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Multi-scale dough adhesion analysis: Relation between laboratory scale, pilot scale and human sensory

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Abstract

Undesired dough adhesion is still a challenge during the production of baked goods. There are various methods for determining the adhesive texture properties of dough. In the majority of scientific papers, dough stickiness is measured analytically by the force-distance recording of dough detachment. In this study, we describe a new multi-scale approach to compare dough adhesion phenomena in a laboratory, pilot sale and human sensory assessment. In it, the adhesive material properties of dough were investigated using a pilot scale toppling device representing dough adhesion behavior in the production process, in the laboratory by texture analysis with the Chen–Hoseney method and furthermore with a new, implemented non-oral human sensory analysis. To simulate different dough adhesion behavior, the dough mechanical and adhesion properties were varied by applying dough-modifying enzymes and different dough storage times. The structural changes in the different wheat dough system were compared by rheological characterization. By characterizing the different adhesion phenomena of the doughs, the sample with bacterial xylanase showed the highest values after 80 min of storage time in all three methods. Correlation analysis revealed a strong relationship between the detachment time (pilot scale) and human sensory assessment attributes (Force $R = 0.81$, Time $R = 0.87$, Distance $R = 0.92$, Stickiness $R = 0.80$) after 80 min of storage time. Even though human sensory assessment showed limits in the detectability of differences in dough adhesion behavior compared to the Chen–Hoseney method, it was better suited to predict machinability.

KEYWORDS
enzymes, machinability, stickiness, texture properties, wheat dough

1 | INTRODUCTION

Adhesion plays a diverse functional role for many baked goods. In some cases, it is desirable and necessary for proper product functionality, but often undesirable dough residues interfere with the

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production process (Heddleson, Hamann, & Lineback, 1993). Especially in large and highly automated bakeries, dough with high adhesive properties often leads to process disruption, product loss, and reduced product quality, for example, by adhering to baskets and conveyor belts (Beck, Jekle, Hofmann, & Becker, 2009; Dobraszczyk, 1997; Grausgruber, Hatzenbichler, & Ruckenbauer, 2003; Hoseney & Smewing, 1999; Laukemper, Jekle, & Becker, 2019; Wang, Watts, Lukow, Schlichting, & Bushuk, 1996).

In general, adhesion is defined as the attraction between two surfaces by contact, or bonding between an adhesive and adherent (Dobraszczyk, 1997; Noren, Scanlon, & Arntfield, 2019). In most food systems, and for dough matrices, adhesion is a combination of adhesive forces, the interaction between a material and a surface, and cohesive forces, the interactions within the material (Hoseney & Smewing, 1999; Kinloch, 1987; Noren et al., 2019; Tock et al., 2013; van Velzen, van Duynhoven, Pudney, Weegels, & van der Maas, 2003). The dominant force cause either adhesive failure (complete separation of dough from the surface) or cohesive failure (remaining residues on the surface after peeling) (Dobraszczyk, 1997). Nevertheless, for dough, not only the ratio of these two forces is decisive for the adhesion phenomena.

Furthermore, dough adhesion depends strongly on its rheological properties, and therefore it is a function of time, temperature, and deformation (Dobraszczyk, 1997; Hoseney & Smewing, 1999; van Velzen et al., 2003). Therefore, the initial adhesive properties of the dough are determined by its composition as well as further modified by processing steps and influenced by additional factors, such as environment properties, throughout the entire process (Huault et al., 2019; Stadnyk, Piddubnyi, Krsnozhon, & Nataliia, 2020; Yildiz, Meral, & Dogan, 2012).

Researchers have long been concerned with the elucidation and evaluation of dough adhesion because of the problems that it creates in the production of baked goods (Laukemper et al., 2019). For adhesive materials, the separation from a surface requires a finite force (Pastewka & Robbins, 2014). Therefore, several instrumental analytical methods were developed to determine the necessary separation force by applying a compression force to the dough and recording the force to withdraw the probe from the dough surface (Chen & Hoseney, 1995a; Couch & Binding, 2003; Ghorbel, Launay, & Heyd, 2003; Grausgruber et al., 2003; Huault et al., 2019; Laukemper et al., 2019; Tock et al., 2013; Wang et al., 1996). In a further development, the stable micro system Chen–Hoseny dough stickiness rig (A/DSC), as an improved version of the Chen and Hoseney stickiness method, has become the most widely used laboratory scale measurement of dough stickiness at present (Grausgruber et al., 2003).

Even though dough adhesion can be determined and studied in the laboratory, the question remains to what extent this corresponds to the adhesion phenomena seen in the production of baked goods. Therefore, earlier studies had already compared and correlated laboratory measured dough properties with human sensory dough stickiness evaluations. By comparing several subjective bakery stickiness assessments with analytical measured dough stickiness, the literature showed correlations between analytically characterized dough properties and a sensory dough adhesion evaluation to strengthen the laboratory methods and their results regarding dough handling and processing properties (Bhattacharya, Narasimha, & Bhattacharya, 2006; Chen & Hoseney, 1994; Dobraszczyk, 1997; Tock et al., 2013; Wang et al., 1996). Furthermore, some studies predicted dough machinability by the stickiness values determined with texture profile analysis and/or the Chen and Hoseney stickiness method cell (Bollaín, Angioloni, & Collar, 2006; Collar, Andreu, & Martínez-Anaya, 1998; Collar, Martinez, Andreu, & Armero, 2000), but a further evaluation with larger dough quantities and process environment conditions is still missing.

In the following study, dough adhesion phenomena were characterized and compared for the first time taking a multi-scale approach by means of a laboratory-, pilot scale and human sensory assessment, as shown in Figure 1. On the laboratory level, a force-time-distance curve of dough detachment by the Chen–Hoseney stickiness method was recorded. For the practical investigation, a pilot scale toppling device was used, which measures the detachment time of doughs after a 180° rotation. Furthermore, a new developed high standardized human sensory assessment was implemented to measure dough adhesion using a defined (human) finger contact procedure. The multi-scale approach is intended to clarify to what extent the different methods capture dough adhesion. The relation of the results on the different scales was tested by performing a correlation test. To simulate different levels of dough adhesion behavior, the dough mechanical and adhesion properties were varied by applying dough-modifying enzymes and different dough storage times. The enzyme-dependent structural changes as a function of time were characterized by rheological frequency sweep tests. Summarizing, the objective of this study is to characterize dough adhesion behavior under the three aforementioned approaches with their relevancy to practical application. The presented work compares the different adhesion determination levels to give new insights into the complex dough adhesion phenomena.

2 | MATERIALS AND METHODS

2.1 | Raw materials and chemical composition

German commercial wheat flour type 550 was obtained from Eduard Walter KG Mühle (Böhl-Iggelheim, Rhineland-Palatinate, Germany). According to the methods of the American Association of Cereal Chemistry international (AACCi) and of the International Association for Cereal Science and Technology (ICC), 14.12 ± 0.14 g moisture per 100 g flour (AACCi 44-01), 12.73 ± 0.08 g protein content per 100 g dry flour (ACCi 46-16, N × 5.7), and 0.52 ± 0.05 g ash per 100 g dry flour (ICC 104/1) were determined. Further ingredients for dough preparation were distilled water, sodium chloride (NaCl, Südsalz GmbH, Bad Friedrichshall, Baden-Württemberg, Germany) and dry yeast (Lesaffre Deutschland, Kehl, Baden-Württemberg, Germany). Dry yeast release glutathione and the already low concentrations weaken the dough and contribute to dough stickiness (Goesaert et al., 2005; Verheyen et al., 2015). According to Verheyen et al., 2015, 12.37 ± 1.17 mg glutathione/1 g dry yeast was analyzed by a photometrical assay which is low in comparison to their determined range of 5.37–81.22 mg/1 g dry yeast. By using the same yeast amount, all samples were exposed to the same artifact. To create different wheat dough samples with varied dough adhesion behavior, enzymes supplied by AB Enzymes GmbH (Darmstadt, Hesse, Germany) were added, as shown in Table 1. The enzyme dosage was

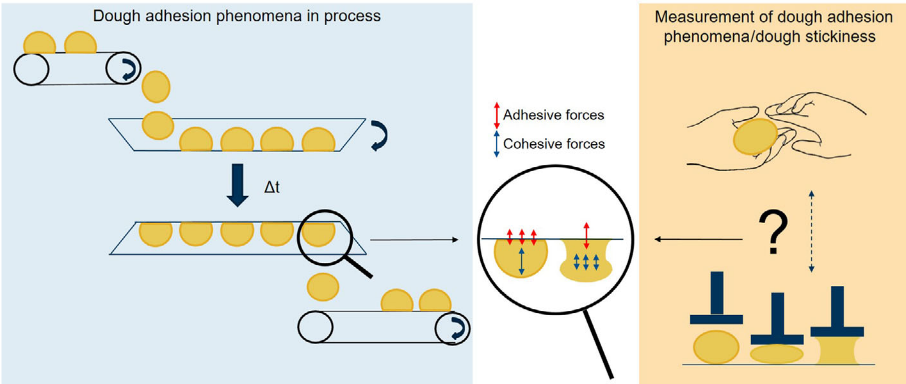

FIGURE 1 Schematic representation of a new approach that considers dough adhesion phenomena on a process-level, laboratory and human sensory scale. Left: exemplary dough adhesion in process by moving and toppling dough pieces. Right: measurements of dough adhesion by fingers (human sensory) and instrumental by the force determination of detachment. Middle: zoom to dough adhesion and detachment regarding adhesive and cohesive forces.

TABLE 1 Used enzymes with abbreviation, specification and dosage to obtain different sticky doughs.

Abbreviations	Enzyme	Dosage	Specification
REF	-	-	-
FX	Fungal Xylanase	50 ppm	EL-2020 003453 Declared enzyme: Xylanase Declared activity: Min. 1700 XylH/g Production strain: *Aspergillus Niger* IUB number: 3.2.1.8 CAS number: 9025-57-4
BX	Bacterial Xylanase	50 ppm	EL-2020 003454 Declared enzyme Xylanase Declared activity: Min. 568 XylH/g Production strain: *Bacillus subtilis* IUB number: 3.2.1.8 CAS number: 9025-57-4
GOX	Glucose oxidase	30 ppm	EL-2020 003457 Declared enzyme: Glucose oxidase Production strain: *Trichoderma reesei* IUB number: 1.1.3.4 CAS number: 9001-37-0
TG	Transglutaminase	30 ppm	EL-2020 003458 Declared enzyme: Transglutaminase Declared activity: Min. 100 TGU/g Production strain: *Streptomyces mobaraensis* IUB number: 2.3.2.13 CAS number: 80146-85-6
CE I	Cellulolytic enzyme I	30 ppm	EL-2020 003459 Declared enzyme: Cellulase Declared activity: Min. 2,400 CU/mg Production strain: *Trichoderma reesei* IUB number: 3.2.1.4 CAS number: 9012-54-8
CE II	Cellulolytic enzyme II	100 ppm	EL-2020 003460 Declared enzyme: Cellulase Declared activity: Min. 35,000 TCU/g Production strain: *Trichoderma reesei* IUB number: 3.2.1.4 CAS number: 9012-54-8

set as the maximum considered concentration given by supplier information. Furthermore, a reference wheat dough system (denoted by the abbreviation REF throughout this work) without enzyme addition was analyzed.

2.2 | Dough preparation

In accordance to AACC method 54–70.01, a torque measuring z-kneader (doughLab; Perten Instruments, Germany) was used to determine the optimum water absorption and kneading time. As a result, the standard wheat dough formulation was 52.98 mL demineralized water, 1.5 g NaCl and 0.2 g dry yeast on 100 g flour. For measuring the stickiness with the Chen–Hoseney method, 50 g wheat flour corrected to 14% moisture with the corresponding standard dough formulation was kneaded in the z-kneader for 215 s at 63 rpm to reach 500 Farinograph units. For the adhesion measurements using the pilot scale method and sensory assessment, 1,500 g wheat flour corrected to 14% moisture with corresponding standard dough formulation were mixed at 25 Hz for 60 s and 50 Hz for 300 s using a laboratory spiral kneader (Diosna Dierks & Söhne, Osnabrück, Germany). The mixing set-up was determined by a human sensory elasticity test performed by an educated baker for comparable dough properties. For the entire adhesion analysis, the proper amount of enzymes were added to dough formulation. Different time scales were considered to characterize time-dependency changes of the dough adhesion behavior. Thus, the dough preparations were stored for 0, 20, and 80 min at 30°C.

2.3 | Determination of dough adhesion behavior

2.3.1 | The Chen–Hoseney stickiness method

The Chen–Hoseney (CH) stickiness evaluation was performed using a texture analyzer (type TA.XT2, Stable Micro System, Godalming, England) with the SMS/Chen–Hoseney Dough Stickiness Rig to determine the dough adhesion effects on a laboratory scale. By pushing and pulling a Perspex stamp from the dough sample, the separation force-distance curve values were recorded to specify the material properties regarding the adhesive behavior of the dough sample. A texture analyzer is used to provide constant compression force for quantifying the tension force. Moreover, the defined extrusion of the dough when using the Chen–Hoseney cell (Figure 2) ensures a minimized dough flowing by keeping the dough close to the stamp surface (Chen & Hoseney, 1995a).

Regarding the measurement procedure, a small piece of dough was transferred into the Chen–Hoseney cell. After placing the cover, the dough was extruded by rotating the screw to move the piston. To obtain a fresh and uniform sample surface, the dough with a thickness of about 1 mm was removed using a spatula. To obtain an equal amount of dough of 1 mm above the screen surface, this process was repeated approximately three times. Before starting the measurement, the cell was positioned centrally under the texture profile analyzer, allowing the dough to rest for 30 s. Regarding the applied test settings, the test and post-test speeds were set to 0.5 mm/s, the applied force to 0.4 N, the trigger force to 0.05 N, the contact time to 0.1 s and the return distance to 4 mm. For performing the measurements, the texture analyzer probe was driven to contact the extruded dough surface. The force required for separating the probe from the dough surface was recorded as a force-time-distance regression (Figure 3) and calculated as the three values positive maximum force, positive area and distance, which can be interpreted as the attributes “stickiness” (N), “work of adhesion” (N·mm), and “sample cohesion/dough strength” (mm) (Abebe, Ronda, Villanueva, & Collar, 2015; Chen & Hoseney, 1995a; Grausgruber et al., 2003; Yildiz et al., 2012). Triplicate determinations with each 10 single measurements were carried out ($n = 30$). The experiments were carried out in an open air condition at room temperature of 20 ± 1.5°C and approx. 50% relative humidity.

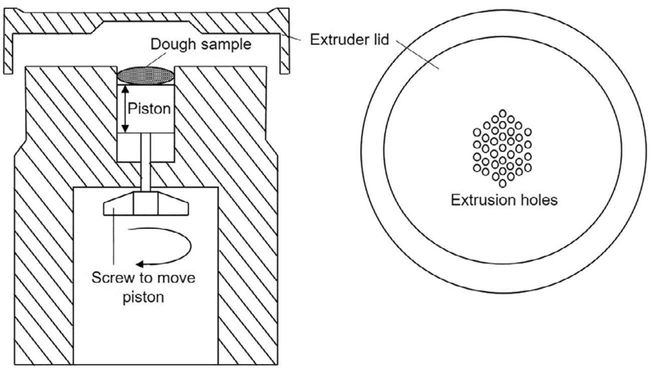

FIGURE 2 Schematic diagram of the side- and top-view of a Chen–Hoseney cell. Adapted with permission from (Grausgruber et al., 2003). John Wiley and Sons.

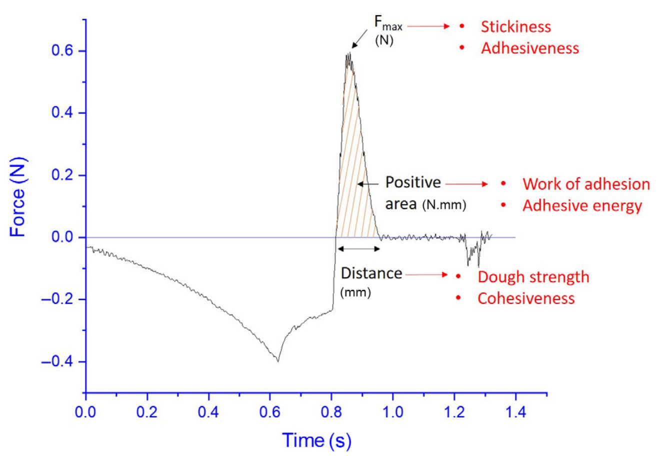

FIGURE 3 Force-time-distance curve from the Chen–Hoseney stickiness example measurement with interpretation attributes.

2.3.2 | Detachment time characterization by a pilot scale toppling device

To determine the dough adhesion effects during processing, a pilot scale toppling device (Figure 4) was used (Laukemper et al., 2019). The experimental set-up enables the consideration of the dough adhesion effects in industry-relevant conditions. The aim was to simulate the toppling of dough pieces from one processing surface to the next (as shown in Figure 4), allowing the elucidation of the adhesion behavior based on the analysis of the detachment time. The device consists of two toppling bowls which are set in motion by electrically driven gear wheels. Dough pieces were placed on the toppling bowls and toppled after adjustable contact times through a 180° rotation of the bowls through gravitational force. The gravity-stimulated detachment of dough depends on the material's or the dough's adhesive behavior. Moreover, a photoelectric laser sensor (Omron E3Z-LR86, Japan) detects the falling dough pieces. The measured falling time is interpreted as the detachment time. Dough samples (Section 2.2) of 55 ± 1 g were formed by a dough divider (bak-tec Rotamat CN, Dreieich, Germany) and placed on proofing cloths made of 100% cotton (NW 97-29, R.Weber GmbH Gisikon, Switzerland) and stored for 80 min in the proofing cell at 30°C and 80% relative humidity. The measurements on the toppling device were performed in triplicate for each dough system.

2.3.3 | Dough adhesion characterization by human sensory evaluation

By means of food sensory tests, different product attributes can be detected by human senses such as smelling, tasting or touching. In this study, the touch senses were used to assess the adhesion properties of the dough systems. The question arises whether humans as measuring tools can detect finer differences or more complex properties than instrumental tools. The test procedure was based on the force-time-distance evaluation of the dough detachment procedure presented in the Chen–Hoseney stickiness method.

For the human sensory evaluation, a sensory panel of 10–15 persons was selected. Prior to the sensory evaluation, extensive panel training was performed to train the selected panelists on defining the kinetics of this custom sensory-adhesion characterization procedure. In order to standardize the procedure as much as possible and to be able to exclude further sources of influencing factors, their hands were cleaned before the evaluation, and the index and middle finger temperature was set to 20°C by a water bath. The temperature of the index and middle finger surface was then determined using an infrared thermometer (ETEKCITY Lasergrip 1,080) and documented in the evaluation form. Before the evaluation of each dough sample, the fingers were briefly cleaned again in a water bath, dried and air-dried again for 10 s.

The freshly cut dough samples were handed and quickly rated by the evaluation panel. In order to obtain comparable results, the reference dough (without enzyme addition) was provided prior to each trial as a touch sensory calibration. Approximately 50 g samples were directly cut with a thickness of ∼20 mm from the prepared bulk dough. To disclose the used approach, the surface of the dough was compressed to ∼10 mm thickness for 1 s using the index and middle fingers (Figure 5) and the samples were rated from 1 to 6 (low to high) according to the attributes listed in Table 2. Moreover, three dough variations were served per trial day. The panelist allocation in terms of time and the selection of the dough samples were randomized. Each dough variation was evaluated three times. The experiments were carried out in an open-air condition at room temperature of 19.9 ± 0.4°C and a relative humidity of 38.4 ± 2.0%. Informed consent was obtained from all participants of the sensory evaluation panel.

2.4 | Rheological measurements

The structural changes in the different wheat dough system were validated by rheological characterization. The viscoelastic behavior of the

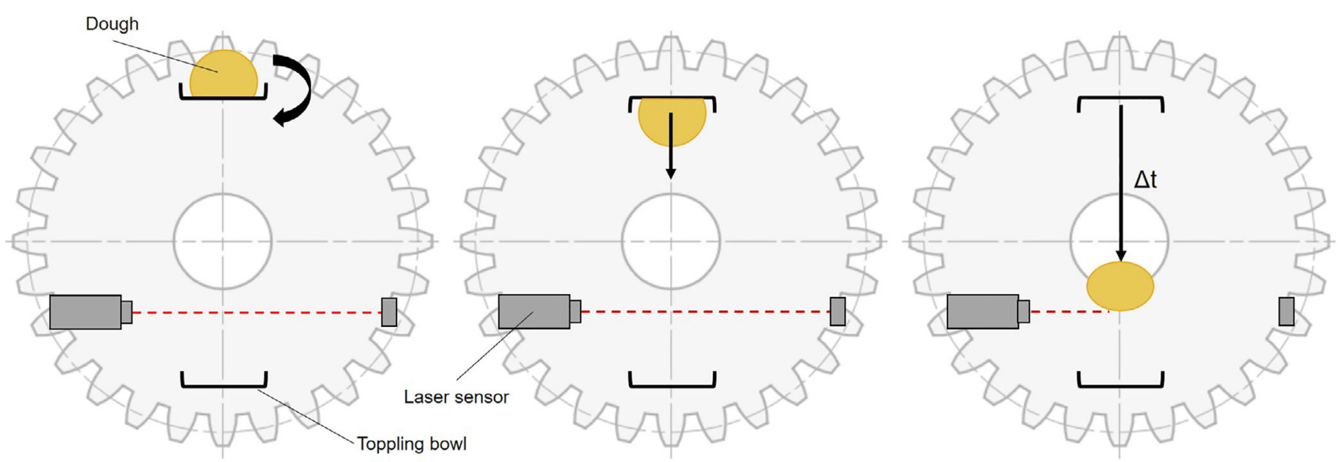

FIGURE 4 Schematic diagram of the side view from the toppling device by toppling a dough piece and determining the detachment time (Δ*t*) by using a laser sensor.

FIGURE 5 Procedure (from left to right) of the human sensory evaluation of the dough adhesion behavior by using fingers.

TABLE 2 Sensory attributes for the dough adhesion human sensory method with definitions, range and example evaluation of the reference dough system without enzyme addition.

Attribute (Unit)	Definition	Minimum score	Maximum score	Reference dough
Adhesive force (–)	Force needed to release the fingers from the surface of the dough	1	6	3
Detachment time (–)	Adhesion time of the dough to completely detach from the fingers	1	6	2
Estimated adhesion distance (mm)	Adhesion distance of the dough to completely detach from the fingers	0	-	3
Overall stickiness (–)	Overall impression of the dough stickiness and adhesion behavior	1	6	2

samples was examined with the AR-G2 rheometer (TA instruments New Castle, New Castle, DE) using a cross-hatched steel plate geometry with a diameter of 40 mm. First, strain sweep measurements were performed to determine the linear-viscoelastic region (LVER) by applying the deformation from 0.01 to 10 at a frequency value of 1 Hz ($T = 20°C$). Afterwards, frequency sweep tests were performed in the determined linear viscoelastic region at a deformation of 0.05%. The applied frequency range was between 0.01 and 100 Hz. Prior to each measurement, a conditioning step was performed for 3 min at 20°C. The measurements were carried out in triplicate. The dynamic rheological parameters such as the complex shear modulus G^*, storage modulus G', and loss modulus G'', were recorded.

2.5 | Statistical analysis

The statistical analysis was performed using OriginPro 2020 (OriginLab Corporation, Northampton, MA). The stated standard deviation accounts for the deviation between the replicate numbers of each method. The homogeneity of variance was reviewed using the Levene test on a significance level of .05. The Kruskal–Wallis test, as a non-parametric test, was used to detect significant differences, which was followed by the pairwise Mann–Whitney test to determine which samples were significantly different. Both tests were done on a significance level of .05. Finally, the correlation between the used methodologies was analyzed using Pearson for all mean values.

3 | RESULTS AND DISCUSSION

3.1 | Rheological characterization by frequency sweep

The addition of enzymes was used to generate a different adhesive behavior of the reference wheat dough system. The conversion from substrate by enzyme addition leads to changes in the dough microstructure. And these changes in dough microstructure can result in changes in the rheological behavior (Jekle & Becker, 2011). To validate the simulation of different adhesion behavior regarding the rheological properties by using enzymes, the different dough systems were characterized by frequency sweep. To compare the different dough systems, the storage modulus G' and the loss modulus G'' measured at 1 Hz are shown in Figure 6.

The focus of the paper is not on the functionalities of the enzymes because they were just used to generate different adhesion behavior. Nevertheless, the results will be briefly discussed in the following. For the fresh dough samples ($t = 0$ min), the storage modulus G' (Figure 6a) and loss modulus G'' (Figure 6b) do not differ between the samples except for bacterial xylanase (BX), which showed lower values for both the viscous and elastic components. This was not expected, since BX solubilizes water-unextractable arabinoxylans (WU-AX) in particular, which can increase the viscosity of dough (Butt, Tahir-Nadeem, Ahmad, & Sultan, 2008). Contrary, fungal xylanase (FX) degrades preferentially water-extractable arabinoxylans (WE-AX), thereby decreasing dough viscosity (Butt et al., 2008), which

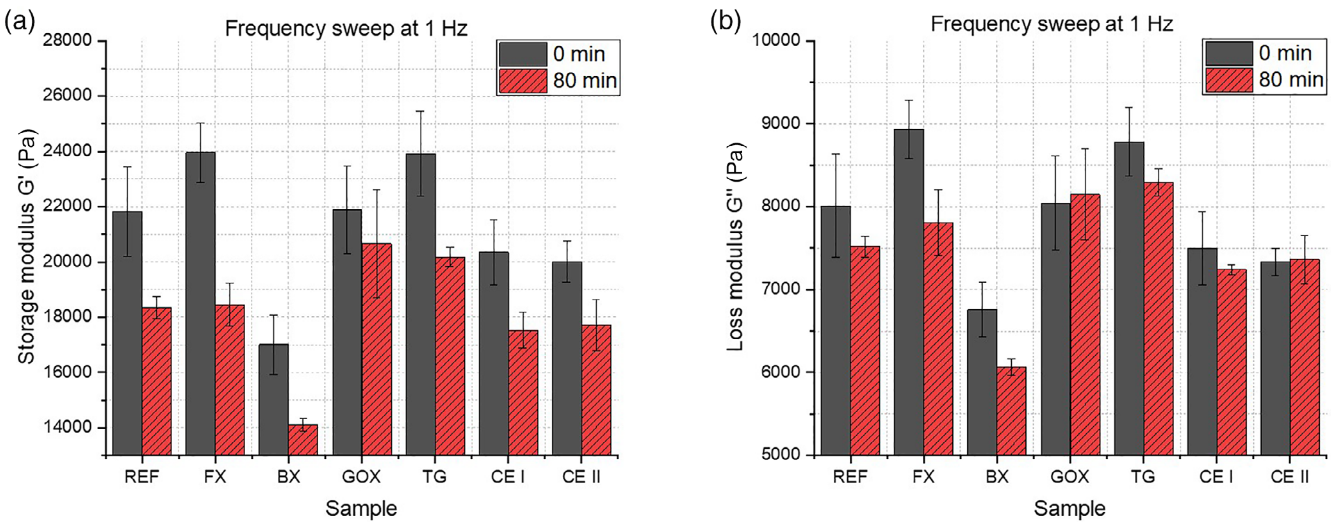

FIGURE 6 Frequency sweep values for varied wheat dough stickiness samples by means of enzyme addition (REF reference without enzyme addition, FX fungal xylanase, BX bacterial xylanase, GOX glucose oxidase, TG transglutaminase, CE I&II cellulolytic enzymes) and two storage times [0 (black) and 80 (red striped) min]: (a) Storage modulus; and (b) Loss modulus. The arithmetic mean is shown with standard deviation ($n = 3$).

cannot be detected in our results. Besides that, it is known that FX improves dough handling by reducing dough elasticity and increasing dough stability (Gioia, Ganancio, & Steel, 2017; Putseys & Schooneveld-Bergmans, 2019). Moreover, glucose oxidase (GOX) showed the lowest changes in rheological properties. Since GOX oxidizes SH groups of gluten protein into S-S bonds by H_2O_2, this strengthens the gluten network and the cross-linking of arabinoxylans in the presence of ferulic acid, leading to an increased bulk viscosity of the dough (Primo-Martín, Wang, Lichtendonk, Plijter, & Hamer, 2005; Putseys & Schooneveld-Bergmans, 2019). Since this could not be seen in our results, one assumption can be that the conditions for the strengthening effect such as the presence of ferulic acid are not given as necessary in our flour quality. Cellulase affects dough consistency comparable to reducing agents, which makes the dough stiffer and firm (Sluimer, 2005). Since there are no big changes in the measured rheological values, this cannot be confirmed for CE I and II. Possible reasons for the differences between the expectations of enzyme treatment on rheological properties and the magnitude of changes include enzyme dosage as well as flour quality (Autio et al., 2005; Primo-Martín et al., 2005). Another possible reason for the differences in the rheological properties by enzyme addition could also be due to the constant kneading time. Autio et al. showed in their work that different enzyme concentrations lead to differences in resistant force and extensibility at the same kneading settings (Autio et al., 2005). Consequently, the different enzyme activity in the kneading process result in different optimum dough development times. Since these were no adjustments for each enzyme treatment, under- but also overkneaded doughs with different rheological properties can presumably result from enzyme addition.

The storage modulus G' values showed the tendency to decrease over storage time. On the one hand, various biochemical processes take place, including the conversion of substrates through yeast fermentation and enzyme activity (Gioia et al., 2017; Struyf et al., 2017). Longer chain molecules are split into shorter molecules, which change the water absorption of the dough and consequently the dough rheology (Gioia et al., 2017). Since only small changes could be seen in the loss moduli G'', these findings suggest that the application of the given enzymes had a rather stronger effect on the elasticity of wheat dough but little impact on the viscosity of the samples over time. The softening and weakening effect during resting by enzyme supplementation and the significant change by xylanase addition were confirmed by the work of Martinez–Anaya and Jiménez (Martínez-Anaya & Jiménez, 1997). The relation between the resultant adhesion behavior and the mentioned rheological response is comprehensively discussed in Section 3.2.

3.2 | Characterization of dough adhesion behavior

3.2.1 | The Chen–Hoseney method

The adhesive properties of the dough samples were determined with the Chen–Hoseney method by evaluating the dough sample detachment force-displacement curve. All results of the Chen–Hoseney method of the different dough systems at different storage times are listed in Table 3. Based on the significant differences, three determined adhesion force levels (high, middle, and low) are shown. For better visibility, the increase in the necessary force in contrast to the reference dough without enzyme addition is highlighted in red, while the decrease is highlighted in green. Basically, different stickiness levels were obtained by adding the enzymes, so that the detectability of the different adhesion behavior of the various dough systems can be compared well within the different methods.

TABLE 3 Separation force curve values from the Chen–Hoseney method for varied dough stickiness samples by means of enzyme addition (BX, CE I&II, FX, GOX, REF, TG) and three storage times (0, 20, and 80 min).

	Fmax/stickiness (N)			Distance/dough strength (mm)			Area/work of adhesion (N.mm)		
	0 min	20 min	80 min	0 min	20 min	80 min	0 min	20 min	80 min
REF	0.59 ± 0.02^{b}	0.59 ± 0.02^{b}	0.59 ± 0.04^{b}	1.47 ± 0.18^{b}	1.52 ± 0.14^{b}	1.51 ± 0.21^{de}	0.42 ± 0.04^{b}	0.42 ± 0.05^{b}	0.42 ± 0.09^{b}
FX	0.57 ± 0.02^{cA}	0.56 ± 0.04^{cAB}	0.59 ± 0.04^{bC}	1.27 ± 0.15^{dA}	1.42 ± 0.18^{cdB}	1.69 ± 0.19^{cC}	0.34 ± 0.05^{deA}	0.36 ± 0.07^{cAB}	0.48 ± 0.09^{dC}
BX	0.64 ± 0.02^{aA}	0.67 ± 0.03^{aB}	0.66 ± 0.03^{aAB}	1.62 ± 0.14^{aA}	1.83 ± 0.14^{aB}	1.85 ± 0.11^{aBC}	0.51 ± 0.03^{aA}	0.60 ± 0.05^{aB}	0.57 ± 0.04^{aC}
GOX	0.57 ± 0.03^{cA}	0.59 ± 0.02^{bB}	0.61 ± 0.03^{bdC}	1.51 ± 0.23^{b}	1.53 ± 0.24^{bc}	1.60 ± 0.18^{bb}	0.38 ± 0.04^{cA}	0.42 ± 0.06^{bB}	0.45 ± 0.05^{bcdBC}
TG	0.59 ± 0.03^{b}	0.60 ± 0.03^{b}	0.61 ± 0.04^{bd}	1.42 ± 0.17^{bc}	1.47 ± 0.15^{bc}	1.51 ± 0.18^{bde}	0.41 ± 0.06^{b}	0.43 ± 0.05^{b}	0.44 ± 0.05^{bc}
CE I	0.56 ± 0.03^{cA}	0.60 ± 0.03^{bB}	0.64 ± 0.03^{aC}	1.37 ± 0.16^{cA}	1.37 ± 0.18^{dAB}	1.50 ± 0.10^{eC}	0.34 ± 0.03^{eA}	0.41 ± 0.07^{bB}	0.46 ± 0.03^{cdC}
CE II	0.57 ± 0.02^{cA}	0.55 ± 0.02^{cB}	0.62 ± 0.03^{dC}	1.35 ± 0.16^{c}	1.38 ± 0.14^{d}	1.40 ± 0.14^{f}	0.36 ± 0.03^{cdA}	0.35 ± 0.02^{cAB}	0.43 ± 0.05^{bC}

Note: The arithmetic mean is shown with standard deviation ($n = 30$). The increase in the necessary force in contrast to the reference dough without enzymes is highlighted in red, while the decrease is highlighted in green. Different small letter suffixes denote significant differences across all enzyme treatments in one column, different capital letters denote significant differences across the three dough storage times in one row (Mann–Whitney test, $\alpha = .05$).
Abbreviations: BX, bacterial xylanase; CE I&II, cellulolytic enzymes; FX, fungal xylanase; GOX, glucose oxidase; REF, reference without enzyme addition; TG, transglutaminase.

The maximum force values determined for detaching the dough systems range from 0.56 to 0.64 N. This agrees with the values reported in the study performed by Konieczny et al., where a basic dough formulation with added enzymes (glucose oxidase and xylanase) showed values from 0.4 to 0.6 N (Konieczny, Stone, Hucl, & Nickerson, 2020). In the mentioned study, bacterial xylanase showed the highest stickiness (Fmax) value (Konieczny et al., 2020). Equally in this study, the addition of bacterial xylanase (BX) confirmed the increase in stickiness with the highest values marked in red in Table 3. In contrast, xylanase from fungal origin (FX) showed less necessary force for detachment, marked in green in Table 3. Fungal xylanase is known to improve dough handling and tolerance in bread-making process by reducing dough elasticity and increasing dough stability and resistance to mechanical stress (Gioia et al., 2017; Goesaert, Gebruers, Courtin, Brijs, & Delcour, 2006; Putseys & Schooneveld-Bergmans, 2019). The enzyme extracted from *Aspergillus spp*. preferentially hydrolyzes WE-AX, promoting gluten protein aggregation by water release (Courtin & Delcour, 2001; Sluimer, 2005). Excessive dosage levels can cause slack and sticky wheat flour doughs due to the high hydrolysis of AX, resulting in an excessive loss in water binding capacity (Gioia et al., 2017; Sluimer, 2005). Since the addition of FX led to a reduction of the measured force peaks, which can be interpreted as stickiness, an excessive dosage can be excluded. The enzyme addition can cause the strengthening of the gluten network or high hydration in the dough system. On the other hand, bacterial xylanase is extracted from *B. subtilis* and hydrolyzes preferentially WU-AX, enhancing dough stability (Gioia et al., 2017). BX addition can improve resistance to mechanical stress during the bread-making process (Goesaert et al., 2006). Similar to fungal xylanase, an excessive dosage of BX leads to sticky doughs (Goesaert et al., 2006), where the excessive degradation of wheat pentosans strongly reduces the water binding capacity and causes dough stickiness (Collar et al., 2000). Since BX showed the highest force peak values at all storage times, an excessive loss of water binding capacity which creates a stickier dough with increased adhesive behavior, can be assumed. Furthermore, BX addition showed only a slight time dependency, which can be seen by the increased values of up to 20 min in Table 3. On the other hand, FX and glucose oxidase (GOX) showed a short-term effect by decreasing values. To illustrate, GOX generates hydrogen peroxide by oxidation, which increases dough strength and stability by improving the gluten network (Goesaert et al., 2006; Konieczny et al., 2020; Putseys & Schooneveld-Bergmans, 2019). This strengthening effect occurs mainly during mixing, where oxygen is present which is needed for the oxidation process (Putseys & Schooneveld-Bergmans, 2019).

Both cellulolytic enzymes initially lower the required release force and increase it after 80 min of storage to a level similar to the dough system with the addition of the BX enzyme. In general, cellulase hydrolyzes cellulose, which results in an increase of lower molecular weight fragments that can bind more water (Gioia et al., 2017). Therefore, cellulose action has numerous benefits such as increased water absorption, increased dough viscosity, decreased stickiness and enhanced machinability (Gioia et al., 2017). The decreased stickiness can just be confirmed for shorter storage times. The addition of TG showed no differences to the reference wheat dough system. An increased dough strength was expected, since TG cross-links proteins by forming covalent isopeptide bonds (Goesaert et al., 2006), but this cannot be seen in the necessary detachment force. In general, some possible mechanisms of enzymes are delineated by the lab scale Chen–Hoseney method. However, these depend on the enzyme activity and dosage, and even though not all expected effects occurred, different adhesion behaviors were obtained, which can be studied further with the other methods.

In earlier studies, the results from the TPA Chen–Hoseney stickiness method for measuring the dough stickiness were only evaluated and interpreted by the parameter force peak as stickiness (Chen & Hoseney, 1994, 1995a, 1995b; Huang & Hoseney, 1999). In some later studies, the interpretation of the measured parameter distance as cohesiveness or stringiness and the determined area as the work of adhesion or adhesive energy were also included (Abebe et al., 2015; Grausgruber et al., 2003; Jekle & Becker, 2011; Yildiz et al., 2012). For the area below the curve, the determined values are in the range of 0.34–0.60 N·mm. The values from the reference dough are in the medium range. Moreover, the dough system with BX addition showed the highest values (marked in red in Table 3) and FX and CE II the lowest (marked in green).

Comparing the force peak results with earlier work, where dough systems from different flour samples, partly fractionation tests and the variation of water content were studied, a higher value range from 0.11 to 2.72 N (partly converted from gram-force) has been obtained (Abebe et al., 2015; Chen & Hoseney, 1994, 1995b; Grausgruber et al., 2003; Huang & Hoseney, 1999; Jekle & Becker, 2011; Wang et al., 2022; Yildiz et al., 2012). This was expected since a much wider range of different doughs was analyzed. The reported distances ranged from 2.01 to 3.08 mm (Grausgruber et al., 2003), 0.01 to 0.11 mm (Jekle & Becker, 2011), 0.62 to 1.22 mm (Yildiz et al., 2012), and from 2.54 to 4.39 mm (Abebe et al., 2015). In this study, distances of 1.27–1.85 mm were determined for the different dough systems with and without the addition of enzymes. The smaller range in the distance values matches well with the smaller range of the measured force peaks. Thus, the variation of the adhesion behavior, which should be only slight but still perceptible, has been achieved.

As already mentioned, the adhesion force is a combination of adhesive (interactions between a material and a surface) and cohesive (interactions within the material) forces (Hoseney & Smewing, 1999; Kinloch, 1987; Noren et al., 2019; Tock et al., 2013; van Velzen et al., 2003). Therefore, the dough properties are also strongly determined by the cohesion of the dough. Low cohesion can cause a weaker dough (more viscous and less elastic), which will adhere to the probe and measured as a sticky dough (Hoseney & Smewing, 1999). Furthermore, Hoseney and Smewing stated to study dough stickiness, the separation of the adhesive and cohesive properties appears imperative (Hoseney & Smewing, 1999). Therefore, the procedure of the Chen–Hoseney method was designed to measure the adhesive force by a clean separation at the probe-dough interface independently of the rheological properties of the dough (Chen & Hoseney, 1994; Grausgruber et al., 2003; Huang & Hoseney, 1999). Armero and Collar compared TPA characterized textural properties (hardness, cohesiveness, chewiness, gumminess and adhesiveness) with stickiness parameters (area, distance and peak) obtained from Chen–Hoseney method and found no significant correlation between stickiness parameters and cohesiveness (Armero & Collar, 1997). This could be another confirmation of the independence of cohesiveness from the Chen–Hoseney method. The method is commonly applied to investigate factors that influence dough stickiness, such as differences in protein composition or mixing time (Laukemper et al., 2019). However, when using the method to measure the adhesive properties, it was shown that many parameters (like surface tension, added enzymes, amount of water added to the dough, etc.) affect the results, which can also affect the dough rheological behavior (Hoseney & Smewing, 1999). If the cohesive forces were completely excluded in the Chen–Hoseney method, it would be expected that the determined distances of the curves would not differ significantly. The results shown in Table 3 cannot confirm the independency by varying distance values between enzyme variation and time. The measured distance describes the traveled distance of the probe until the dough strain breaks, indicating the cohesiveness or dough strength of the sample. The FX and BX samples showed increased dough strength by increased distance values over time. Thus, since xylanases solubilize WU-AXs and degrade WE-AXs, which decreases the interference with the gluten network, a more stable dough was expected (Goesaert et al., 2006; Pescador-Piedra et al., 2009; Putseys & Schooneveld-Bergmans, 2019). Higher values in adhesion distance suggest a higher elongation of the dough in the detachment procedure which can be due to an elastic gluten network but also due to a softer dough. Therefore, not just adhesive forces at the interface between dough and contact material, but cohesive forces are also decisive for the detachment behavior. As differences in the detachment distance can be measured with the Chen–Hoseney method, a strict exclusion of cohesive dough properties cannot be confirmed. On the contrary, the dough system with cellulolytic enzyme II showed no changes in adhesion distance, where the force changed significantly over time by constant dough strength. Thus, the change in adhesion can maybe be induced by different wetting behavior of the dough which changes over time. To evaluate this hypothesis, a method to study dough wetting behavior regarding adhesion phenomena should be developed.

The area under the curve is determined by the maximum force and distance. Since the same significant differences between samples for work of adhesion and stickiness exist, it can be assumed that Fmax is dominating the curve result. Nevertheless, the attributed work of adhesion results from the interplay of adhesive and cohesive forces. Thus, one could assume that the work of adhesion reflects the entire course of the curve, which corresponds better to real adhesion phenomena like the ones seen in production processes.

3.2.2 | Toppling device

The adhesive properties of the dough samples are determined with the pilot scale toppling device by evaluating the dough sample detachment time. All results of the toppling device of the different dough systems are listed in Table 4. For the fresh dough samples ($t = 0$ min),

TABLE 4 Detachment time results using a toppling device for varied dough stickiness samples by means of enzyme addition (BX, CE I&II, FX, GOX, REF, TG) and two storage times (0 and 80 min).

	Detachment time (s)	
	0 min	80 min
REF	0.41 ± 0.01[cdbA]	13.85 ± 9.87[bdeB]
FX	0.58 ± 0.23[aA]	17.68 ± 39.17[bceB]
BX	0.44 ± 0.01[bA]	> 4,800[aB]
GOX	0.40 ± 0.01[dA]	0.53 ± 0.04[gB]
TG	0.42 ± 0.01[cA]	8.88 ± 7.11[eB]
CE I	0.40 ± 0.00[dA]	175.00 ± 267.90[bB]
CE II	0.41 ± 0.01[dA]	3.11 ± 1.64[fB]

Note: The arithmetic mean is shown with standard deviation ($n = 9$). The increase in detachment time in contrast to the reference dough without enzymes is highlighted in red, while the decrease is highlighted in green. Different small letters suffices denote significant differences across all enzyme treatments in one column, different capital letters denote significant differences across the two storage times in one row (Mann–Whitney test, $\alpha = .05$).
Abbreviations: BX, bacterial xylanase; CE I&II, cellulolytic enzymes; FX, fungal xylanase; GOX, glucose oxidase; REF, reference without enzyme addition; TG, transglutaminase.

the detachment times are observed to be between 0.40 and 0.58 s. Thus, the values are all low and the doughs detach well and quickly after the rotation movement. FX showed the highest detachment time, marked red in Table 4. Compared to the Chen–Hoseney method results, where FX as a fresh dough sample showed the lowest adhesive properties, this was not expected. Furthermore, in the toppling device results for the fresh dough samples, all other samples except FX showed very low standard deviation values. One assumption for the different behavior of the dough with FX addition can be changes in surface energy—and therefore adhesion – may be induced by the wetting behavior of the dough (Laukemper, Becker, & Jekle, 2021). The lowest detachment time has been observed for the fresh dough systems with GOX and CE I, which is also consistent with the values from the Chen–Hoseney method. However, CE II with the lowest values in force, distance and area would also be expected to have a low detachment time. Nevertheless, there are no significant differences to the reference dough system.

After 80 min of storage time, the detachment time for all dough systems increased significantly. Also, Yildiz et al. showed increased dough stickiness by increasing resting time by using the texture analyzer Chen–Hoseney stickiness method (Yildiz et al., 2012). Furthermore, in the work of Laukemper et al., the duration of adhesion increased significantly with time for different contact surfaces (Laukemper et al., 2019). Due to the change in dough properties over time resulting in a more fluid dough, it can flow into cavities of the contact material, which increases the contact area and thus further strengthens the interactions between the two contact surfaces (Laukemper et al., 2019; Laukemper et al., 2022). Thus, softer doughs should lead to higher detachment times, which is confirmed by the rheological characterization of BX (Section 3.1), which showed a high softening effect after 80 min and the highest detachment time. On the contrary, hardly any increase in release time was observed for GOX. It has been shown in the literature that the addition of glucose oxidase to dough systems leads to drying effects with the exposure to oxygen (Goesaert et al., 2006; Putseys & Schooneveld-Bergmans, 2019). Because of the use of proofing cloths on the perforated trays of the toppling bowls, continuous oxygen supply can be assumed. Therefore, the drying and the continuous oxygen supply, which may cause an enzymatic reaction on the dough surface, could be a possible reason for the short detachment times, even after 80 min of storage time.

In addition, the values show a wide range of detachment times, from 0.53 to 4,800 s and, in some cases, very large standard deviations. In the case of the toppling device, the dough detachment is a combination of shear-driven and gravitational force where the dough drops down after rotation. Therefore, it can be concluded that the shear-driven detachment by the toppling device of the doughs is very variable with longer storage times and that there is no explicit adhesion behavior for each dough system.

Maybe a different and irregularly inflow of the dough into the proofing cloth can strengthen the high variety in the determined values. In industrial application, the adhesion behavior is determined by the adhesive properties but also from the rheological behavior of the dough, which is further influenced by various extrinsic factors. For a high comparability to the production process, dough samples have been stored in a proofing cell, but fluctuations in the regulation of the relative humidity and temperature cannot be excluded, which can further lead to an irregularly inflow. Nevertheless, this represent given production conditions. Moreover, since adhesion is a surface phenomenon, the contact material should be mentioned as a main influencing factor for dough adhesion (Laukemper et al., 2019).

3.2.3 | Human sensory test

The adhesive properties of the dough samples were determined by using the human sense of touch. All human sensory test results of the different dough systems are listed in Table 5. As shown in the previous sections, increased values are highlighted in red, while decreased values are highlighted in green. Hardly any significant differences have been perceived. Nevertheless, it is noticeable that after 80 min, BX showed the highest values in all four adhesion evaluation criteria of the method. That detection of a different adhesive behavior could be due to the softening effect of the dough system, which can be confirmed by the dough's rheological response (Section 3.1). Especially after 80 min, the low values of storage modulus G' and loss modulus G'' can be interpreted as really weak and soft dough. This is in agreement with the results from the study from Wang et al., a comparison of dough profiling, an adaption of the two compression texture profile analysis, with a sensory dough stickiness scoring (Wang et al., 1996). High correlations between parameters measured from profiling curve with sensory values confirmed the coherence between measured

TABLE 5 Dough adhesion behavior evaluation by human sensory for varied dough stickiness samples by means of enzyme addition (BX, CE I&II, FX, GOX, REF, TG) and three storage times (0, 20, and 80 min).

	Force (1–6)			Time (1–6)			Distance (mm)			Stickiness (1–6)		
	0 min	20 min	80 min	0 min	20 min	80 min	0 min	20 min	80 min	0 min	20 min	80 min
REF	3.00 ± 0.71	2.92 ± 1.00	2.88 ± 0.72^{bc}	2.38 ± 0.65	2.42 ± 0.90	2.25 ± 1.13^{cd}	4.16 ± 3.34	3.96 ± 2.28	5.53 ± 5.29^{bc}	2.31 ± 0.85	2.25 ± 0.62^{ab}	2.38 ± 0.81^{cd}
FX	2.42 ± 1.00^{A}	3.31 ± 1.03	3.39 ± 0.92^{abB}	2.17 ± 0.72^{A}	2.54 ± 1.13	3.06 ± 0.94^{bB}	2.50 ± 1.48^{A}	4.96 ± 2.79^{B}	7.25 ± 5.93^{abcB}	2.08 ± 0.90^{A}	2.50 ± 0.90^{a}	3.17 ± 0.92^{abB}
BX	3.09 ± 1.04	3.33 ± 1.07	3.86 ± 1.23^{a}	2.95 ± 0.72^{A}	3.25 ± 1.48	4.13 ± 0.83^{aB}	4.09 ± 2.81^{A}	11.50 ± 10.29^{B}	12.77 ± 9.11^{aB}	2.91 ± 0.83	3.08 ± 1.24^{a}	3.87 ± 0.99^{a}
GOX	2.27 ± 0.79	2.73 ± 1.19	3.00 ± 1.00^{abc}	1.82 ± 1.08	2.36 ± 1.12	2.27 ± 1.19^{cd}	2.83 ± 2.81	4.91 ± 4.12	5.53 ± 5.32^{bc}	1.91 ± 0.94	2.18 ± 0.87^{ab}	2.18 ± 0.98^{cd}
TG	2.70 ± 0.95	2.82 ± 0.98	2.95 ± 0.60^{bc}	2.20 ± 0.79	2.00 ± 1.18	2.25 ± 0.72^{d}	2.80 ± 1.55^{A}	3.77 ± 3.70^{AB}	5.50 ± 4.26^{bcC}	2.20 ± 1.03	1.73 ± 0.90^{b}	2.08 ± 0.65^{d}
CE I	3.00 ± 0.87	2.82 ± 0.98	3.18 ± 0.95^{abc}	2.44 ± 0.73	2.64 ± 1.21	2.94 ± 1.03^{bc}	3.94 ± 2.65	5.95 ± 5.21	8.09 ± 6.58^{ab}	2.33 ± 0.71	2.64 ± 1.29^{ab}	2.82 ± 1.07^{cb}
CE II	2.80 ± 1.03	3.36 ± 1.12	2.63 ± 0.90^{c}	2.20 ± 0.92	2.91 ± 1.30	2.16 ± 1.01^{d}	2.40 ± 2.01	5.05 ± 4.74	4.67 ± 4.05^{c}	2.10 ± 0.88	2.91 ± 1.30^{a}	2.05 ± 0.97^{d}

Note: The samples were rated from 1 to 6 (low to high). The arithmetic mean is shown with standard deviation ($n \geq 33$). The increase in contrast to the reference dough without enzymes is highlighted in red, while the decrease is highlighted in green. Different small letter suffixes denote significant differences across all enzyme treatments in one column, different capital letters denote significant differences across the three storage times in one row (Mann–Whitney test, $\alpha = .05$).

Abbreviations: BX, bacterial xylanase; CE I&II, cellulolytic enzymes; FX, fungal xylanase; GOX, glucose oxidase; REF, reference without enzyme addition; TG, transglutaminase.

viscoelastic properties with varying degree of stickiness (Wang et al., 1996).

The human sensory evaluation showed detection limits of the differences in adhesion behavior. The targeted small differences between the samples, which could be confirmed in the Chen–Hoseney method by small value ranges in comparison to other studies (Section 3.2.1), could not be detected by the human senses. The baker's classic dough stickiness test is to touch the dough by hand and if it sticks to the hand, the dough is considered sticky (Hoseney & Smewing, 1999). This is a very simplified version of the assessment, especially, since the adhesive behavior depends on both the adhesive and cohesive properties of the dough (Hoseney & Smewing, 1999). Nevertheless, tendencies such as increases over time are evident, but these are not significant. Overall, humans seem to be too inaccurate as a measuring instrument.

3.3 | Correlation between the methods

In this study, the dough adhesion behavior was analyzed on an instrumental, pilot-scale processing and human sensory levels. Different parameters were obtained in each method. In addition to comparing the methods, the respective interpretation of the parameters within a method was considered. Therefore, the three stickiness quantities of the Chen–Hoseney (CH) method, namely, force, distance and area are tested for their correlation (shown in Figure 7). Without storage time ($t = 0$ min), the samples showed high correlation values between the three attributes (Figure 7a) in the Chen–Hoseney stickiness method. Additionally, a high correlation is observed at a storage time of 20 min (Figure 7b). Just after 80 min, only the attributes distance and work of adhesion showed a significantly linear correlation (Figure 7c), which could be due to the increasing influence of the dough elongation on the adhesion or detachment behavior. Thus, the exclusion of the cohesive properties in the CH measurement method cannot be excluded after a longer storage period, at least for these dough systems. In addition, the question arises at which point a dough system is too soft or the elongation is too high to influence the measurement.

In addition, the comparison of the laboratory scale with the process-oriented toppling device is shown in Figure 7. For the fresh dough samples (Figure 7a), no correlation could be found. After 80 min, the toppling device detachment time correlated positively with the CH distance ($R = 0.78$) and area ($R = 0.93$), which suggests that the dough inflow and flow properties are the dominating effects for the adhesion behavior in the pilot scale.

The comparison between the laboratory adhesion values with the dough handling properties is presented by the correlation coefficient in Figure 8. The human sensory (HS) test was based on a force-time-distance recording as in TPA Chen–Hoseney method. Without storage time ($t = 0$ min), as shown in Figure 8 a, the stickiness measured by the human sensory test correlate with the force (stickiness, $R = 0.87$) and area (work of adhesion, $R = 0.81$) measured by the CH method. Furthermore, the detachment time determined in HS correlates with the CH measured force ($R = 0.79$). The CH measured distance does

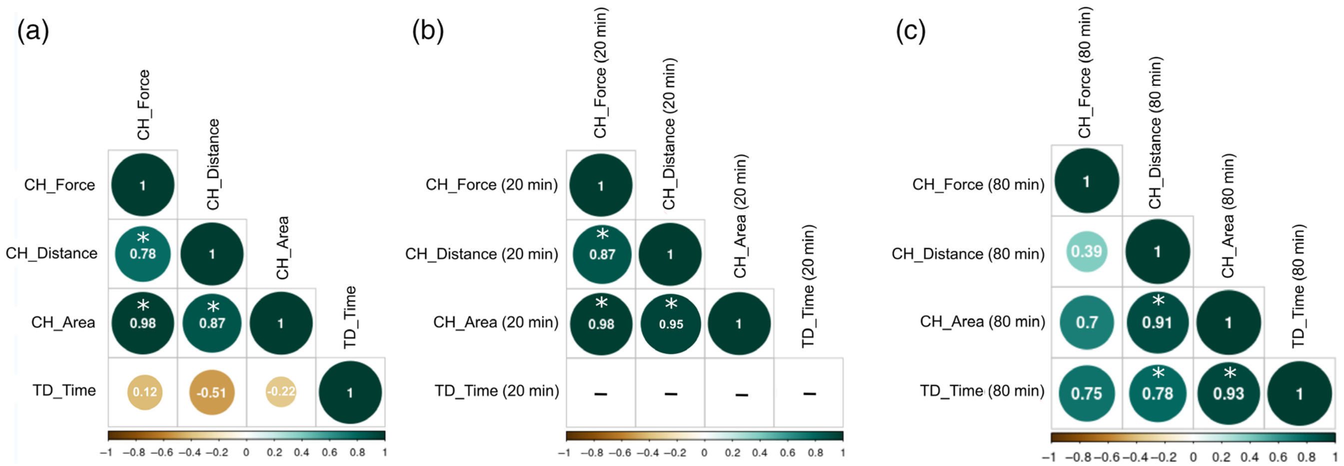

FIGURE 7 Pearson correlation coefficients between the Chen–Hoseney (CH) method attributes force, distance and area; and the toppling device (TD) time determined at: (a) 0 min; (b) 20 min; (c) 80 min. Significant linear correlation is marked with *.

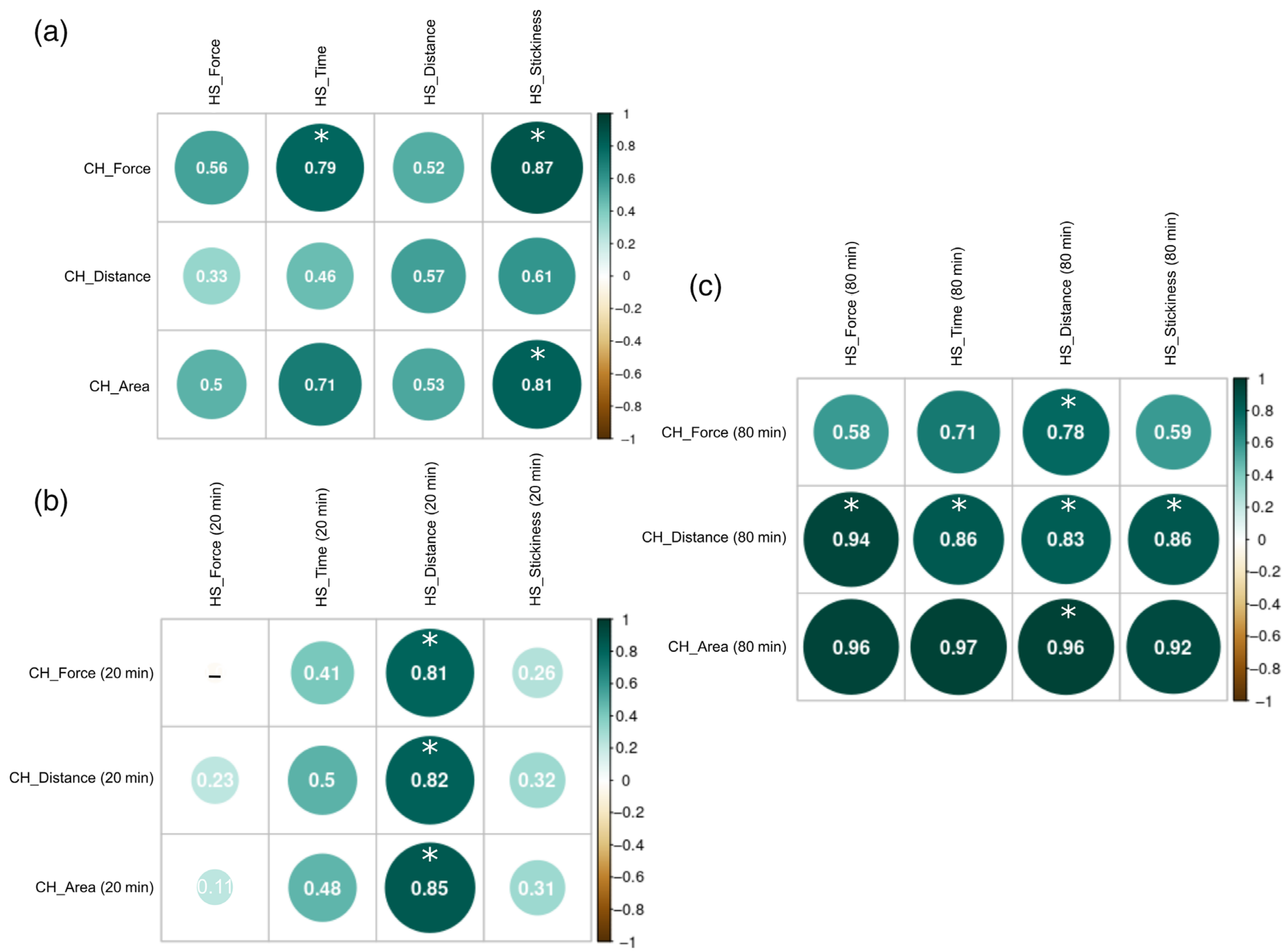

FIGURE 8 Pearson correlation coefficients between the Chen–Hoseney (CH) method attributes force, distance and area; and human sensory (HS) attributes force, time, distance and stickiness at: (a) 0 min; (b) 20 min; (c) 80 min. Significant linear correlation is marked with *.

not correlate with the human sensory attributes, which suggests that the flow properties/dough strength were less relevant for the handling adhesion phenomena for the fresh dough samples. After a 20 min storage time (Figure 8b) time, the human sensory determined distance is positively correlated with all three CH attributes. After an 80-min storage time (Figure 8c), both the distance recorded with CH

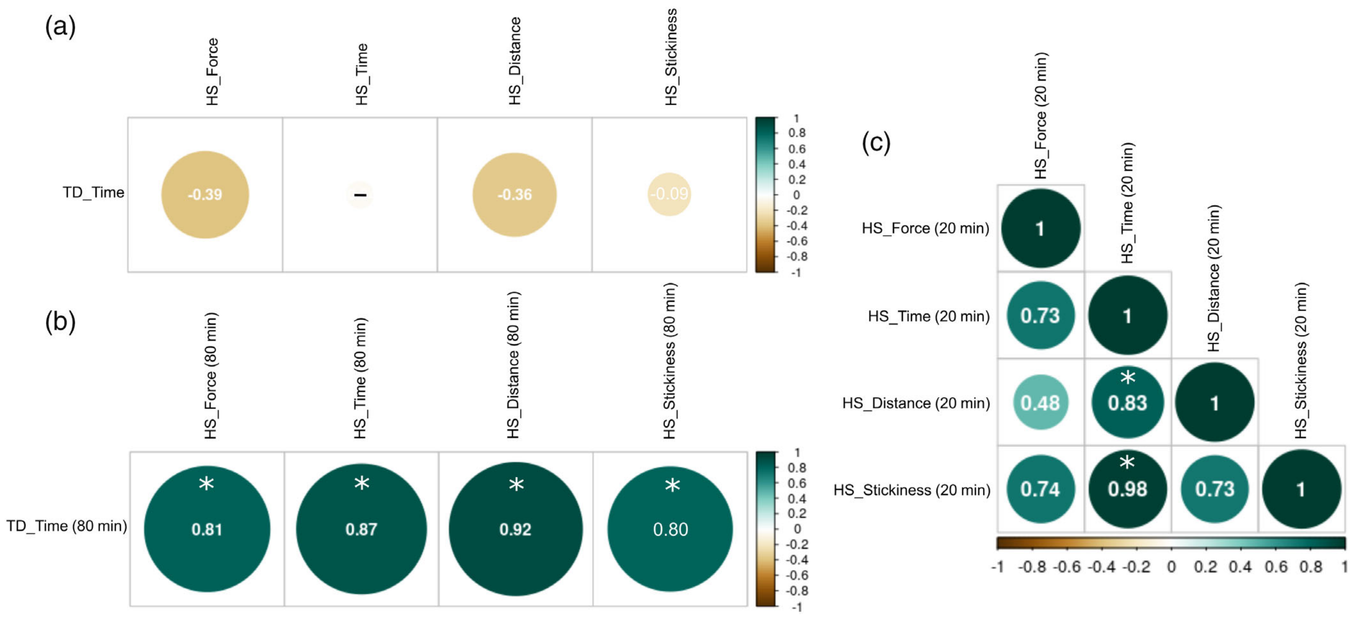

FIGURE 9 Pearson correlation coefficients between toppling device (TD) detachment time and human sensory (HS) attributes force, time, distance and stickiness determined at: (a) 0 min; (b) 80 min; and (c) Pearson correlation coefficients for human sensory attributes at 20 min. Significant linear correlation is marked with *.

and the distance assessed with HS correlate with all other parameters. One explaination may be the softening behavior of the dough samples over time. The changes in dough cohesion can lead to significant discrepancies in the adhesion behavior.

Regarding the adhesion effects on the process and human sensory evaluation, there were no correlations observed for the fresh dough samples, shown by the low correlation coefficient in Figure 9a. In contrast, after 80 min of storage time, high correlation coefficients between toppling device and all human sensory parameters have been seen (Figure 9b. Force $R = 0.81$, Time $R = 0.87$, Distance $R = 0.92$, Stickiness $R = 0.80$). As already mentioned, the doughs become softer over time. The flow of the doughs into the proofing cloth structure, which is decisive for the detachment behavior and thus the detachment time, coincides very well with the characterized adhesion properties obtained by the human sensory test. By contrast, the values obtained from the Chen–Hoseney stickiness method showed a significant correlation to the detachment times from the pilot scale toppling device only after 80 min and for the attributes distance ($R = 0.78$) and area ($R = 0.93$). Thus, the human sensory test is much better suited for predicting machinability than the analytical determination using the Chen–Hoseney method.

4 | CONCLUSION

Undesired dough adhesion which leads to remaining dough residues and results in process disruption, among other things, is still a challenge during the production of baked goods. Therefore, various methods for determining the adhesive material properties to predict dough machinability were investigated and compared. In this new approach, the dough adhesion phenomenon was characterized and compared on the process, instrumentally and human sensory level. Therefore, the Chen–Hoseney (CH) stickiness method, a pilot scale toppling device and a new developed human sensory analysis were used. The aim was to investigate to what extent the different methods capture the adhesion behavior of each dough system. There were no correlations between the toppling device and the two other methods for fresh dough samples ($t = 0$ min). Consequently, this results in the hypothesis that the adhesive properties for fresh dough samples are driven by different mechanisms or influencing variables, which cannot be determined in all three methods. On the one hand, the contact material to the dough (Plexiglas, finger and proofing cloth), but also the detachment mechanism differs. In the case of the toppling device, the dough detachment is a combination of shear-driven and gravitational force where the dough drops down after rotation. For the CH method and the human sensory test, the material pulls off from the dough surface after contact. One question can be whether these differences are primarily determined on the material side by dough stickiness or by interactions of the dough with the contact material. Even process adhesion behavior cannot be predicted by other methods in the small-time scale, for the higher time scale, commonly given in process, human sensory seems suitable for predicting machinability. Thus, high correlation coefficients between detachment time and human sensory evaluation have been found. After 80 min of storage time, there was no correlation between the determined force in the Chen–Hoseney method and the toppling device detachment time. For the dough systems of this study, the stickiness values from the Chen–Hoseney stickiness method are not suitable for predicting machinability, as it has been published in some earlier studies. The work of adhesion best reflects the adhesive effects in the process because both the adhesive and cohesive forces were determined and confirmed by the correlations between the CH attributes distance and work of adhesion with the process detachment time after 80 min. Furthermore, the correlation between CH distance and work of adhesion with sensory parameters can be explained with the softening behavior of the dough over time, which can be detected by dough handling and laboratory after 80 min. The changes in cohesion led to a different elongation of the dough, and were recorded both by human sensory and TPA measurement. For the first time, a profound analysis of dough adhesion was carried out at different levels (laboratory, human sensory and process). In this first intensive examination of dough adhesion, it was shown that fine differences cannot be detected with human sensory analysis as it is possible with the Chen–Hoseney method. However, the correlation between human sensory analysis and the toppling device confirmed the most suitable predictive power of machinability by humans. Thus, variables influencing adhesion behavior can be better studied with the Chen–Hoseney method, but cannot be contextualized with machinability.

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