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RESEARCH ARTICLE

Dough-making performance of composite whole-grain sorghum and whole-grain wheat flours as assessed by a micro-doughLAB assay

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Abstract

Background and Objective: Owing to its climate-smart agronomic characteristics and health-promoting attributes, there is great interest in using sorghum in bread and other dough-based food product making. The objectives here were to develop a small-scale (4 g) Micro-doughLAB instrument-based assay to assess the dough-making performance of whole-grain sorghum flours in sorghum-whole grain wheat composites and to assess grain/flour factors affecting sorghum dough-making performance.

Findings: The optimal Micro-doughLAB assay conditions for 50:50 ratio sorghum:wheat composites were 64% water absorption (14% flour basis), 30°C mixing temperature, 120 rpm mixing speed, and an 87 mNm target peak torque (much lower than wheat flour). The assay showed excellent precision, well within the AACC DoughLAB method specification. Data from 23 white normal sorghum lines revealed significant ($p < .05$) differences in dough peak torque, development time, stability, and softening. Peak torque was highly significantly correlated ($p < .001$) with flour damaged starch.

Conclusions: This assay has revealed that although sorghum lines differ in dough-making quality, none approach the quality of bread wheat. Further, damaged starch plays a predominant role in sorghum dough-making performance.

Significance and Novelty: Because of its small scale, this assay is particularly useful for the assessment of the dough-making flour quality of new sorghum lines.

KEYWORDS
damaged starch, dough rheology, Micro-doughLAB, sorghum-wheat composite flour, whole-grain sorghum

1 | INTRODUCTION

Sorghum is gaining global interest as a source of flour for bread-making and other dough-based products (Capriles et al., 2016; Khoddami et al., 2021; Rumler & Schönlechner, 2021). This is a consequence of the increased understanding of the potential health benefits associated with the consumption of sorghum foods (Espitia-Hernández et al., 2022; Xiong et al., 2019), sorghum's gluten-free status, and the drought- and high-temperature-tolerant nature of sorghum as a crop (Hadebe et al., 2017). As with all cereal grains, whole-grain sorghum flour is a better source of dietary fiber, protein, essential micronutrients such as iron and B vitamins, and health-promoting phytochemicals than refined sorghum flour (Espitia-Hernández et al., 2022; Xiong et al., 2019). The flour of white tan-plant-type sorghums (also referred to as food-grade sorghums) is considered particularly useful in food products because it has a bland taste and lighter color (Tuinstra, 2008).

However, it is challenging to incorporate a substantial proportion of sorghum flour into leavened bread because its flour does not form a viscoelastic and gas-holding dough, as associated with wheat flour (Sharanagat et al., 2022; Taylor et al., 2016). This is largely due to significant compositional and structural differences between kafirin, the sorghum prolamin protein, and wheat gluten (Taylor & Taylor, 2023), including kafirin's higher hydrophobicity, the predominantly α-helical and highly folded conformation of the kafirin polypeptides. These limit the protein-water and protein-protein interactions required for hydration and development of a functional dough from sorghum flour.

Notwithstanding this, there is evidence that some sorghum types can have better dough and bread-making properties. For example, a 30% substitution of refined wheat flour with decorticated sorghum flour from a mutant high protein digestibility line was found to give a dough with higher extensibility and bread with higher loaf volume than with a normal protein digestibility sorghum line (Goodall et al., 2012). Related to this, flour of a mutant sorghum line with both waxy and high protein digestibility traits had much higher solubility than its closely related nonwaxy and normal protein digestibility line (Elhassan et al., 2015). This was attributed to its less dense endosperm texture, high amylopectin content, and differing endosperm protein composition.

To expand the use of sorghum in dough-based foods, including leavened bread and flatbreads, pasta and noodles, cakes, and cookies, it would be desirable to select types that have optimal dough-making functionality. However, the instruments that have been used to date to evaluate the dough-making quality of sorghum-wheat composite doughs, such as the Mixograph (Goodall et al., 2012), Farinograph (Jafari et al., 2017), and Mixolab (Torbica et al., 2019), have the limitation that a large quantity of sorghum flour is required. This is impractical within breeding programs where only a few grams of grain may be available (Tömösközi & Békés, 2016).

Therefore, in this study, 50:50 ratio of whole-grain sorghum–whole-grain wheat flour was evaluated with respect to its water absorption and mixing requirements to form a fully developed composite dough using a Micro-doughLAB instrument, which has a 4 g sample size and a torque of up to 1000 mNm (Perten Instruments, 2013). The effects of water addition, mixing temperature, and speed on the dough-mixing parameters were first evaluated and the levels of these parameters to give maximum dough strength were determined. According to Torbica et al. (2019), further optimization of this instrument's operating protocol is required for harmonization with industry dough-mixing conditions. The optimized method developed was then applied to evaluate the dough-making quality of 23 white normal sorghums to identify sorghum factors influencing dough quality.

2 | MATERIALS AND METHODS

2.1 | Materials

Twenty-one normal sorghum lines and three samples of an Australian commercial normal non-tannin white sorghum cultivar (Liberty) (Truong et al., 2017) were kindly donated by Nuseed (Toowoomba). One Liberty cultivar sorghum sample was cultivated in Norwin and served as the reference, designated Liberty-reference. The other two samples, designated Liberty-1 and -2, were both cultivated in Clifton for two consecutive years.

An Australian commercial hard white bread wheat cultivar (Emu Rock) was kindly donated by InterGrain. Its bread-making quality parameters were as follows: Falling Number, 436 s; wet gluten content, 27.8%; dry gluten content, 8.6%; water-binding capacity,19.3; and Gluten Index, 72.9. Its water absorption under the developed optimized doughLAB method was 65.6%.

The sorghum and wheat grains were milled separately using an SR 300 Retsch Mill fitted with a 250-μm opening size screen to produce whole-grain flours. These were vacuum-packed and stored at 4°C before analysis. The moisture contents of the Liberty-reference sorghum flour and whole-grain wheat flour were 9.7 g/100 g and 10.8 g/100 g, respectively, and their protein contents were 12.2 g/100 g (dry basis, db) and 12.0 g/100 g (db), respectively.

2.2 | Flour analyses

Moisture content was determined by AACC Method 44-15.02 (Cereals and Grains Association, 2024). Test weight (hectoliter weight) was determined by AACC Method 55-10.01 and expressed as kg/hL. Protein content (N × 6.25) for sorghum and (N × 5.70) for wheat was determined by a Dumas combustion method, AACC Method 46-30.01. Damaged starch was determined using an SDmatic amperometric type instrument (Chopin Technologies) based on the iodine dye binding principle. The results were expressed in AACC 76-31.01 method equivalents as calculated by the instrument. The falling Number of wheat flour was determined by AACC Method 56-81.04 and the gluten parameters by AACC Method 38-12.02 (Cereal and Grains Association, 2024). Micro-doughLAB optimum water absorption was determined by AACC Method 54-70.01, as described in the manufacturer's manual.

2.3 | Optimization of Micro-doughLAB assay

A 50:50 (w/w) ratio of sorghum flour to wheat flour was chosen as preliminary work indicated that the 30:70 ratio, as used by Torbica et al. (2019), gave insufficient differentiation between sorghum lines. To develop the assay, the optimal WA (percentage of water required during mixing to yield optimum dough consistency [resistance]) of the 50:50 Liberty-reference sorghum-wheat flour composite was determined. The AACC doughLAB mixing rheology Method 54-70.01 was followed, and mixing tests were performed using a range of water addition levels between 60.0% and 64.0% (flour basis) to determine the optimum mixing consistency of the sorghum-wheat composite dough.

The effects of mixing temperature and speed were then studied using 64.0% water addition. Mixing parameters measured were peak torque (peak dough resistance (mNm), energy (Wh/kg) to peak torque, dough development time (DDT, min), dough stability (min) above 87 mNm), and softening (mNm) at 5 min after peak torque. Three dough mixing temperatures were investigated: 30°C, according to AACC Method 54-70.01 (Cereals and Grains Association, 2024); 35°C, as used by Goodall et al. (2012); and 45°C, as it is above the glass transition temperature of kafirin prolamin proteins (Schober et al., 2011). Four mixing speeds were investigated: 63 rpm, according to AACC Method 54-21.02), 95 rpm, the mid-point between 63 rpm and 120 rpm; 120 rpm, according to AACC Method 54-70.01; and 150 rpm, a more extreme speed.

2.4 | Application of the assay

The dough-making properties of the 21 sorghum lines and the two samples of sorghum cultivar Liberty were determined in triplicate using the conditions developed in the study, which were 64% water absorption (14% flour basis), 30°C mixing temperature, 120 rpm mixing speed, and 87 mNm as target peak torque (Table 1), which were based on the findings using the Liberty-reference sorghum (see Section 3.1).

2.5 | Statistical analyses

The main effects of mixing speed and temperature were analyzed by one-way analysis of variance (ANOVA). Individual means were compared by Tukey post hoc test with $p < .05$ considered as significant. The dough-making properties of the sorghum lines and Liberty samples were also compared by one-way ANOVA with individual means compared by Tukey post hoc test. Data were analyzed using SPSS V24.

TABLE 1 Optimized Micro-doughLAB method parameters for determination of the dough quality of 50:50 ratio whole-grain sorghum–whole-grain wheat composite flours, adapted from Method 54-70.01 (Cereal and Grains Association, 2024).

Time (min:s)	Type	Value
00:00	Temperature	30^{0}C
00:00	Speed	63 rpm
00:30	Speed	120 rpm
10:00	End of test	
Premix time (min:s)	00:30	
Premix speed (rpm)	63	
Dough-mixing time (min:s)	10:00	
Dough-mixing speed (rpm)	120	
Dough-mixing temperature (°C)	30	
Target torque (mNm)	87 ± 3[a]	
Flour weight (g)	4.00 ± 0.01[b]	
Water addition	(64.0% flour basis)[b]	

[a]Optimum dough consistency obtained for the Liberty reference sorghum-wheat composite dough.

[b]14% Moisture basis, corrected for sample moisture.

3 | RESULTS AND DISCUSSION

3.1 | Development of Micro-doughLAB assay for whole-grain sorghum flour

3.1.1 | Water addition

Figure 1 shows the effect of water addition on the Micro-doughLAB mixing curves for a 50:50 whole-grain Liberty reference sorghum–wholegrain wheat composite flour. A low water addition (60% water, 14% flour basis) was required to achieve a similar peak torque as obtained with the wheat flour dough, that is, 130 mNm, which is typical of wheat flours using this instrument (Torbica et al., 2019). However, at this water addition, the mixing curve of the sorghum–wheat composite dough was excessively noisy, and the dough was stiff, crumbly, and not cohesive, which was clearly a result of insufficient water to hydrate the dough. The water addition was, therefore, progressively increased. Increasing the water level in the composite dough progressively decreased the noise but also reduced the peak dough consistency. Sixty-four percent water addition produced the smoothest torque curve, and the dough had the closest consistency to the wheat flour dough. However, the maximum torque was only 87 mNm, showing the weakening effect of the sorghum flour in the composite dough. Notwithstanding this, the dough-making performance of the sorghum–wheat flour composite was far better than that of sorghum alone, where a maximum torque of only 40 mNm was obtained. Based on these findings, 64% water addition was selected for the assay method to assess the dough-making quality of whole-grain sorghum cultivars. The effects of mixing temperature and speed on dough quality were then studied.

3.1.2 | Effects of mixing temperature and speed

Mixing the Liberty reference-wheat composite flour at 30°C gave the highest peak torque, whereas mixing at higher temperatures decreased the peak torque (Figure 2a). The lower torque at high mixing temperatures was likely due to a greater dough plasticizing effect (Cappelli et al., 2020). In contrast, peak torque increased with mixing speed. This is because a higher mixing speed imparts more energy to the dough, resulting in the breaking and making of more chemical bonds that are responsible for the development of the dough (Codina & Mironeasa, 2013; Jazaeri et al., 2015). At all mixing speeds, increasing temperature strongly

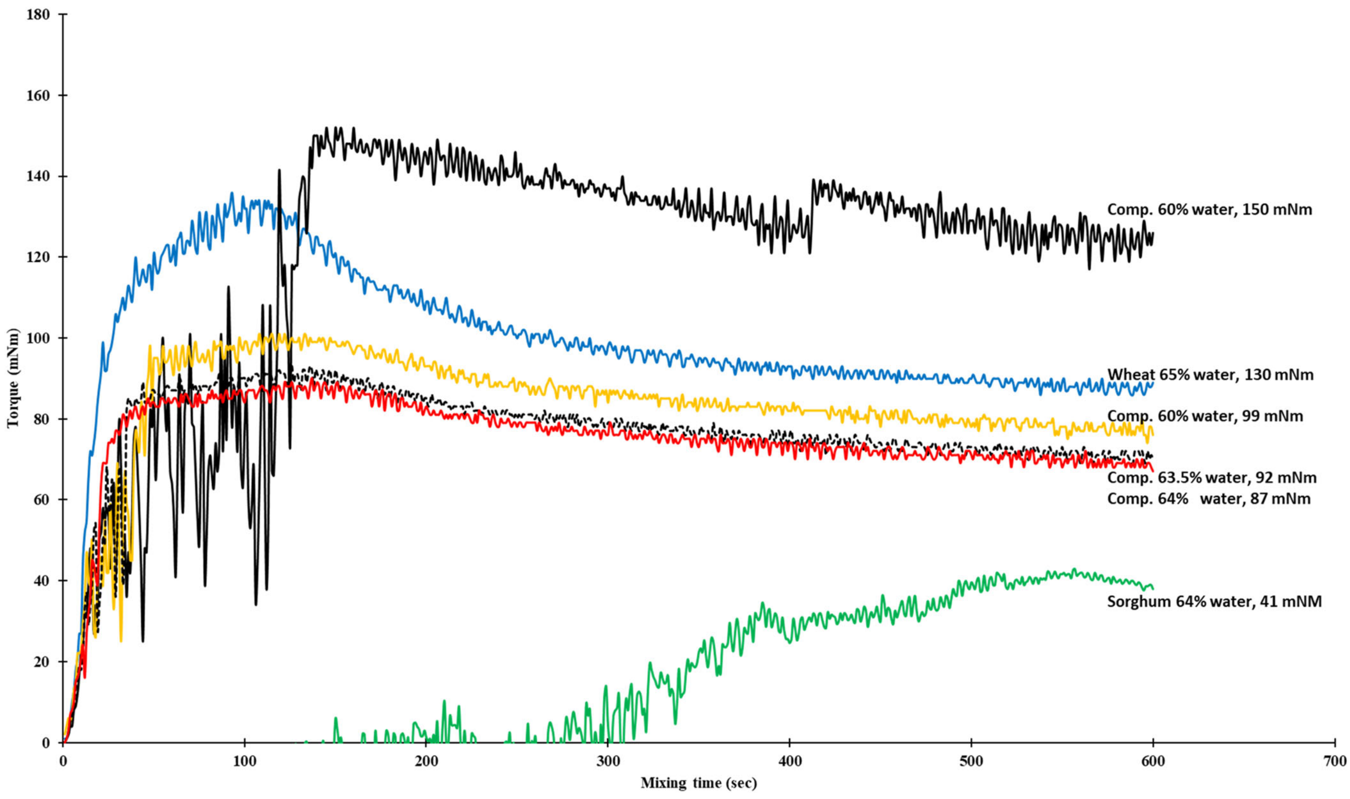

FIGURE 1 Effect of water addition level on the Micro-doughLAB dough mixing curves of 50:50 whole-grain Liberty sorghum-whole-grain wheat composite flour. [Color figure can be viewed at wileyonlinelibrary.com]

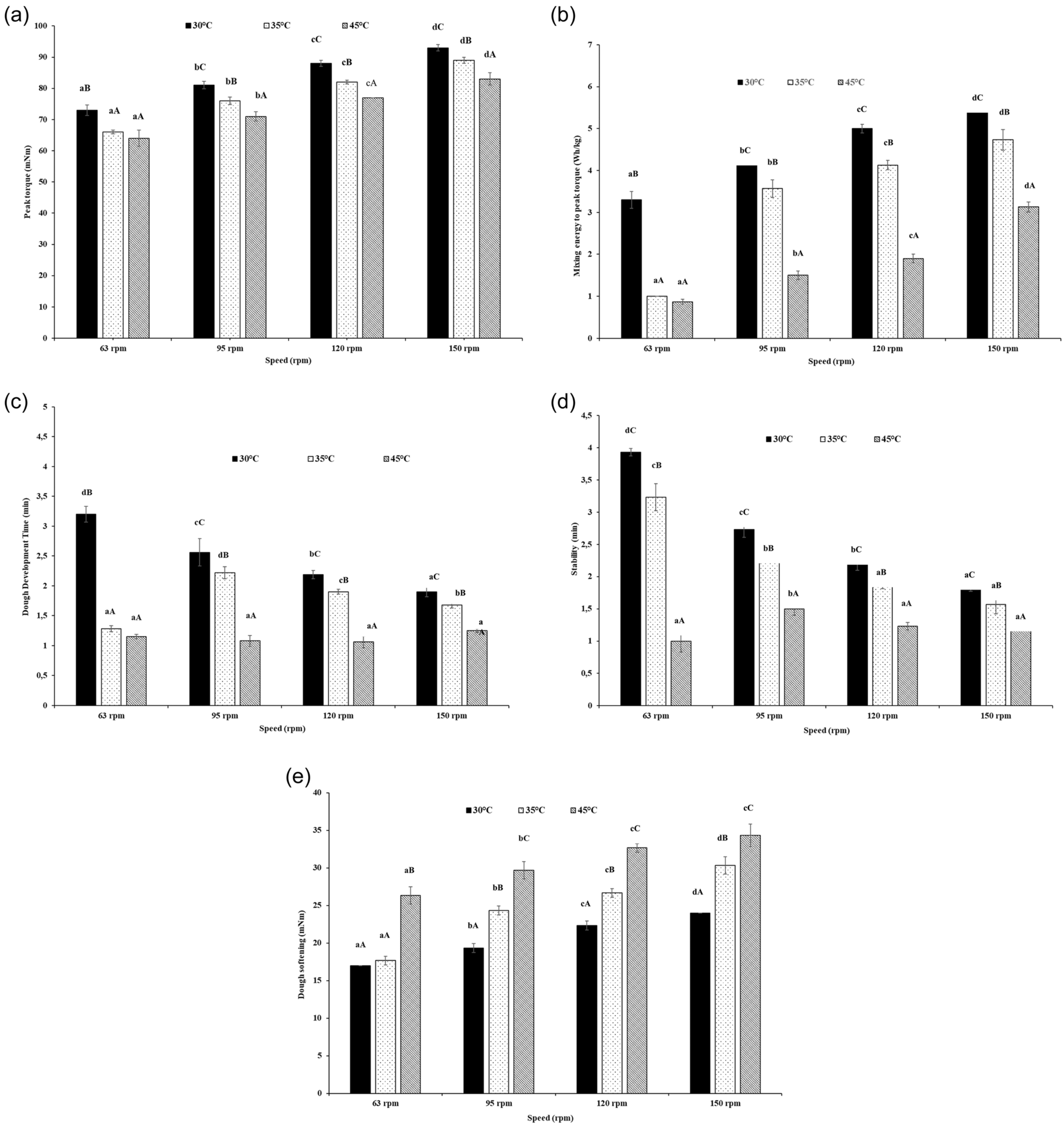

FIGURE 2 Effects of Micro-doughLAB mixing and speed on various dough quality parameters of a 50:50 Liberty whole-grain sorghum–whole-grain wheat composite flour. a–d With the same mixing temperature at different speeds are significantly different ($p < .05$), A–C with the same speeds at different temperatures are significantly different ($p < .05$). Vertical bars = ± standard deviation, $n = 3$. (a) Peak torque, (b) Energy to peak torque, (c) Dough development time, (d) Dough stability, and (e) Dough softening.

reduced mixing energy (Figure 2b). In contrast, mixing energy increased with mixing speed. As the mixing energy was calculated from the torque, these findings were expected and the explanations for the effects are the same as for the torque effects.

At any given mixing speed, DTT decreased with increasing mixing temperature (Figure 2c). This was likely due to increased molecular mobility with increasing temperature. Dough mixed at 30°C and 63 rpm had the longest DDT compared to those mixed at the same temperature using 95, 120, and 150 rpm. The reduction in DDT with mixing speed is a reflection of higher mixing speed imparting greater mechanical energy, as shown in Figure 2b.

Concerning dough stability, at all mixing speeds, the stability of the sorghum-wheat composite dough mixed at lower temperatures (30°C and 35°C) was significantly higher ($p < .05$) than when mixed at high temperature (45°C) (Figure 2d). The composite dough mixed at 30°C and 63 rpm had the longest stability. However, the peak torque of this dough was significantly lower than the target peak torque of 87 mNm (Figure 1), which indicates that the low mixing speed underdeveloped the dough. By comparing the stability of the doughs with peak torque values close or equal to the target peak torque, it is evident that the stability of the composite dough mixed at 30°C and 120 rpm was significantly higher than that mixed at 35°C and 150 rpm ($p < .05$) (Figure 2d). This suggests that sorghum-wheat composite doughs mixed at 30°C and 120 rpm were more tolerant to overmixing than at high mixing speed. Examination of dough softening behavior (Figure 2e) confirmed this. Softening was significantly less at lower mixing temperature (30°C) than at high temperature (45°C), and as the mixing speed increased, softening increased concomitantly and significantly ($p < .05$). This means that the higher the mixing temperature and speed, the greater the dough overdevelopment, which is indicative of dough breakdown.

Based on these findings, a dough mixing temperature of 30°C and mixing speed of 120 rpm were selected for the whole-grain sorghum–whole-grain wheat composite dough assay method. The 30°C temperature gave the highest dough stability (Figure 2d) and a Micro-doughLAB mixing speed of 120 rpm maximized dough stability (Figure 2c,d). This mixing speed has been found to correlate with several quality parameters of wheat bread produced using a commercial-type high-speed dough mixer (Torbica et al., 2019).

3.2 | Assay method precision

The precision of the Micro-doughLAB mixing method was determined by measuring the peak torque of the Liberty sorghum-wheat composite dough daily in triplicate over 3 days. Precision was expressed as relative standard deviation (%). Within-day precision was 1.3%, 1.1%, and 1.3% for Days 1–3, respectively. The inter-day repeatability was 1.0%. These data demonstrate appropriate precision and repeatability. According to the AACC doughLAB Method 54-70.01, precision for peak torque should not exceed 4% among replicates and days (Cereals and Grains Association, 2024).

3.3 | Evaluation of the dough-making performance of different sorghum lines

Regarding the dough-making performance of the 23 test sorghums, none were closely similar to the bread wheat reference (Table 2). All produced doughs with much lower peak torque, only 57%–67%. This finding is in general agreement with other research. Abdelghafor et al. (2013) and Dube et al. (2021) both found progressively lower Extensograph dough maximum resistance (resistance to extension) with an increasing proportion of sorghum in sorghum–wheat composite flours. The dough-weakening effect of sorghum flour inclusion can be attributed to the dilution of wheat gluten.

The sorghum-wheat composite DDTs were all longer, and generally substantially longer, 22%–56% longer than the wheat reference (Table 2). Researchers have found differing effects of sorghum flour inclusion on the DTT of sorghum–wheat composition flours (Rumler & Schönlechner, 2021). Earlier work from this laboratory indicated that while Farinograph DTT of 30:70 blends of sorghum:wheat flours showed a somewhat longer DTT than the wheat flour alone, with 50:50 blends DTT was considerably shorter (Yousif et al., 2012). However, an important difference in this present work was that both sorghum and wheat flours were whole grain, that is, not refined. It has been proposed that the longer dough development of bran-rich flours is due to the slower water absorption property of bran delaying gluten network formation (Packkia-Doss et al., 2019). The sorghum-wheat composite doughs were, however, stable for longer than the wheat dough, 54%–269% longer, and softened less, 33%–55%. However, these figures by themselves are somewhat misleading and have to be seen in the context that the sorghum-wheat composite doughs were far weaker (much lower peak torque).

The evaluation of three samples of the Liberty sorghum cultivar, which had been cultivated in two different environments and three different years, made it possible to assess whether dough-forming performance in normal sorghum types was strongly cultivar-associated. This was not evidently the case. For example, the Liberty reference gave the highest peak torque but had the shortest DTT (Table 2). In contrast, Liberty-1 and -2 doughs had significantly lower peak torque, and Liberty-2 dough had a significantly longer development time.

Pearson's correlations were performed to determine whether dough-forming performance was associated with any of the measured sorghum grain/flour physicochemical characteristics (Supporting Information S1: Table S1). With the 22 lines that formed a cohesive dough, Micro-doughLAB mixing performance was not associated with protein, unlike the situation with wheat (Tozatti et al., 2020). However, the

TABLE 2 Micro-doughLAB dough-mixing properties of whole-grain white sorghum lines in a 50:50 flour blend with whole-grain wheat.

Sample	Grain type (Tan-plant or not)	Test weight (kg/hL)	Protein content (g/100 g dry basis)[a,b]	Damaged starch (AACC 76-31)	Peak torque (resistance) (mNm)[a]	Dough development time (DDT) (min)[a]	Dough stability (min)[a]	Dough softening (mNm)[a]
Liberty-reference	*No*	*ND*[c]	*12.2 ± 0.1*	*5.24*	***88.0^{h} ± 1.0***	*2.2^{a} ± 0.1*	*2.2^{ab} ± 0.1*	*22.3^{fg} ± 0.6*
NGT17N216	Almost	77.6	12.6 ± 0.4[c]	3.39	74.0^{a} ± 1.7	**2.8^{fg} ± 0.1**	2.5^{abc} ± 0.1	13.7^{a} ± 1.2
18G393	Yes	74.4	10.6 ± 0.3	3.06	76.3^{ab} ± 0.6	2.7^{def} ± 0.1	2.6^{abc} ± 0.1	17.7^{bcd} ± 0.1
18G553	Almost	71.0	11.8 ± 0.1	3.18	77.0^{ab} ± 1.0	2.7^{def} ± 0.1	2.8^{bc} ± 0.1	18.0^{bcde} ± 0.0
NGT17N191	Almost	76.8	10.7 ± 0.2	3.78	77.7^{abc} ± 0.6	2.7^{def} ± 0.1	2.7^{abc} ± 0.1	18.7^{bcde} ± 0.1
Liberty-1	No	ND	13.7 ± 0.4	3.22	78.0^{abcd} ± 1.0	2.4^{abc} ± 0.1	2.3^{ab} ± 0.1	20.7^{defg} ± 0.1
18G388	Yes	75.8	13.0 ± 0.2	3.38	78.3^{bcd} ± 3.1	2.6^{cde} ± 0.1	2.8^{bc} ± 0.1	15.3^{ab} ± 1.2
18G537	Almost	78.8	19.4 ± 0.1	3.88	78.3^{bcd} ± 1.2	2.4^{abc} ± 0.0	2.3^{ab} ± 0.1	16.0^{ab} ± 1.7
Liberty-2	No	74.4	11.2 ± 0.4	3.43	78.3^{bcd} ± 1.2	2.6^{cde} ± 0.0	2.7^{abc} ± 0.1	18.7^{bcde} ± 2.1
NGT16N436	Yes	ND	13.6 ± 0.1	4.21	78.7^{bcd} ± 2.5	2.7^{def} ± 0.1	2.8^{bc} ± 0.1	19.7^{cdef} ± 1.5
18G391	Yes	75.2	15.7 ± 0.3	3.70	79.7^{bcde} ± 1.5	2.4^{abc} ± 0.1	2.0^{ab} ± 0.1	17.0^{abc} ± 1.0
18G390	Yes	76.4	14.1 ± 0.2	3.49	80.0^{bcde} ± 1.0	2.5^{bcd} ± 0.1	2.4^{abc} ± 0.1	17.3^{bcd} ± 1.2
18G389	Yes	77.2	13.6 ± 0.2	3.84	80.0^{bcde} ± 1.7	2.6^{cde} ± 0.0	2.5^{abc} ± 0.1	18.3^{bcde} ± 1.5
NGT17N192	Almost	78.6	10.8 ± 0.1	3.71	80.0^{cde} ± 1.0	2.7^{def} ± 0.1	3.0^{bc} ± 0.2	18.3^{bcde} ± 1.5
NGT17N208-2	Yes	76.2	13.2 ± 0.3	3.45	81.3^{cdef} ± 0.6	2.7^{def} ± 0.1	2.7^{abc} ± 0.1	17.3^{bcd} ± 0.1
18G552	Almost	76.2	9.7 ± 0.0	4.16	81.7^{cdef} ± 0.6	2.5^{bcd} ± 0.1	2.7^{abc} ± 0.1	20.0^{cdefg} ± 0.0
NGT16N438	Yes	ND	14.0 ± 0.0	5.66	81.7^{cdef} ± 0.6	2.5^{bcd} ± 0.1	**3.5^{c} ± 1.7**	**23.3^{g} ± 0.1**
NGT17N217	No	79.2	10.3 ± 0.1	3.75	82.0^{def} ± 1.7	2.3^{ab} ± 0.1	2.2^{ab} ± 0.1	21.3^{defg} ± 1.5
NGT17N184	No	ND	14.6 ± 0.0	4.26	83.0^{efg} ± 1.0	2.7^{def} ± 0.1	3.1^{bc} ± 0.1	19.7^{cdef} ± 0.1
NGT16N435	Almost	75.4	12.2 ± 0.0	4.22	83.3^{efg} ± 1.5	2.5^{bcd} ± 0.1	2.7^{abc} ± 0.1	20.0^{cdefg} ± 1.0
NGT16N437	Yes	ND	14.6 ± 0.3	4.52	84.7^{fg} ± 1.5	2.4^{abc} ± 0.1	2.3^{ab} ± 0.1	22.3^{fg} ± 1.5
NGT16N434-2	Yes	ND	13.8 ± 0.1	4.52	86.3^{gh} ± 0.6	2.6^{cde} ± 0.0	3.1^{bc} ± 0.1	19.7^{cdef} ± 1.2
NGT17N208-1	Yes	ND	14.7 ± 0.1	4.58	87.0^{gh} ± 0.0	2.6^{cde} ± 0.0	2.9^{bc} ± 0.1	18.7^{bcde} ± 0.1
NGT16N434-1[d]	*Yes*	*ND*	*13.4 ± 0.3*	*6.76*	*100.0^{i} ± 1.0*	*3.1^{h} ± 0.1*	*1.6^{a} ± 0.4*	*30.1^{h} ± 1.0*
Whole-grain wheat standard[e]	*Not applicable*	*ND*	*12.0 ± 0.2*	*5.87*	*130.0 ± 1.0*	*1.8 ± 0.0*	*1.3 ± 0.0*	*42.0 ± 0.0*

Note: **Bold** = Line with the highest value for the parameter (excluding line NGT16N434-1), Underline = Line with the highest value for the parameter (excluding line NGT16N434-1).

[a]Mean ± standard deviation, $n = 3$. Mean values in a column with different superscript letters are significantly different ($p < .05$). Reference torque for sorghum 87 mNm.

[b]Protein content calculated using N × 6.25 for sorghum and N × 5.70 for wheat.

[c]Not determined, insufficient grain to obtain multiple samples required for this assay.

[d]The mixing curve to peak torque of this sample was noisy, indicating a lack of formation of a cohesive dough.

[e]Mean ± standard deviation, $n = 3$. Mean values in a column with different superscript letters are significantly different ($p < .05$). Reference torque 130 mNm.

parameters of dough peak torque (resistance), dough stability (min > 87 mNm), and dough softening were all significantly correlated ($p < .001$, $p < .05$, and $p < .05$, respectively) with flour damaged starch content. This association can be explained in terms of the greater swelling of damaged starch due to higher water absorption and binding by the starch granules (Barrera et al., 2007), which would impart greater strength to the dough

(Wang et al., 2020). At the same time, this dough exhibited greater softening with overmixing, as a result of the collapse of the swollen starch granules.

The level of damaged starch in sorghum flours is associated with kernel hardness (strength) (Taylor et al., 2006), as is the case with wheat (Tozatti et al., 2020). Endosperm hardness seems to be strongly genetically controlled in sorghum (Suguna et al., 2021). In turn, sorghum kernel hardness, as measured by resistance to abrasive decortication, was found to be highly significantly correlated with grain test weight ($p < .001$) (Chiremba et al., 2011). In this present study, the correlation between the test weight of the lines and flour-damaged starch ($r = .462$) was only significant at $p < .1$. The probable reason that this correlation was relatively low was that it was based on only 15 of the 23 lines, as there was insufficient of the other lines to determine their test weight.

4 | CONCLUSIONS

The developed Micro-doughLAB assay can distinguish between the dough-making performance of different whole-grain sorghum flours. Flours from different normal sorghum lines exhibit a range of dough peak torque (resistance), dough development time, dough stability, and softening. As the assay uses only 2 g of sorghum flour in a 50:50 blend with whole-grain wheat flour, it should be particularly useful for assessing the dough-making flour quality of new sorghum lines.

However, none of the sorghum lines analyzed approached the quality of wheat standard with respect to important bread dough-making parameters. Specifically, their doughs were much weaker (lower peak torque) and generally had substantially longer dough development times. Hence, it is likely that even the best sorghum lines would be more suitable for flatbread and other dough-based product-making than for leavened bread-making when used as whole-grain flour. The intention is to evaluate this in future work.

Probably the most significant finding is that Micro-doughLAB dough peak torque (strength) was highly significantly correlated with the level of damaged starch in whole-grain sorghum flour. This finding indicates the predominant role of starch in sorghum flour dough-making performance.

AUTHOR CONTRIBUTIONS

Stuart K. Johnson: Conceptualization. **Koya A. P. Dovi** and **Stuart K. Johnson**: Experimental design. **Stuart K. Johnson** and **Koya A. P. Dovi**: Funding acquisition. **Stuart K. Johnson**, **Vicky A. Solah**, and **John R. N. Taylor**: Supervision. **Koya A. P. Dovi**: Investigation. **Koya A. P. Dovi** and **John R. N. Taylor**: Data curation. **Koya A. P Dovi**: Writing–original draft. **John R. N. Taylor**, **Koya A. P. Dovi**, **Stuart K. Johnson**, and **Vicky Solah**: Writing–editing and review.

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