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Optimization of Temperature and Time for High-Quality Roasted Barley (*Kolo*)

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ABSTRACT
The consumption of roasted barley (kolo) is prevalent in all regions of Ethiopia. However, high-temperature heat treatment can result in the formation of acrylamide in roasted starchy foods. Acrylamide can be a health hazard if continuously consumed at high levels. This research contributes to optimize temperature and duration of roasting barley and investigate their impact on acrylamide formation, sensory profile, and nutritional profile of kolo sourced from both street vendors and industrial processors in Addis Ababa, Ethiopia. Locally produced kolo samples exhibited higher acrylamide contents ranging from 216.60 to 334.80µg/kg, while industrially processed kolo had lower values ranging from 200.28 to 308.95µg/kg. Results indicate that roasting temperature and duration significantly ($p<0.05$) affected acrylamide levels of kolo. The optimal roasting conditions of 352 ℃ for duration of 2 minutes gave desirability of 0.71. The optimum roasting conditions resulted in kolo with acrylamide of 148.64µg/kg, protein of 11.88%, ash of 3.28%, fat of 2.80%, crude fiber of 14.72%, carbohydrates of 67.35%, lightness (L^*) of 57.50%, yellowness (b^*) of 33.89%, redness (a^*) of 15.52%, taste of 8.35, texture of 8.92, odor of 8.10 and overall sensory acceptability score of 8.18. Roasting barley grains transform them into value-added products and/ or nutritional food ingredients.

KEYWORDS
Acrylamide; Barley; *Kolo*; Physico-chemical composition; Roasting

1. INTRODUCTION

Barley (*Hordeum vulgare* L.), an ancient crop, holds significant agricultural and culinary importance, it is grown worldwide in temperate climates during both summer and winter seasons and initially cultivated for human consumption, barley has become one of the foremost cereals globally [1]. Ethiopia's rich diversity of native barley types has established it as a center of diversity for this crop. Barley is cultivated in Ethiopia as both a main-season crop, known as "*meher*", in higher elevation Dega regions, and as a "*belg*" crop in various areas and its cultivation is prominent in several regions, including Arssi, Bale, Shoa, Welo, Gojam, and Gonder [2]. Barley is widely distributed across the country's growing regions, and it holds a special place in Ethiopian agriculture referred to as *'Gebis ye ehil negus'*, barley is considered the king of all crops due to its versatility in preparing various traditional Ethiopian dishes [3].

In the highlands, barley has been utilized in the creation of a diverse range of traditional foods, including *kolo* (roasted barley), *kita*, *dabo* (bread), *beso*, *genfo*, *chuko*, *tihlo*, *shorba* (soup), *kinche*, and *injera*. Households in Ethiopia produce a variety of local beverages, both alcoholic and non-alcoholic, using barley grains for daily consumption or special occasions including *Tella*, *shamet*, and *korefe*. Traditional

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Ethiopian roasted Barley, known as *kolo*, is a popular and culturally significant food in Ethiopia. It is widely consumed as a snack and forms an integral part of Ethiopian culinary traditions [4].

Traditional roasted barley, locally known as "*kolo*", is mostly made by roasting whole barley grains until they turn brown and develop a crunchy texture. However, the roasting process can lead to the formation of acrylamide in the *kolo*, which raises concerns about its safety for consumption. Acrylamide, a prevalent compound found in high-temperature processed food, possesses genetic, toxic, and carcinogenic properties, and has the potential to induce nerve damage [5]. The formation of acrylamide occurs primarily through the reaction between carbonyl compounds and amines during processes involving high temperatures [6]. Acrylamide is classified by the International Agency for Research on Cancer (IARC), a division of the World Health Organization (WHO), as a Group 2A probable carcinogen [7]. Researchers have investigated the effects of heating temperature and heating time on Acrylamide formation [5], [7], [8], [9], [10]. By adjusting these parameters, it is possible to reduce the formation of acrylamide during food processing. Currently, there has been no research directly evaluating roasted barley or *kolo* in some local markets and investigating roasting parameters on the roasting of barley to produce *kolo*.

In this study, the researchers selected the roasting temperature range from 350 °C to 400 °C and the time range from 2 to 5 minutes based on preliminary findings [11], [12]. This range was also chosen considering practical industry practices, as many local producers of *kolo* typically operate within these parameters to achieve a desirable flavor and texture while minimizing production time. By aligning the experimental conditions with those commonly used in the industry, the study aims to ensure that the findings are applicable and beneficial for commercial production. This study contributed to evaluate acrylamide content, nutritional profile, and sensory properties of roasted barley or *kolo* in different areas and investigate roasting parameters.

2. MATERIALS AND METHODS

2.1. Materials

To assess the levels of acrylamide in roasted barley or "*kolo*" in Ethiopia, specific regions known for their barley production and expertise in *kolo* roasting were carefully chosen for the study. The Addis Ababa sub-cities (Arada, Lideta, Addis Ketema, Nifas Silk-Lafto, and Kirkose) were selected as the sampling locations for *kolo* samples at three separate sampling times, considering the city's significance as a major urban center where *kolo* is commercially produced and highly dense suburbs. Five *kolo* samples from five different brands in the industry were taken. Samples were collected from shops and street vendors using randomized lottery sampling methods. Untreated barley (*Hordeum vulgare* L.) of the "*senef gebs*" variety was obtained from Adet Agricultural Research Centre (AARC) in Bahir Dar and stored under dry and cold conditions until used for the experiment. All chemicals used in this study were of analytical grade.

2.2. Experimental Treatment and Design

A response surface design using central composite design (CCD) was employed to optimize the roasting time and temperature with 13 runs. The roasting temperature and time ranged from 350 °C to 400 °C and 2 to 5 minutes, respectively. A quadratic model was used to determine the optimal roasting conditions.

2.3. Step to Produce *Kolo*

During the preparation of *kolo*, the bran was separated from the grain using two consecutive dehulling steps: *fitega* and *shiksheka* [4]. The whole grains of barley were first soaked in hot water (T = 50 °C) for 2 hours, then rubbed by beating/pounding the grain in a mortar with a pestle (the *fitega* process). After the bran was removed from the grain by subsequent blowing, the grain was deeply roasted using a roaster machine. Finally, the roasted grain was dehulled a second time by either mildly beating the grain with a mortar and pestle (the *shiksheka* process) or rubbed by hand to remove the remaining hulls.

2.4. Roasting of The Barley

The barley was roasted using a roaster machine manufacture by Hayle Engineering (Adiss Ababa, Ethiopia) with capacity of 10 kg, which operates at high temperatures and is locally constructed. The machine was first heated to the desired roasting temperature, and 10 kg of barley was placed into the roasting cylinder. The barley was roasted for various combinations of times and temperatures (350 to 400 °C for 2 to 5 minutes). The roasted barley was then tipped out into a cooling tray and allowed to cool for an average of 3 minutes by blowing cold air over the cooling plate. Once cooled, the roasted barley or *kolo* was packed in a sealed plastic bag and stored at 4 °C until analysis.

2.5. Acrylamide Determination

Kolo samples were prepared for acrylamide analysis using solid-phase extraction (SPE) cleanup, following the method outlined by Endeshaw and Belay (2020) [13]. Specifically, 2.5 g of *kolo* powder in a 50 ml centrifuge tube. The mixture was combined with 25 ml of water and 5 ml of n-hexane, mixed thoroughly for 5 minutes, and then centrifuged (Universal 320, Andreas Hettich GmbH & Co. KG, Tuttlingen, Germany) at 2509 g (4000 rpm) for 5 minutes. The upper hexane layer was carefully removed, and 1 ml each of Carrez I and Carrez II solutions were added to the remaining sample. This mixture was centrifuged again at 2509 g (4000 rpm) for 5 minutes. The resulting clear intermediate layer was further purified by adding another 1 ml each of Carrez I and Carrez II solutions, followed by vigorous mixing for 5 minutes and a final centrifugation at 2509 g (4000 rpm) for 5 minutes. The clear layer was then transferred to an SPE column, which had been preconditioned with 1 ml of methanol and 1 ml of water. The extract was passed through the column, discarding the first five drops, and 4 ml of the filtrate was collected and concentrated to dryness under nitrogen gas. The residue was reconstituted in 2 ml of water, filtered through a 0.20 µm filter disk, and then transferred to autosampler vials for acrylamide determination using High-Performance Liquid Chromatography-Diode Array Detector (HPLC-DAD).

Acrylamide levels in various *kolo* samples were quantified using HPLC (Agilent 1260 Infinity HPLC, Agilent Technologies, USA). Separation of compounds was performed with an Agilent ZORBAX Eclipse Plus column (4.6 × 100 mm, 3.5 µm, Agilent Technologies, USA). Data was processed using Agilent Open Lab CDS software (Agilent Technologies, USA). The flow rate was set to 0.50 ml/min, and the column temperature was maintained at 30 °C. The total analysis time was 15 minutes, comprising 10 minutes for acquisition and 5 minutes for post-run. A 20 µL injection volume was used. The mobile phase consisted of 99% HPLC-grade water and 0.1 % acetic acid solution. Acrylamide detection was performed with a diode array detector set to 210 nm. Calibration curve linearity was assessed by plotting peak areas against analyte concentration and evaluating the fit of the linear regression. Method sensitivity was determined with a Limit of Detection (LOD) of 5 µg/l. The method's precision, evaluated by analyzing replicate samples, yielded a Relative Standard Deviation (RSD %) of 2.31%.

2.6. Determination of Chemical Composition

The determination of chemical composition was conducted using the method of AOAC 2016 [14], [15].

2.7. Determination of Color

A tristimulus colorimeter (Chromameter- 2 Reflectance, Minolta, Osaka, Japan) equipped with a CR 300 measuring head was used. The color was expressed as L^*, a^*, and b^* (luminosity, red value, and yellow value, respectively, on the Hun-Ter scale) [16].

2.8. Sensory Analysis

Sensory evaluations of *kolo* were conducted based on the report by Schlörmann, et al, (2019) [17], with 20 untrained assessors (10 men and 10 women, aged 20-48 years, worked within the labs and gave verbal consent after being screened for any known gluten or food allergies). The samples were presented simultaneously to the assessors to rank the attributes according to the assessors' liking intensity of those attributes (preferred attribute elicitation). The assessors evaluated texture (soft to crunchy to hard), odor (roasted odor: weak to strong), taste (roasted taste: weak to strong), and overall acceptability as quality characteristics, assigning points from one (weak characteristic) to nine (extreme characteristic), with five as optimal. Due to their hard structure, barley kernels were not subjected to sensory evaluation.

2.9. Statistical Analysis

All tests were performed in duplicates. Response surface design (RSD) was used to optimize the roasting time and temperature, and Minitab 19 was used for conducting the experiments. One-way ANOVA was used to determine the effect of roasting conditions on the acrylamide content, nutritional composition, color properties, and sensory values of roasted barley, or *kolo*. Multiple comparison tests using the Fisher pairwise comparison technique was applied to compare the means of each parameter between different *kolo* samples.

3. RESULTS AND DISCUSSION

3.1. Acrylamide Content of *Kolo*

The study compared acrylamide levels in street-sold and industrially processed *kolo* samples. Street *kolo* samples (AC to AD) exhibited higher acrylamide content, ranging from 216.60 µg/kg to 334.80 µg/kg, while industrially processed samples (IA to IC) had lower levels, ranging from 200.28 to 308.95 µg/kg (Table 1). Sub City A (AC) samples recorded the highest acrylamide levels, while industrially processed samples consistently had lower concentrations.

The acrylamide content in street *kolo* samples exceeded the benchmark level of 150 µg/kg set by the Commission Regulation (EU) 2017/2158, ranging from 216.60 to 334.80 µg/kg. Industrially processed samples demonstrated significantly lower acrylamide levels ($p<0.05$). Table 1 summarizes the acrylamide contents of the samples.

Table 1. Acrylamide contents of *kolo* samples collected from street vendors and *kolo* processors.

Samples	Acrylamide content (µg/kg)
AC	334.80 ± 49.80^{a}
ID	308.95 ± 9.40^{ab}
AE	304.00 ± 35.90^{ab}
IE	287.80 ± 9.20^{abc}
AB	280.10 ± 25.30^{abcd}
AA	245.60 ± 29.20^{bcd}
AD	216.60 ± 19.20^{cd}
IA	213.00 ± 15.70^{cd}
IB	200.39 ± 4.30^{d}
IC	200.28 ± 0.90^{d}

The data presented as the mean ± sd. Treatments with the same letter across columns are not significantly different ($p>0.05$).

AA = street *kolo* samples from sub-city A; AB = street *kolo* samples from sub-city B; AC = street *kolo* samples from sub-city c; AD = street *kolo* samples from sub-city D; AE = street *kolo* samples from sub-city e; IA = industrially processed *kolo* sample brand A; IB = = industrially processed *kolo* sample brand B; IC = = industrially processed *kolo* sample brand C; ID = = industrially processed *kolo* sample brand D; IE = = industrially processed *kolo* sample brand E.

The significantly higher acrylamide levels in street *kolo* samples compared to industrial samples (Table 1) highlight the importance of controlled roasting conditions. Industrial processing methods, such as husk removal and roasting at higher moisture content, contribute to reducing acrylamide formation. The findings align with prior studies, which reported similar levels in roasted barley and breakfast cereals [11], [12], [18]. According to the European Food Safety Authority, acrylamide is generally not found in large quantities in boiled foods, but it can be present at notable levels in certain processed foods, particularly those subjected to roasting. The reduced acrylamide content in industrially processed *kolo* samples is attributed to the roasting process, which occurs after the removal of husks from the barley or when the barley has a higher moisture content. This method helps minimize acrylamide formation, as acrylamide tends to form more readily at higher temperatures and lower moisture levels, as noted by the European Food

Safety Authority [19].

3.2. Effect of Temperature and Time on The Acrylamide Content of *Kolo*

The acrylamide content of *kolo* was significantly influenced by roasting temperature and time ($p<0.05$). Among the tested conditions, the highest acrylamide content was observed at 410 °C for 4 minutes (299.73 µg/kg), and the lowest at 339.64 °C for 4 minutes (106.65 µg/kg) (Table 2). The optimal roasting conditions were identified as 352 °C for 2 minutes, producing acrylamide levels of 148.64 µg/kg with a desirability of 0.72.

The R^2 value of the model was 0.76, indicating a moderate fit for acrylamide formation predictions. A surface plot (Figure 1) demonstrated the relationship between roasting parameters and acrylamide formation.

Table 2. Optimization of the acrylamide content in roasted barley or *kolo*.

Temperature (°C)	Time (min)	Run number	Acrylamide (µg/kg)
410	4	13	299.73 ± 1.17[a]
400	2	2	290.14 ± 8.03[a]
400	6	11	286.80 ± 14.60[a]
375	6.83	10	260.61 ± 6.85[b]
375	4	1	221.40 ± 14.30[c]
375	4	3	216.40 ± 19.40[cd]
375	4	9	211.34 ± 0.78[cd]
375	4	8	209.51 ± 0.11[cde]
350	6	7	207.63 ± 8.87[cde]
375	4	4	198.96 ± 0.52[de]
350	2	6	190.54 ± 1.60[de]
339.64	4	5	106.65 ± 4.71[g]
375	1.17	12	104.56 ± 3.78[g]

The data presented as the mean ± sd. Means that do not share a letter are significantly different (P<0.05).

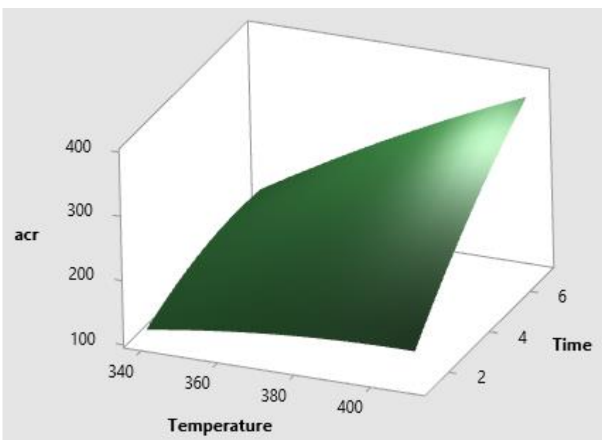

Figure 1. Surface plot of acrylamide.

The study demonstrated that acrylamide formation increases with higher temperatures and prolonged roasting times (Table 2), consistent with the Maillard reaction dynamics. High temperatures (e.g., 410 °C) resulted in excessive acrylamide formation, while moderate temperatures (e.g., 375 °C) offered a better balance for moisture evaporation and reaction control, thereby reducing acrylamide content.

The optimized roasting conditions (352 °C for 2 minutes) achieved both lower acrylamide content and higher desirability (0.72) as illustrated in Figure 1, surpassing previous optimization outcomes [14], [20]. These findings suggest actionable strategies for the food industry to ensure regulatory compliance and meet consumer safety expectations.

3.3. Moisture Content of *Kolo*

The moisture levels of *kolo* ranged from 1.19% to 10.42%, as outlined in Table 3. The highest moisture content was observed at 339.64 °C for 4 minutes, while the lowest was at 375 °C for 6.83 minutes. Significant differences ($p<0.05$) were found across treatments. Moisture content decreased with increasing temperature and time due to the evaporation of water, with initial moisture levels of barley also affecting the results [21], [22].

Table 3. Chemical composition of *kolo* samples.

Temp. (°C)	Time (min)	Run number	Moisture (%)	Protein (%) db	Fiber (%) db	Fat (%) db	Ash (%) db	CHO (%) db
339.64	4	5	10.42 ± 0.05^{a}	12.94 ± 0.06^{a}	15.39 ± 0.23^{a}	2.27 ± 0.08^{g}	2.77 ± 0.01^{f}	66.64 ± 0.10^{fg}
350	2	4	8.98 ± 0.01^{b}	11.31 ± 1.58^{cdef}	14.27 ± 0.06^{bcd}	2.96 ± $0.67e^{f}$	3.79 ± 0.14^{b}	67.67 ± 2.06^{def}
375	1.17	12	8.89 ± 0.16^{b}	11.57 ± 0.32^{bcd}	13.63 ± 0.09^{cdef}	3.14 ± 0.74^{de}	3.10 ± 0.02^{d}	68.58 ± 0.35^{bcde}
400	2	6	8.58 ± 0.11^{b}	10.92 ± 0.25^{cdefgh}	13.40 ± 0.39^{efg}	3.98 ± 0.00^{abc}	3.48 ± 0.02^{c}	68.24 ± 0.16^{cde}
375	4	1	4.45 ± 0.17^{c}	10.42 ± 0.04^{efgh}	14.46 ± 0.01^{b}	3.62 ± 0.01^{bcd}	2.22 ± 0.01^{h}	69.47 ± 0.28^{abc}
375	4	10	4.39 ± 0.57^{c}	11.13 ± 0.15^{cdefg}	14.72 ± 1.26^{ab}	3.41 ± 0.04^{cde}	2.76 ± 0.00^{fg}	67.99 ± 0.40^{cdef}
375	4	3	4.38 ± 0.08^{c}	12.40 ± 0.08^{ab}	14.10 ± 0.01^{bcde}	3.26 ± 0.03^{de}	3.06 ± 0.07^{d}	67.19 ± 0.76^{ef}
375	4	7	4.13 ± 0.06^{cd}	11.72 ± 0.60^{bc}	15.48 ± 0.12^{a}	3.73 ± 0.06^{abcd}	3.96 ± 0.04^{a}	65.13 ± 0.16^{g}
350	6	8	3.95 ± 0.08^{d}	11.36 ± 0.04^{bcde}	13.04 ± 0.07^{fg}	2.50 ± 0.08^{fg}	2.88 ± 0.13^{ef}	70.22 ± 0.24^{a}
375	4	9	3.76 ± 0.19^{d}	10.61 ± 0.38^{defgh}	14.34 ± 0.49^{bc}	3.14 ± 0.04^{de}	2.89 ± 0.13^{ef}	69.04 ± 1.05^{abcd}
410	4	13	2.57 ± 0.14^{e}	10.01 ± 0.30^{h}	12.61 ± 0.09^{g}	4.28 ± 0.09^{a}	3.02 ± 0.01^{de}	70.10 ± 0.47^{ab}
400	6	2	1.80 ± 0.02^{f}	10.18 ± 0.44^{gh}	12.84 ± 0.08^{fg}	4.11 ± 0.17^{ab}	2.61 ± 0.04^{g}	70.27 ± 0.28^{a}
375	6.83	11	1.19 ± 0.08^{g}	10.27 ± 0.25^{fgh}	13.47 ± 0.68^{def}	3.93 ± 0.08^{abc}	3.78 ± 0.01^{b}	68.57 ± 0.52^{bcde}

Means that do not share a letter are significantly different ($P<0.05$).

3.4. Protein Content of *Kolo*

Protein content ranged from 10.01% to 12.94%, with the highest value recorded at 339.64 °C for 4 minutes. Significant differences ($p<0.05$) were noted across treatments, and the R^2 and adjusted R^2 for the predictive model were 59% and 29.71%, respectively. Protein content showed a decline at higher temperatures, attributed to denaturation and Maillard reactions [23], [24].

3.5. Fiber Content of *Kolo*

Fiber content varied between 12.61% and 15.48%, with the highest value observed at 375 °C for 4 minutes. The R^2 and adjusted R^2 of the model were 75.80% and 58.51%, respectively. Fiber content was better preserved at lower temperatures, but its reduction at higher temperatures indicates possible thermal degradation of complex carbohydrates into simpler compounds [25], [26].

3.6. Fat Content of *Kolo*

Fat content ranged from 2.27% to 4.28%, with the highest level at 410 °C for 4 minutes. The model showed a strong R^2 of 88.68% and an adjusted R^2 of 80.59%. Fat content increased with higher roasting temperatures, likely due to thermal degradation of glycolipids [13]. The R^2 model of fat was 88.68% (Figure 2) indicating a significant difference (P<0.05) between temperature and time conditions of roasting of barley samples from different locations.

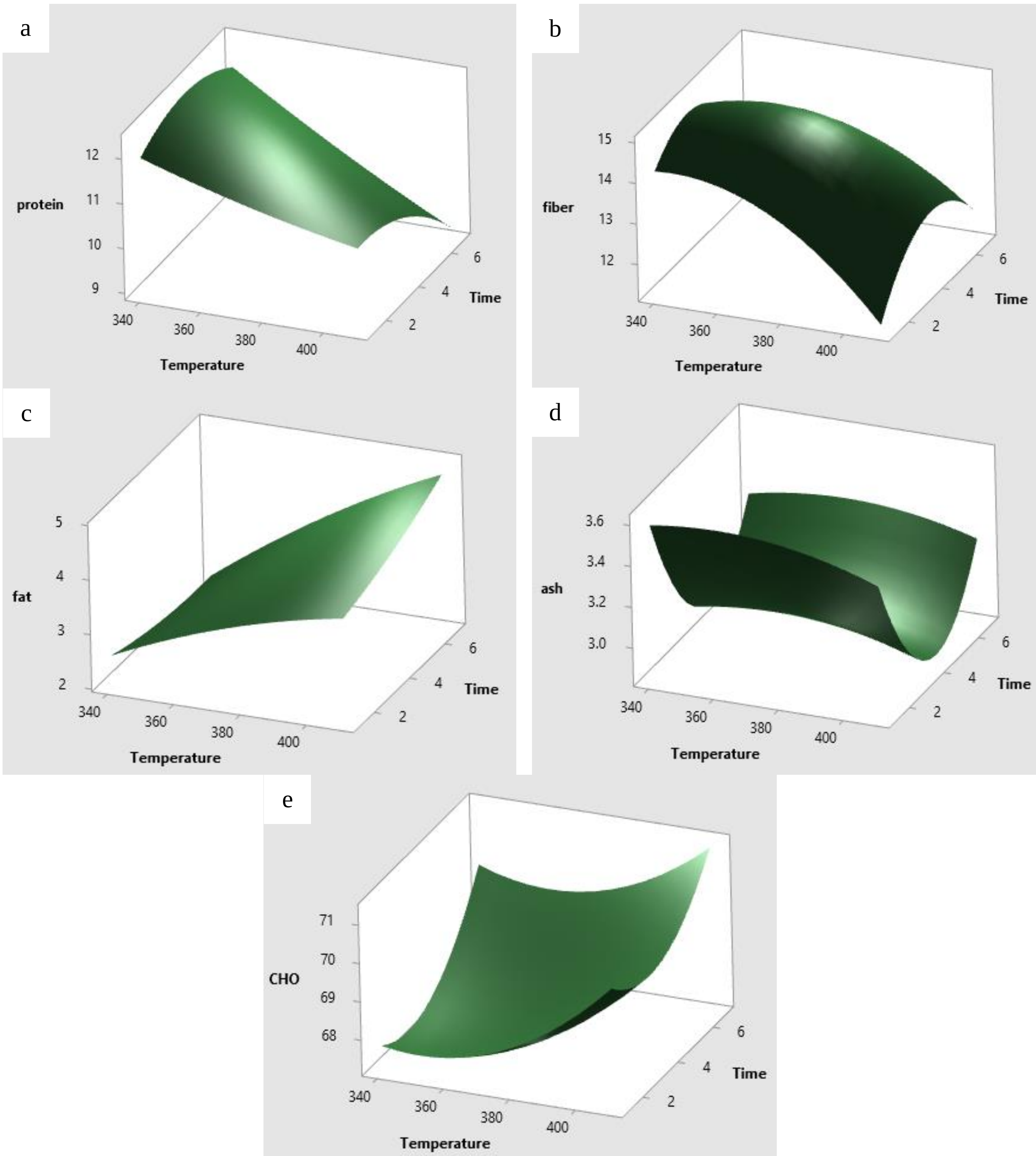

Figure 2. Surface plot of protein (a), fiber (b), fat (c), ash (d), and carbohydrate (e).

3.7. Ash Content of *Kolo*

Ash content ranged between 2.22% and 3.96%, with variability observed across roasting conditions. The model's R^2 was 16.19%, indicating it was not statistically significant. Ash content, indicative of mineral concentration, varied across samples [27]. However, the R^2 model was 16.19%, indicating no significant difference (P>0.05) between the samples and/ conditions.

3.8. Carbohydrate Content of *Kolo*

Carbohydrate levels varied between 65.13% and 70.27%, with the highest values seen at 400 °C for 6 minutes. The R^2 for the model was 35.54%. Carbohydrate content increased at elevated temperatures (Table 3), driven by the breakdown of starch into simpler sugars, aligning with observations in a similar study [24], [28]. Contrary to the expected variation in high levels of sugars, there was an R^2 model of 35.54 indicating no significant difference (P>0.05) between the samples or conditions of roasting. These findings highlight the interplay of roasting conditions on the nutritional and compositional attributes of *kolo*.

3.9. Color Properties of *Kolo*

The study examined the color properties (L^*, a^*, b^*) of *kolo* samples at different temperatures and roasting times, revealing significant variations in these parameters and highlighting the influence of roasting conditions on the barley's appearance. The L^* values, which measure lightness, consistently decreased as the roasting temperature and time increased, indicating a darkening of the barley samples with more intense roasting. The highest L^* value recorded was 57.94 at 350 °C for 2 minutes, whereas the lowest values were 26.54 at 400 °C for 6 minutes and 26.87 ± 0.24 at 410 °C for 4 minutes (Table 4). The significant differences in L^* values (p<0.05) indicated that higher temperatures and longer roasting times result in darker samples.

The redness (a^*) values, indicating redness, generally decreased with increasing temperature and roasting time, reflecting a reduction in red hues. The highest a^* value of 16.57 was observed at 350 °C for 2 minutes, and the lowest a^* value of 8.90 ± 0.55 was recorded at 400 °C for 6 minutes (Table 4). The significant p-values (p<0.05) for these differences suggest that the reduction in redness is statistically meaningful, likely due to the breakdown of red pigments and the dominance of browning reactions that mask the red tones. The model's coefficient of determination (R^2) of 83.53% and adjusted R^2 of 71.76% indicates a strong explanatory power of the model in predicting redness within the design space.

Table 4. Color properties of *kolo*.

Temp. (°C)	Time (min)	Run number	L^*	a^*	b^*
350	2	4	57.94 ± 2.35[a]	16.57 ± 0.23[a]	33.87 ± 0.92[cde]
375	1.17	12	54.43 ± 1.92[ab]	9.61 ± 0.14[f]	29.75 ± 1.20[efg]
375	4	1	54.15 ± 2.35[abc]	14.89 ± 2.38[ab]	35.25 ± 0.65[bcd]
375	4	10	52.58 ± 5.40[abcd]	14.09 ± 1.69[abc]	38.03 ± 0.06[a]
400	2	6	51.97 ± 5.66[bcd]	11.14 ± 0.34[def]	32.25 ± 0.38[d]
339.64	4	5	56.78 ± 1.35[a]	16.34 ± 0.63[a]	35.72 ± 0.01[bcd]
375	4	7	49.43 ± 3.38[bcde]	13.04 ± 0.07[bcd]	33.32 ± 0.42[cd]
375	4	3	48.35 ± 1.12[cde]	14.08 ± 0.22[abc]	36.44 ± 0.01[abc]
375	4	9	48.22 ± 2.84[de]	13.21 ± 2.06[bcd]	36.62 ± 0.23[ab]
350	6	8	44.06 ± 0.22[ef]	10.85 ± 0.72[def]	30.42 ± 0.42[ef]
400	6	2	26.54 ± 1.33[g]	8.90 ± 0.55[ef]	24.67 ± 0.01[gh]
375	6.83	11	40.16 ± 0.57[f]	10.31 ± 0.11[ef]	28.68 ± 0.32[g]
410	4	13	26.87 ± 0.24[g]	10.31 ± 2.02[abc]	28.68 ± 0.23[g]

The b^* values, representing yellowness, showed variability across different roasting conditions. Higher b^* values were seen at moderate roasting conditions, such as 38.03 at 375 °C for 4 minutes, while lower b^* values were recorded at the highest temperatures and longest times, with 24.67 at 400 °C for 6 minutes (Table 4). The statistically significant differences (p<0.05) indicate that moderate roasting enhances yellowness due to the formation of Maillard reaction products, whereas very high temperatures and prolonged roasting lead to pigment degradation or the formation of darker compounds, reducing the yellowness [29], [30]. The developed model had a coefficient of determination (R^2) of 86.56% and an adjusted R^2 of 76.95%. This indicates that the developed model equation was significant ($p<0.05$) in navigating design space for yellowness.

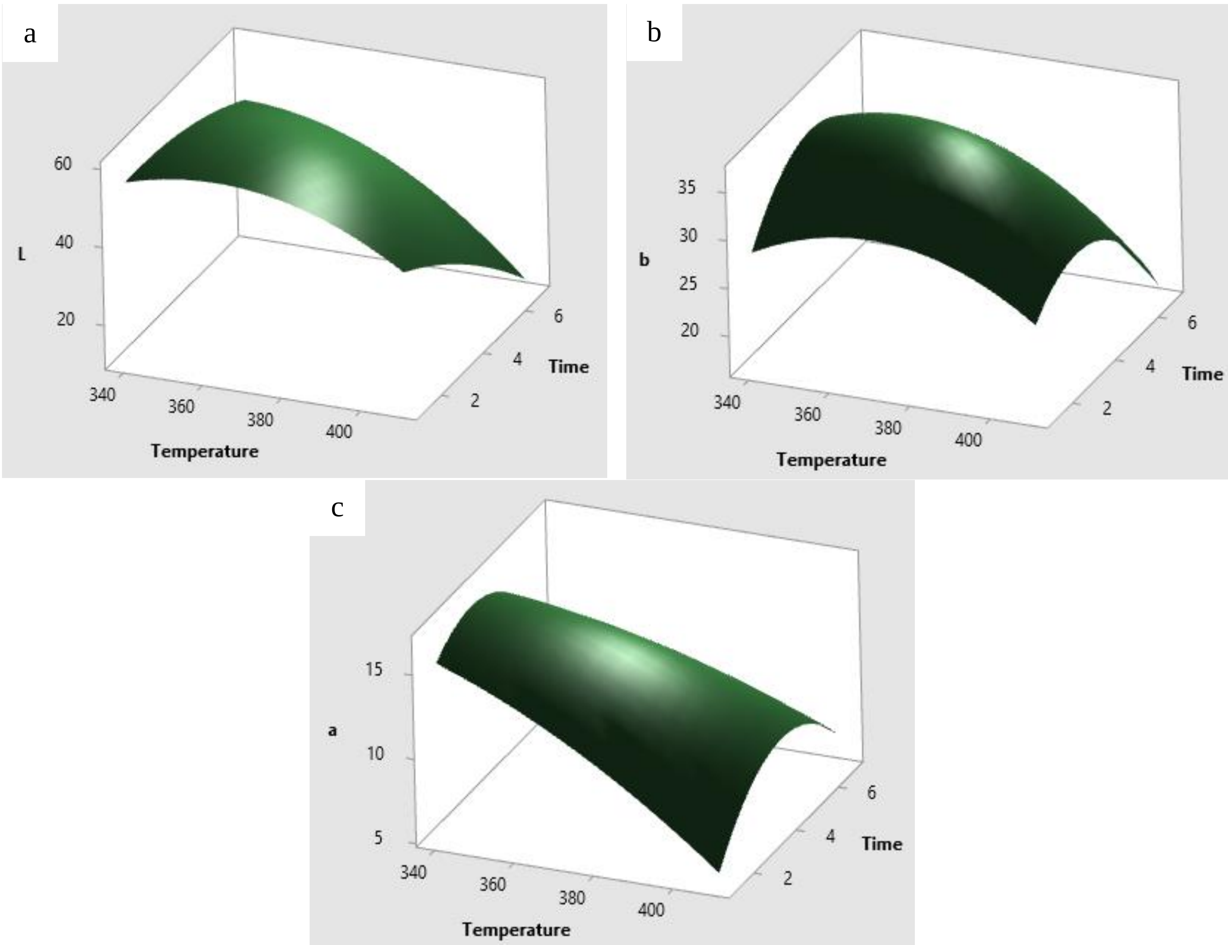

Figure 3. Surface plot of color properties. Lightness (a), yellowness (b), and redness (c).

As shown in Figure 3 (a, b, and c), the optimal conditions for achieving the highest lightness content of 57.70%, yellowness content of 33.89%, and redness value of 15.52%, respectively were a temperature of 352 °C and a duration of 2 minutes. The findings of this study are consistent with previous research on roasted grains and coffee, where increased roasting time and temperature resulted in darker colors (Table 4) and complex flavor profiles due to Maillard reactions and caramelization [31], [32]. Similar studies have reported these reactions as responsible for changes in color properties, supporting the results of this research. For instance, higher roasting temperatures in coffee beans led to darker colors, which align with the results obtained in the roasted barley samples [31]. Moderate roasting enhances color properties while extreme conditions lead to pigment degradation, corroborating the trends seen in this study [29]. Elevated temperatures help to lower the activation energy barrier of the reaction, thereby increasing the rate of degradation of Amadori rearrangement products (ARP), which are responsible for browning [33]. The significant differences in L^* values ($p<0.05$) indicated that higher temperatures and longer roasting times result in darker samples due to more pronounced Maillard reactions and caramelization. The L^* model achieved a coefficient of determination (R^2) of 90.41% and an adjusted R^2 of 83.56% (Figure 3). However, the a^* (redness) and b^* (yellowness) had higher values 83.53% and 86. 56% respectively. These high values indicate that the developed model equation was statistically significant ($p<0.05$) for navigating the design space for color. However, as shown in Figure 3 (a, b, and c), the optimal conditions for achieving the highest lightness content of 57.70%, yellowness content of 33.89%, and redness value of 15.52%, respectively were a temperature of 352 °C and a duration of 2 minutes confirming that these are the best conditions for roasting barley.

3.10. Sensory Evaluation of *Kolo*

The sensory properties of *kolo* were evaluated using a scale from 1 to 9 for odor, taste, texture, and overall acceptability across different roasting conditions. Odor ratings ranged from 3.99 to 8.55 (Table 5). The highest score was observed at 375 °C for 4 minutes (8.55), indicating a strong and desirable aroma. Conversely, the lowest score was at 400 °C for 6 minutes (3.99), suggesting a less pronounced aroma, potentially due to over-roasting. The developed model had a coefficient of determination (R^2) of 88.35% and an adjusted R^2 of 80.03%. This indicates that the developed model equation was significant ($p < 0.05$) in navigating design space for odor.

Taste evaluations varied from 4.21 to 8.46 (Table 5). The highest taste score occurred at 350 °C in 2 minutes (8.46), indicating a rich and favorable taste profile. In contrast, the lowest taste rating was at 410 °C for 4 minutes (4.21), indicating a less preferred taste due to excessive roasting. The developed model had a coefficient of determination (R^2) of 96.21% and an adjusted R^2 of 93.51%. This indicates that the developed model equation was significant ($p<0.05$) in navigating design space for taste.

Texture ratings ranged from 4.78 to 8.92 (Table 5). The highest texture score was at 350 °C for 2 minutes (8.92), suggesting a desirable texture profile with optimal roasting conditions. The lowest texture score was at 375 °C for 6.83 minutes (4.78), indicating a less favorable texture, possibly due to prolonged roasting affecting crispness and mouthfeel. At high temperatures or prolonged roasting times, moisture evaporates, which can lead to excessive dryness and a hard texture, reducing the crispness. Additionally, prolonged exposure to heat can break down the cell walls of barley kernel, negatively impacting mouthfeel by making it tougher or grainier. The model demonstrated a coefficient of determination (R^2) of 73.15% and an adjusted R^2 of 53.97%, indicating that it was not significant ($p<0.05$) for exploring the design space related to texture.

Overall acceptability scores ranged from 4.12 to 8.34 (Table 5). The highest acceptability score was observed at 339.64 °C for 4 minutes (8.34), indicating high overall satisfaction among tasters. The lowest overall acceptability score was at 410 °C for 4 minutes (4.12), suggesting that this condition resulted in the least favorable product overall. The model exhibited a coefficient of determination (R^2) of 85.97% and an adjusted R^2 of 75.94%, signifying that the model equation was significant ($p<0.05$) for navigating the overall design space.

Table 5. Sensory evaluation of *Kolo*.

Temp. (°C)	Time (min)	Run number	Odor	Taste	Texture	Overall acceptability
375	4	1	6.54 ± 0.91^{bcd}	6.92 ± 0.32^{bc}	6.97 ± 0.38^{bc}	6.72 ± 1.07^{bcd}
400	6	2	3.99 ± 0.34^{ef}	4.32 ± 025^{efg}	5.76 ± 0.16^{defg}	5.32 ± 0.77^{defg}
375	4	3	6.98 ± 0.54^{bc}	6.32 ± 0.47^{cde}	5.98 ± 0.18^{def}	5.89 ± 0.48^{cde}
350	2	4	8.33 ± 1.01^{ab}	8.46 ± 0.61^{a}	8.92 ± 0.99^{a}	8.12 ± 0.89^{ab}
339.64	4	5	8.39 ± 0.73^{a}	7.98 ± 0.96^{ab}	8.76 ± 0.83^{ab}	8.34 ± 0.59^{a}
400	2	6	5.34 ± 0.19^{cde}	5.98 ± 0.59^{cdefg}	6.76 ± 0.38^{cd}	5.55 ± 0.72^{cdef}
375	4	7	6.79 ± 0.39^{bc}	6.71 ± 0.41^{bcd}	8.43 ± 0.72^{ab}	5.98 ± 0.40^{cde}
350	6	8	6.30 ± 0.35^{bcde}	6.70 ± 0.46^{bcd}	4.90 ± 0.63^{efg}	5.67 ± 0.58^{cdef}
375	4	9	8.21 ± 1.10^{ab}	6.12 ± 1.15^{cdef}	6.87 ± 0.97^{bcd}	6.23 ± 1.29^{bcde}
375	4	10	8.55 ± 1.03^{a}	7.09 ± 0.43^{bc}	6.43 ± 0.73^{cde}	6.98 ± 1.43^{bc}
375	6.83	11	4.23 ± 0.56^{de}	4.98 ± 0.79^{defg}	4.78 ± 0.39^{efgh}	5.39 ± 1.06^{defg}
375	1.17	12	5.65 ± 0.37^{cde}	7.54 ± 0.68^{abc}	6.90 ± 0.48^{bc}	6.54 ± 0.19^{bcd}
410	4	13	4.12 ± 0.28^{def}	4.21 ± 0.39^{efgh}	4.67 ± 0.14^{efgh}	4.12 ± 0.59^{ef}

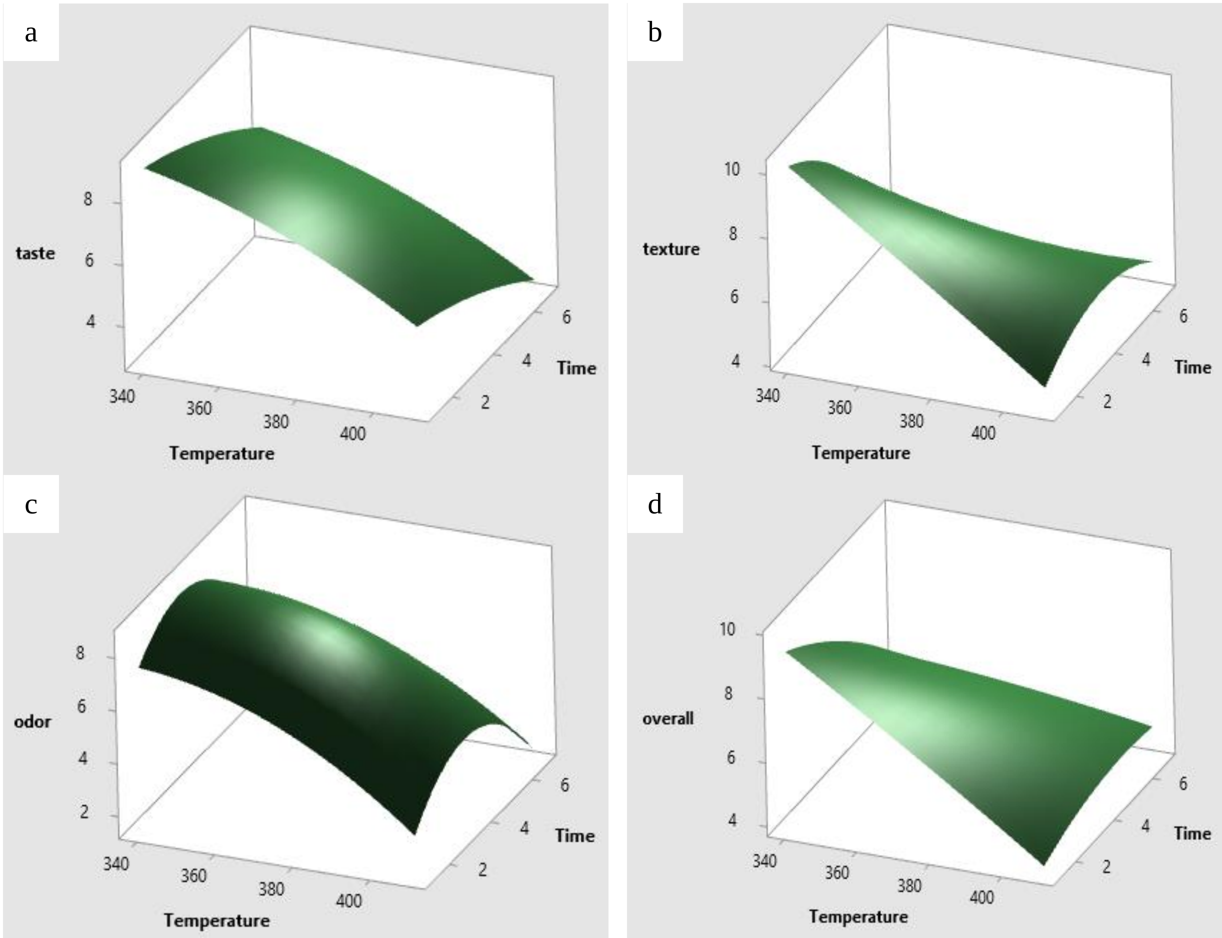

Figure 4. Surface plot of sensory evaluation. Taste (a), texture (b), odor (c), and overall acceptability (d).

The findings of this study are consistent with previous research on roasted chickpeas, particularly in the form of sattu, where variations in roasting time and temperature have demonstrated significant impacts on sensory attributes such as taste and overall acceptability [34]. This research has consistently shown that higher roasting temperatures, such as 200 °C and 228 °C, lead to reduced taste ratings of 7.20 and 6.22, respectively, and lower overall acceptability scores of 8.66 and 8.42 (Table 5). This suggests that prolonged exposure to heat during roasting can diminish the desirable sensory qualities of roasted products. Similar studies have documented these reactions as influential in altering sensory properties, consistent with the outcomes observed in this research. Roasted carob pod powders exhibit sweeter profiles with caramel-like notes and cacao-like aromas when roasted at lower temperatures [35]. Conversely, higher roasting temperatures impart a more astringent taste with aromas reminiscent of coffee and roasted notes. Flavoring compounds can degrade at elevated temperatures, especially over prolonged periods. Increased heat accelerates chemical reactions like oxidation, thermal degradation, and Maillard reactions, all of which can lead to the breakdown of these compounds. This degradation process alters the original flavor profile by diminishing delicate aromas, potentially introducing undesirable flavors, and overall reducing the sensory quality. As depicted in Figure 4 (a, b, and c), optimal conditions involving a temperature of 352 °C and a duration of 2 minutes were identified for maximizing attributes such as taste (8.35), texture (8.92), odor (8.10), and overall acceptability (8.18) of *kolo* products.

4. CONCLUSION

In conclusion, this study assessed the acrylamide content, chemical composition, color properties, and sensory attributes of street-sold and industrially processed roasted barley (*kolo*) samples. The street *kolo* exhibited significantly higher acrylamide levels exceeding regulatory benchmarks, compared to industrially processed samples. Optimal roasting conditions were identified as 352 °C for 2 minutes, to achieve desirable color, reduced acrylamide content, enhanced nutritional values, and enhanced sensory properties with desirability of 0.72. These findings underscore the critical role of roasting parameters in minimizing acrylamide formation while optimizing the nutritional quality and sensory appeal of *kolo*, offering actionable insights for both industry practices and consumer health. It is recommended to do pre-treatment (i.e, soaking) barley before roasting to reduce acrylamide formation and retain nutrients and desirable sensory attributes in *kolo*. Further work will be recommended on the evaluations of (i) cost savings of using the optimized conditions of 352 °C for 2 minutes to the industry (ii) impact on the environment and (iii) different barley varieties to identify those naturally low in acrylamide precursors for high-quality *kolo* production.

AUTHOR CONTRIBUTION

All author contributed equally to the main contributor to this paper. All authors read and approved the final paper. **Tewodros Mebratie Bimrew**: Writing (original draft), review & editing, formal analysis, investigation. **Surafel Yihune**: Writing (original draft), review & editing, formal analysis. **Isabella Nyambayo**: Writing (original draft), review & editing, supervision.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest to declare.

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