lactic acid caused a reduction in pH and a rise in acidity as the storage duration grew. The data also reveal that Iron has no impact. Also, different types of iron salts resulted in different pH and acidity levels. Instantaneous post-manufacturing pH were 4.6, 4.5, and 4.5, respectively; subsequent storage periods saw those levels drop to 3.60, 3.59, and 3.50, respectively. The acidity of the yogurt was unaffected by the addition of Iron just after manufacture. Iron salts of different types increased acidity.

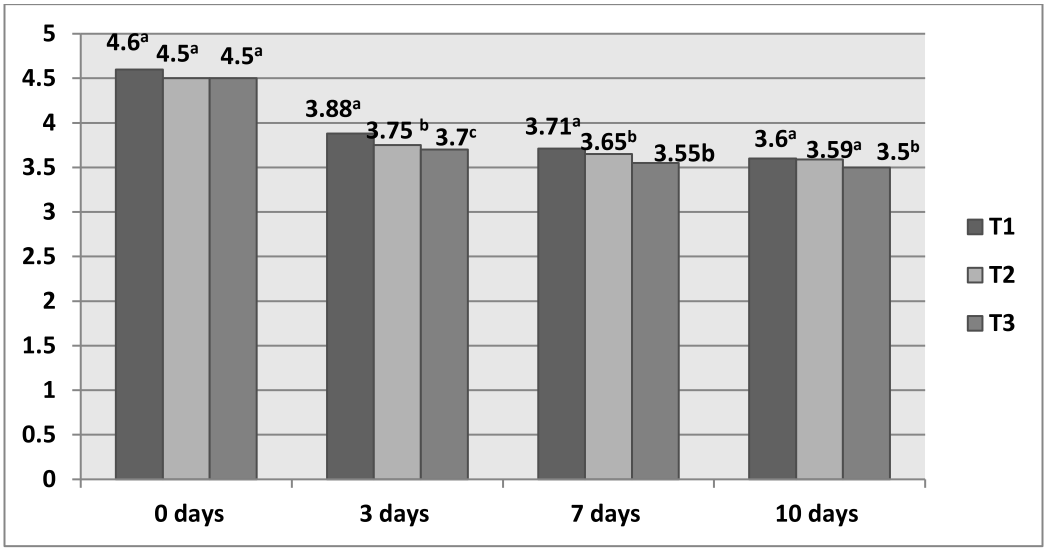

Figure 1: pH of unfortified and iron-fortified yoghurt samples for four storage periods
*Different letters within column indicating of significant differences (p<0.05)

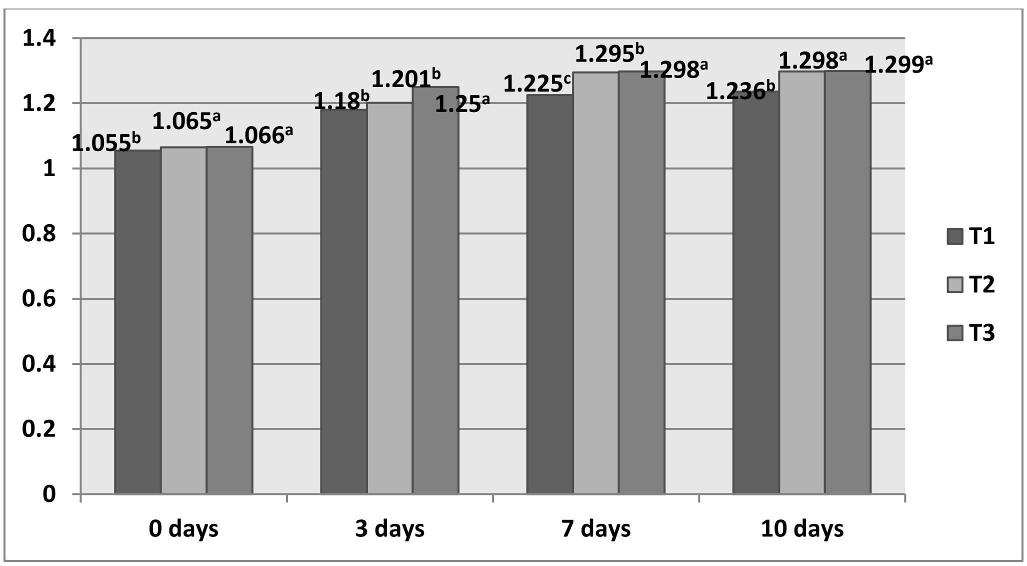

Figure 2: Total titratable acidity of unfortified and iron-fortified yoghurt samples for four storage periods
*Different letters within column indicating of significant differences (p<0.05).

The findings corroborated those of [17,18]. which revealed that, depending on the iron salts employed for fortification, the pH and the acidity rises after storage. After 10 days of storage, the acidity levels of the samples rose to 1.236, 1.298, and 1.299%, respectively, from their initial manufacture values of 1.055, 1.065, and 1.066, according to the data. The starter bacteria break down the lactose sugar into lactic acid and other organic acids. This lowers the PKA inside the cell to 3.83, making the cell membrane more permeable to substances like lactate and acetate. As a result, the pH, and the acidity increases for longer periods of storage [19].

Peroxide value

The peroxide value is an indicator of fat oxidation and, thus, product spoilage. Figure (3) shows the peroxide value for T1, T2, and T3 when stored for 0, 3, 7, and 10 days. It was observed that there were significant differences in the peroxide value at the probability level of $p<0.05$. It was observed that the value of peroxide increased with increasing storage periods, as the values at the beginning of storage reached 1.85, 1.88, and 1.87 MeqO2/kg for each of the treatments T1, T2, and T3, respectively, and at the end of the storage period, they increased to 2.01, 2.16, and 2.15 MeqO2/kg, respectively.

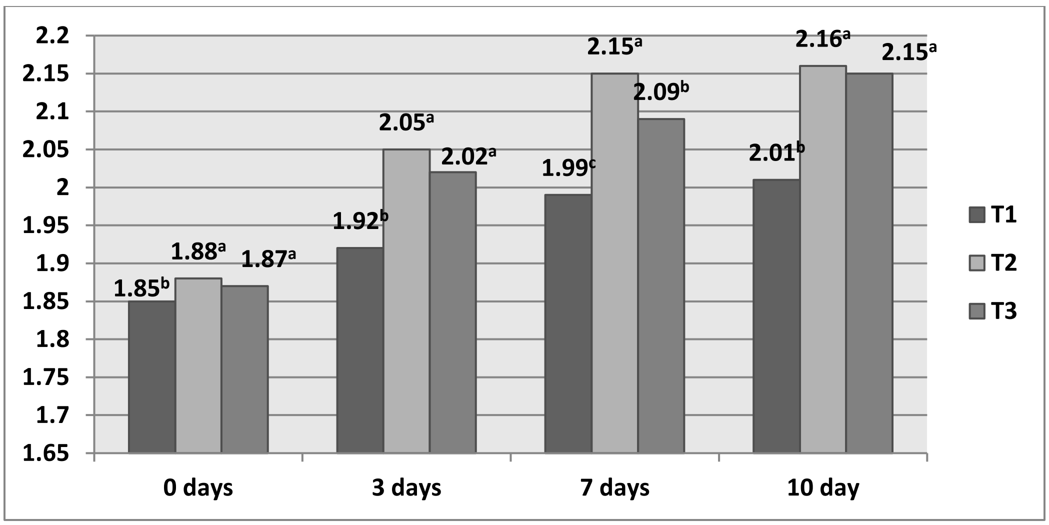

Figure 3: Peroxide value (MeqO2/kg) for samples of unfortified and iron-fortified yoghurt for four storage periods.

*Different letters within column indicating of significant differences ($p<0.05$).

The antioxidant activity of yoghurt leads to enzymatic protein degradation, which leads to the production of peptides with the ability to inhibit food fat peroxides by seizing free radicals, inhibiting peroxides, and binding to metal ions [20]. The results also show a slight increase in fat oxidation for the T2 and T3 iron-fortified samples compared to the unfortified control treatment. This is attributed to the presence of Iron, which promotes fat oxidation, the formation of free radicals, and the production of a metallic taste [21]. The decrease in fat oxidation in yoghurt is due to the milk's content of vitamin E and lactoferrin protein, which work to bind iron ions and also donate a hydrogen atom to free radicals, thus reducing the continued occurrence of auto-oxidation [22].

Lactic Acid Bacteria

In Table (2), we can see the lactic acid bacteria counts for T1, T2, and T3 after 0, 3, 7, and 10 days of storage. The numbers of lactic acid bacteria showed significant differences at the $p<0.05$ level of probability. As the storage period increased, the number of bacteria also increased, reaching 45 x 10^6, 50 x 10^6, and 55 x 10^6 CFU/ml at the beginning of storage. On the other hand, it hit 75 x 10^6 by the time the storage period was over. Furthermore, 90 x 10^6 CFU/ml and 95 x 10^6 CFU/ml, respectively. The results also show that the effect varies according to the type of Iron used and the percentage of acidity. Lactic acid bacteria benefit from amino acids, peptides, proteins, nitrogen sources, carbohydrates, and fatty acids as a source of energy, so the proportions of components in milk products decrease after fermentation [23]. The growth of lactic acid bacteria increases in the yoghurt of dairy products. Fortification does not reduce these numbers, and they also increase during storage, which leads to a decrease in the number of pathogenic bacteria and the elimination of spoilage caused in foods [24]. Aquilanti et al. (2012) indicated that fortification of cheese with minerals reduces the growth of various types of bacteria, as it works to inhibit species of *Lactobacillus* bacteria [25]. The positive ions Mn, Ca, Mg, and Sr work to remove cations from proteins when they bind to metals, which reduces the effect of metals. On bacteria, the pH decreases due to the interaction of components of the bacterial cell positive for the Gram stain, including lactic acid bacteria.

Table 2: Number of lactic acid bacteria for samples of unfortified and iron-fortified yoghurt for four storage periods

Treatments	1st	2th	3th	10^{th}
T1	45×10^{6c}	55×10^{6c}	60×10^{6b}	75×10^{6c}
T2	50×10^{6b}	55×10^{6b}	75×10^{6b}	90×10^{6b}
T3	55×10^{6a}	61×10^{6a}	85×10^{6a}	95×10^{6a}

*Different letters within column indicating of significant differences ($p<0.05$).

Viscosity estimation

Rheological tests are important tests to determine the properties of food materials. They are one of the main factors, in addition to flavor and appearance, that determine the extent of sensory acceptance of that food by the consumer [26]. Indicators of yoghurt quality include viscosity, which is associated with the product's stability and flavor [27]. In Figure 4, we can see the viscosities of T1, T2, and T3 after 0, 3, 7, and 10 days of storage. The results showed that there were notable variations at the 0.05 level of probability. The data demonstrated that viscosity increased with increasing storage times, peaking just after production. Upon storage, they rose to 2800, 2890, and 2879 cp, respectively. Following 10 days, they reached 2900, 2950, and 2940 cp. The decrease in pH and increase in acidity cause yoghurt's viscosity to rise after storage [28]. Figure 2 shows that compared to the control sample T1, the viscosity of the Iron-fortified T2 and T3 samples was higher. This finding suggests that the addition of minerals, such as Iron, increases the product's viscosity because of the high proportion of extra solids. According to Jasim and Saadi (2020), this is because Iron may bind casein molecules, which improves the viscosity and increases the strength of the bonds [29]. Because the yoghurt gel matrix is sensitive to changes in the ionic binding strength of the salt molecules used for reinforcing, the viscosity of the gel varies with the kind of salts applied [27].

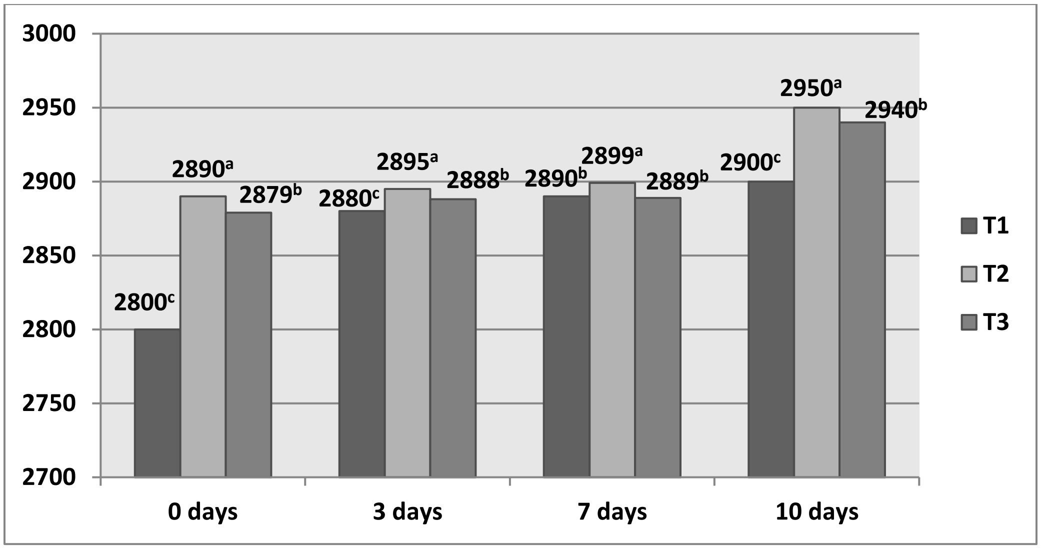

Figure 4: Viscosity values for unreinforced and iron-reinforced yoghurt samples for four storage periods
*Different letters within column indicating of significant differences (p<0.05)

Hardness

Figure (5) indicates the hardness values of treatments T1, T2, and T3 when stored for 0, 3, 7, and 10 days. It was noted that no significant differences appeared between the treatments at the probability level of p<0.05. The results showed an increase in hardness with increasing storage periods, and it reached the beginning of storage at 98.70, 99.80, and 99.70 g. It increased after storage, and after 10 days of storage, it reached 100.10, 101.10, and 00.601 g. The percentages varied depending on the type of iron compound used. Adding Iron of both types, T2 ferrous sulfate and T3 ferrous diglycines, led to an increase in the hardness property of the yoghurt. Compared with the control sample T1, the reason for the increase in hardness in the product after fortification with Iron is due to its ability to form bridges between casein molecules and coagulate them, thus increasing the bonding forces between the molecules and increasing the cohesion within the protein bar, which increases the hardness [30]. A difference in hardness was observed. Depending on the type of salts added, the values of the T2 and T3 parameters varied as a result of the difference in the ionic strengths of the salts used, which affected the yoghurt gel [29]. The reason for the decrease in elasticity after storage is attributed to increased proteolysis or decreased moisture content, which reduces its elasticity [31]. Liu et al., (2015) attributed the reason for the high hardness during storage to the low humidity upon evaporation, and the high hardness in the samples reinforced with minerals compared to the control samples is due to the high percentage of solids, and this is directly proportional to the cohesion of the samples [32]. Patrignani et al., (2006) indicated that the hardness standard in yoghurt is closely related to solids and protein content, as the hardness increases with their increase [33].

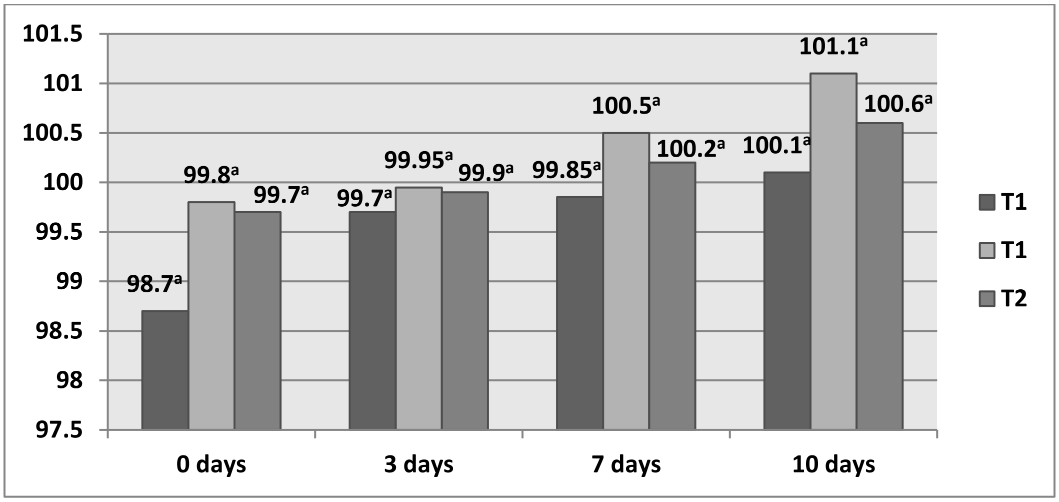

Figure 5: Hardness values for unreinforced and iron-reinforced yoghurt samples for four storage periods
*Different letters within column indicating of significant differences (p<0.05)

Whey separation

The most crucial indicator of yoghurt quality during storage is spontaneous whey separation [34]. When particles are absent, heat treatment is inadequate, or the pH is less than 4.4, leaching occurs [35]. Table 6 shows the predicted values of spontaneous whey exudation after 0, 3, 7, and 10 days in storage for treatments T1, T2, and T3. At a probability threshold of p<0.05, it was observed that the treatments were not significantly different from one another. As the testing durations increased, whey exudation increased as well. Storage: It was observed that the yoghurt supplemented with ferrous sulfate outperformed the rest of the treatments, as the values for the treatments reached 5.5, 6.8, and 6.4%, respectively, and the values increased after storage, reaching 7.9, 8.9, and 8.5% after 10 days. This is due to the increase in whey purity. Extended storage leads to an increase in total acidity and a decrease in pH values [36].

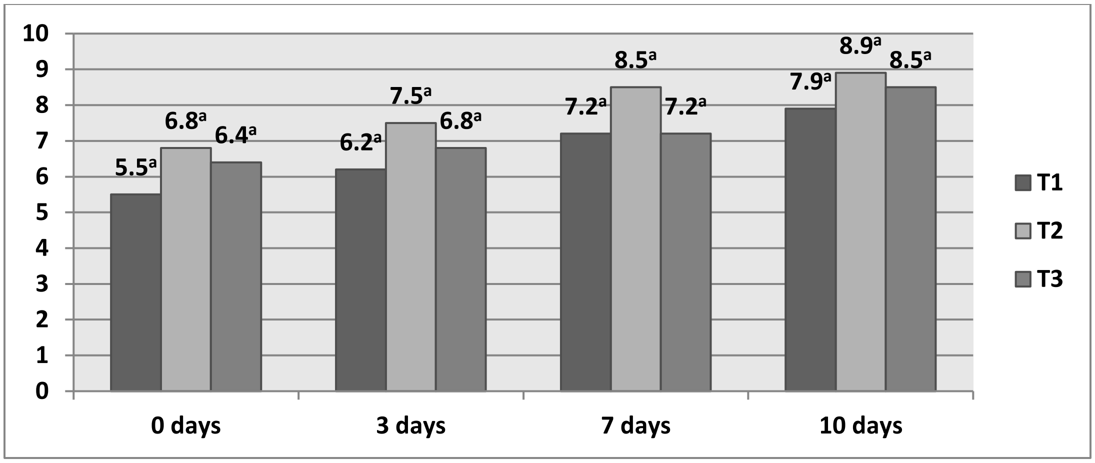

Figure 6: Whey separation of unfortified and iron-fortified yoghurt samples for four storage periods
*Different letters within column indicating of significant differences (*p*<0.05)

Iron content

Table 7 illustrates the predicted iron concentrations after 0, 3, 7, and 10 days of storage for treatments T1, T2, and T3. There were notable differences between the treatments, with a probability threshold of $p<0.05$. The findings demonstrated that the treatments significantly raised the iron content. In the zero-storage period, T2 and T3 were 0.61 and 0.80 mg/kg, respectively, whereas T1, the control sample, was 0.039 mg/kg. Over the course of the storage periods, the iron content dropped dramatically; on the tenth day, it was at its lowest, amounting to 0.026, 0.50, and 0.68 mg./kg for each treatment. Results showed that ferrous sulfate-fortified samples outperformed all other treatments. Debasmita and Binata Nayak (2017) indicated that the samples of yoghurt fortified with Iron are nutritionally rich and acceptable, and they are also a suitable way to enhance Iron in food, as noted. The amount of Iron in the yoghurt increases, and its quantity decreases as the storage period increases [37].

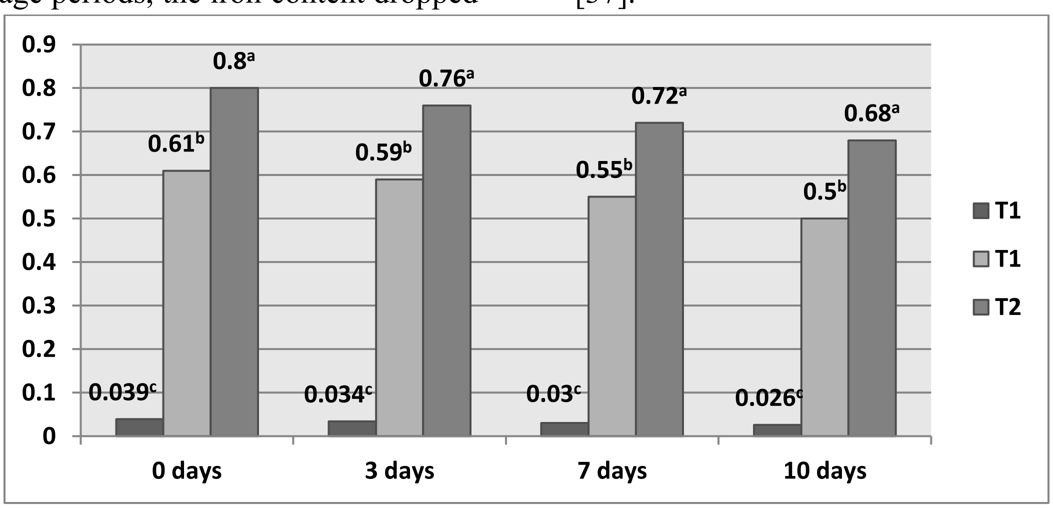

Figure 7: Iron quantity for unfortified and iron-fortified yoghurt samples for four storage periods
*Different letters within column indicating of significant differences (*p*<0.05).

Sensory evaluation

Ten food experts from the College of Agriculture's Department of Food Sciences documented their sensory assessment findings for treatments T1, T2, and T3 after 0, 3, 7, and 10 days of storage in Table 3. The features of color, texture, flavor, and overall acceptance did not show any significant variations between the treatments after fortification at the probability threshold of P<0.05 within the one storage period. However, significant differences were found between different storage periods. T1 performed very well, earning a score of 85.9, while treatments T2 and T3 achieved scores of 85.0 and 85.2, respectively. T1 also recorded the best sensory characteristics compared to treatments T2 and T3. In terms of general acceptance, it reached 22.7, 22.3, and 22.5, respectively, and both treatments, T1 and T2, received the highest rating for taste and flavor, 17.8. Treatment T3 also obtained the highest score in terms of texture, 31.5, as fortification with Iron in small percentages did not affect the general acceptance of the yoghurt product. Consumers place more stock in sensory quality indicators when evaluating dairy products than in their chemical makeup, which loses value with time owing to storage and expiry, producing color and taste changes caused by excessive acidity [24]. According to Kahraman and Ustuno (2012) the hardness increases after reinforcement with metals like Iron since strength is related to the quantity of additional metals [38].

Table 3: Sensory evaluation of raw and fortified milk samples for four storage periods

Treatments	Storage periods/day	Color/20	Textur/35	Flavor/20	general acceptability/25	Total /100
T1	0	15.2[a]	30.2[a]	17.8a	22.7[a]	85.9[a]
	3	14.5[a]	30.0[a]	16.7[a]	20.5[b]	81.7[b]
	7	12.8[b]	30.0[a]	16.5[a]	19.3b	78.6[c]
	10	10.9[c]	29.5[a]	17.6[a]	19.3[b]	77.3[d]
T2	0	14.8[a]	30.1[a]	17.8[a]	22.3[a]	85.0[a]
	3	14.0[a]	30.2[a]	16.3[a]	20.5[b]	81.0[b]
	7	13.1[b]	30.0[a]	14.2[b]	19.2[b]	76.5[c]
	10	10.5[c]	27.5[b]	14.0[b]	19.1[b]	71.1[d]
T3	0	15.0[a]	31.5[a]	16.2[a]	22.5[a]	85.2[a]
	3	15.5[a]	30.0[a]	15.2[a]	19.5[b]	80.2[b]
	7	13.8[b]	30.1[a]	15.0[a]	18.2[b]	77.1[c]
	10	11.0[c]	30.2[a]	15.0[a]	18.1[b]	74.8[d]

*Different letters within column indicating of significant differences (p<0.05)

4-CONCLUSION

In conclusion, the fortification of yoghurt with iron presents a dual-faceted scenario of significant public health promise coupled with substantial technological challenges. This study unequivocally demonstrates that the incorporation of iron profoundly influences the physicochemical and sensory properties of yoghurt. The pro-oxidant nature of iron is the primary factor driving these changes, leading to lipid oxidation, which manifests as undesirable rancid flavours, and to protein matrix interactions, which result in textural defects such as increased syneresis and a weaker gel structure. Furthermore, colour alteration towards unappealing shades is a major visual hurdle that can deter consumer acceptance. The critical finding of this research is that the choice of the iron compound is the most decisive factor in determining the final quality of the fortified yoghurt. While soluble salts like ferrous sulphate offer high bioavailability, they cause the most severe detrimental effects on product quality. In contrast, less reactive forms such as microencapsulated iron or iron pyrophosphate, although potentially less bioavailable, succeed in preserving the sensory attributes and overall acceptability of the yoghurt to a much greater extent.

Therefore, the successful development of a marketable iron-fortified functional yoghurt hinges on a delicate balance between nutritional efficacy (bioavailability) and product quality. The use of advanced strategies, particularly microencapsulation and the incorporation of chelating agents or antioxidants, is not merely beneficial but essential to mitigate oxidative reactions and mask metallic off-flavours. From an industrial perspective, this research provides a foundational framework for selecting appropriate iron fortificants and optimizing processing parameters. Future research should focus on long-term storage studies to monitor the stability of the fortified products, in vivo assessments to confirm the bioavailability of iron from the optimized formulations, and exploring novel iron compounds or synergistic antioxidant systems that can further bridge the gap between maximum nutrient delivery and minimal sensory impact. Ultimately, overcoming these technical barriers is paramount to harnessing the full potential of yoghurt as an effective vehicle for combating iron deficiency anaemia on a global scale.

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