Intermediate wheatgrass (Thinopyrum intermedium) and grain sorghum as novel, sustainable ingredients in extruded precooked pasta and expanded snacks – Life cycle assessment, physicochemical properties and product quality

by

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Abstract

This thesis explores the potential of Intermediate Wheatgrass (IWG) and sorghum as sustainable alternatives to conventional grains in the production of extruded precooked pasta and expanded snacks, while evaluating their environmental impacts through a life cycle assessment (LCA). IWG, with its deep root system, enhances soil health and carbon sequestration, addressing challenges like soil erosion and high water usage. Sorghum offers sustainability benefits in water-scarce regions, with comparable or improved product performance.

Six pasta formulations incorporating wheat, IWG, and sorghum were assessed for functionality and cooking performance. Pasta made solely from wheat exhibited the highest cooking loss at 5.6%, while IWG pasta had 3.9%, and sorghum pasta achieved the lowest cooking loss at 1.9%. RVA analysis revealed wheat's higher peak viscosity (1064 cP) compared to sorghum (979 cP) and IWG (443 cP), suggesting differences in starch binding and degradation that influenced cooking outcomes.

The study also examined the properties of IWG and sorghum in expanded snack production. IWG snacks exhibited the highest density at 0.28 g/cm³ compared to corn (0.12 g/cm³) and sorghum (0.14 g/cm³), indicating potential differences in textural outcomes. Expansion ratios revealed that sorghum achieved 10.22, significantly higher than IWG's 5.80, while corn reached 10.58. In terms of hardness, IWG snacks measured 22.95 kg, notably harder than corn (15.54 kg) and sorghum (12.96 kg). These findings highlight opportunities to balance texture and sustainability in snack formulations.

LCA results showed sorghum with the lowest Global Warming Potential (GWP) at 0.09 kg CO2 eq/kg for snacks and 0.11 kg CO2 eq/kg for pasta. IWG exhibited higher direct GWP (0.31 kg CO2 eq/kg for pasta) but transformed into a carbon sink when considering carbon

sequestration and straw allocation, reducing net GWP to -0.7 kg CO2 eq/kg. These findings underscore IWG's potential to offset emissions through soil organic carbon sequestration (42 tons C/hectare), while sorghum offers low emissions with favorable product properties.

This research highlights the environmental and functional advantages of integrating IWG and sorghum into food systems, contributing to more sustainable agricultural practices and product development.

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Chapter 1 - Introduction

1.1 Background

Conventional grain production, particularly wheat, plays a critical role in global food systems but is fraught with environmental challenges. These challenges include soil erosion, high water usage, and reliance on synthetic inputs, which can degrade soil health and threaten biodiversity (DeHaan, 2018; Chapman et al., 2022). As reliance on staple crops like wheat, rice, and maize continues to rise, accounting for approximately 35% of global caloric intake (Ross-Ibarra, 2007), the need for sustainable alternatives becomes increasingly urgent. Innovative grains such as *Thinopyrum intermedium,* also known as Intermediate Wheatgrass (IWG), and sorghum have emerged as viable options to mitigate some of these issues, offering potential benefits for soil health, carbon sequestration, and resilience against climate change (Soto-Gómez & Pérez-Rodríguez, 2022; Ruiz-Giralt, 2023).

IWG, a perennial grain, boasts a deep root system that helps reduce soil disturbance and erosion while enhancing carbon sequestration (DeHaan, 2018). Similarly, sorghum is recognized for its drought resistance, making it an attractive alternative, particularly in regions facing water scarcity (Ruiz-Giralt, 2023). Together, these grains provide promising pathways for sustainable agricultural practices, yet their applications in food products require further investigation.

1.2 Overall Objectives

The growing concern regarding the environmental impacts of conventional grain production necessitates the exploration of sustainable alternatives. This research aims to investigate the potential of IWG and sorghum as innovative ingredients in extruded food products, specifically precooked pasta and expanded snacks. By focusing on these alternative

grains, the study seeks to enhance product quality while reducing the environmental footprint associated with traditional grain production.

Through this research, cooking characteristics, and textural properties of pasta and snack products made from IWG and sorghum will be evaluated. It is anticipated that incorporating these grains will lead to products with improved nutritional profiles and lower environmental impacts, thereby meeting consumer demands for healthier and more sustainable food options.

The findings from this study are expected to help with advancements in product development, enabling food manufacturers to better understand the functional properties of IWG and sorghum. This knowledge can help optimize formulations, allowing for quick adaptations to ingredient sourcing challenges and potential cost reductions. As global populations continue to rise, the need for diverse, sustainable grain sources becomes increasingly crucial. This research aims to contribute to the ongoing efforts to transition towards more sustainable food systems that prioritize environmental benefits for all.

1.3 Chapter 2 Objectives

In Chapter 2, the focus is on evaluating the functionality of IWG and sorghum in the context of extruded precooked pasta. The hypothesis posits that different flour combinations will significantly impact the cooking characteristics, texture, and overall quality of the pasta products. Key objectives include assessing cooking loss percentages to determine product yield and quality, and performing texture analysis to gauge the sensory attributes influenced by these alternative grains.

Additionally, this chapter aims to establish correlations between the specific flour formulations and the resultant cooking properties, including cooking time and texture profile. By investigating these relationships, the research seeks to identify optimal formulations that can

meet the desired quality standards for pasta, thereby enhancing the potential for IWG and sorghum in pasta applications.

1.4 Chapter 3 Objectives

Chapter 3 will shift the focus to the production of expanded snacks, utilizing corn, IWG, and sorghum as primary ingredients. The hypothesis is that the inclusion of IWG and sorghum will influence key quality attributes such as expansion ratio, bulk density, and hardness, which are critical for consumer acceptance. The objectives for this chapter include characterizing the textural properties of the snacks and identifying the optimal processing parameters necessary for maximizing product expansion.

This research investigated how variations in ingredient ratios affect the final snack product's physical attributes. By establishing a comprehensive understanding of how these grains contribute to snack formulations, this chapter provides insights that will inform product development and improve the overall quality of expanded snacks made from alternative grains.

1.5 Chapter 4 Objectives

Chapter 4 applies a life cycle assessment (LCA) to evaluate the environmental impacts of the developed pasta and snack products. The objectives include assessing key impact categories such as Global Warming Potential (GWP), freshwater ecotoxicity, and eutrophication to offer a comprehensive analysis of the sustainability of each product. Additionally, this chapter aims to compare the environmental impacts of using IWG and sorghum against traditional wheat and corn, highlighting the potential benefits of incorporating these innovative grains in food production.

By integrating LCA into this research, the chapter seeks to provide valuable insights into the trade-offs and benefits associated with IWG and sorghum, ultimately guiding food

manufacturers towards more sustainable practices. The findings will contribute to a better understanding of how alternative grains can play a vital role in developing sustainable food systems that meet both consumer needs and environmental goals.

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Chapter 2 - Intermediate Wheatgrass (*Thinopyrum intermedium*) and Sorghum as Sustainable Ingredients in Extruded Precooked Pasta

Abstract

This study focuses on the use of Intermediate Wheatgrass (IWG), wheat, and sorghum as primary ingredients in extruded precooked pasta, aiming to address environmental challenges associated with traditional production methods. IWG, with its deep root system, presents opportunities for reducing soil erosion and enhancing carbon sequestration, while sorghum offers a sustainable option, particularly for regions facing water scarcity. The technical feasibility of these grains was assessed to determine their potential for mitigating the ecological footprint of pasta manufacturing. Six distinct pasta formulations were extruded using a pilot-scale twin-screw extruder, incorporating wheat flour, IWG flour, sorghum flour, and various 50/50 flour combinations. Detailed analyses were conducted on both the raw materials and extruded samples to evaluate ingredient functionality, degree of degradation, extent of gelatinization, and texture characteristics. Cooking loss percentages were measured to assess the performance of each formulation during the precooking process. Results indicated that pasta made with only wheat flour had the highest cooking loss percentage at 5.6%, compared to 3.9% for IWG flour and 1.9% for sorghum flour. The wheat/IWG combination also exhibited a high cooking loss of 5.6%, likely due to the lower binding capacity of wheat, as evidenced by its higher peak viscosity of 1064 cP, compared to sorghum (979 cP) and IWG (443 cP). This research highlights the potential for incorporating IWG, wheat, and sorghum in pasta formulations to achieve both quality standards and environmental benefits. The findings suggest a promising path toward

more sustainable pasta production practices. Future research will explore life cycle assessments and consumer acceptance to further validate these innovative grain combinations in sustainable food production.

2.1 Introduction

Challenges in Conventional Wheat Production

To understand the potential of innovative grains like IWG and sorghum, it's crucial to address the challenges in conventional wheat production. Wheat's dominance in staple foods has led to significant environmental and sustainability issues. The annual replanting cycle of wheat results in frequent soil disturbance, which exacerbates soil erosion and reduces its carbon sequestration capacity.

Human nutrition relies heavily on three main grains—rice, wheat, and maize—accounting for about 35% of caloric intake (Ross-Ibarra, 2007). Over the past six decades, production of these grains has expanded due to technological advancements and intensified agricultural practices. However, this expansion comes with serious environmental concerns. Intensive monoculture systems, reliant on heavy inputs such as fertilizers and pesticides, threaten biodiversity, water resources, and ecosystems (Soto-Gómez & Pérez-Rodríguez, 2022). Issues such as water contamination, loss of biodiversity, and contributions to climate change are prevalent, alongside soil erosion caused by both wind and water.

Monoculture practices, common in wheat farming, further degrade soil health. Continuous cultivation of a single crop depletes nutrients, increases pest and disease susceptibility, and erodes biodiversity. The reliance on synthetic inputs exacerbates environmental pollution and challenges the sustainability of these practices (DeHaan, 2018; Chapman et al., 2022). Wheat cultivation's high water demands strain water resources, especially

in water-scarce regions. Mechanization in wheat farming adds to fossil fuel consumption and greenhouse gas emissions, increasing the carbon footprint associated with wheat production (DeHaan, 2018; Chapman et al., 2022).

Addressing the Research Gap: IWG and Sorghum as Alternative Grain

This research not only identifies these challenges but also explores potential solutions, specifically focusing on IWG. While it shows potential for improving soil health and carbon sequestration, there is a lack of comprehensive studies on utilizing IWG in palatable and sustainable food products. This research aims to fill this gap by investigating IWG in extruded precooked pasta—a novel approach that combines sustainability with consumer convenience. This study not only addresses the environmental challenges of conventional wheat production but also explores the potential of IWG to create a more diverse and resilient agricultural landscape.

Innovative Aspects of IWG and Sorghum

The introduction of IWG and sorghum as alternative grains offers promising solutions. IWG's perennial nature mitigates issues of annual replanting, soil disturbance, and erosion. Its deep root system enhances soil structure and resilience while contributing to carbon sequestration. A study by Tang et al. (2023) highlights that perennial grain cropping increases Soil Organic Carbon (SOC) and microbial activity, improving soil physical and hydraulic properties, which can enhance water retention and reduce nutrient leaching.

IWG's higher transpiring biomass and deep-water access result in elevated evapotranspiration rates compared to annual crops. This efficient water use, managed through stomatal resistance, enables IWG to adapt to varying environmental conditions, including periods of low rainfall (de Oliveira et al., 2018; de Oliveira et al., 2020).

Sorghum, with its drought resistance, presents an environmentally friendly option, especially in water-scarce regions (Ruiz-Giralt, 2023). The integration of IWG and sorghum into agriculture helps mitigate the environmental impact of monoculture and fosters resilient agricultural systems capable of adapting to climate change.

Innovative Aspects of Precooked Pasta

Turning to the end product, this research explores precooked pasta's innovative aspects. Unlike traditional pasta, made using low-shear extrusion and wheat semolina, precooked pasta undergoes extrusion cooking, making it fully cooked and reducing home preparation time. This approach enhances consumer convenience by delivering a product that cooks faster than traditional pasta. Studies by Wójtowicz et al. (2020) and Vignola et al. (2018) reveal that new precooked pasta products have unique chemical compositions and quality characteristics, offering a more diverse culinary experience.

Alavi et al. (2019) further emphasize the role of high-moisture extrusion cooking in precooked pasta production. This process enables starch gelatinization, forming a cohesive product matrix even without gluten, which is particularly beneficial for alternative grains such as sorghum. Their findings also demonstrate that additives like monoglycerides can enhance the texture and reduce cooking loss, though sensory attributes such as texture and mouthfeel remain challenging to optimize compared to traditional wheat pasta (Alavi et al., 2019).

This research investigates the potential of IWG and sorghum as sustainable alternatives to conventional wheat in precooked pasta production. Precooked pasta is hypothesized to rely more heavily on starch than protein, which may present challenges for IWG due to its lower starch content. However, incorporating IWG could enhance overall product quality through innovative formulation and processing techniques. This study examines how the unique properties of IWG

and sorghum influence pasta quality and contribute to sustainable food production, addressing challenges associated with conventional wheat-based products.

More specifically, raw materials with higher starch content and gelatinization temperatures are expected to yield extrudates with better quality. Combining grains may produce synergistic effects, improving functionality through additive interactions. Extrusion processing is anticipated to increase the Water Solubility Index due to starch degradation. For pasta quality, higher pasting temperatures are expected to reduce cooking loss and water holding capacity, while lower pasting temperatures may lead to earlier starch granule fracturing, increasing degradation, cooking loss, and water absorption. Additionally, higher water holding capacity is hypothesized to correlate with softer pasta.

Research supports that pasta absorbs more water than raw flour due to cooking-induced starch degradation, with well-gelatinized starch improving water absorption while limiting leaching, as seen in sorghum pasta (Benhur et al., 2015). Higher pasting temperatures have been shown to reduce cooking loss by enhancing starch binding, as demonstrated in studies on wheat and sorghum (Rooney, 1986; Svihus, 2005). Additionally, starch degradation during cooking influences hardness more than water holding capacity alone, with wheat's high water holding and hardness linked to starch breakdown, while sorghum's protein-starch interactions help protect starch structure and reduce both hardness and water holding (Marti, 2010; Svihus, 2005).

By evaluating the raw material functionality of wheat, sorghum, IWG, and their combinations, and analyzing the product quality of pasta made with these ingredients, this chapter aims to advance the understanding of alternative grains in precooked pasta and make progress in sustainable food production and agricultural practices.

2.2 Materials and Methods

2.2.1 Ingredients & Formulation

2.2.1.1 Ingredients

All purpose, refined wheat flour was obtained from Kansas State University Department of Grain Science Hall Ross Flour Mill (Manhattan, KS), IWG flour was obtained from Sustain-a-Grain (McPherson, KS), and Sorghum flour was obtained from Nu-Life Market (Scott City, KS). Proximate Analysis was determined by Midwest Labs (Omaha, NE) and is presented in Table 2-1. Protein analysis followed MWL FO 014, based on AOAC 992.15, USDA/FSIS CLG-PRO04.04, and ISO 14891:2002 (E), IDF 185:2002 (E), where a homogenous sample was combusted in a nitrogen analyzer, and nitrogen gas was measured to calculate protein content. Starch analysis followed WC 047, based on AOAC 996.11 and YSI Application Note 319, using enzymatic hydrolysis with alpha amylase and amyloglucosidase to convert starch to glucose, quantified using a glucometer. Total dietary fiber analysis followed MWL FO 027, based on AOAC 991.43, involving defatting, de-sugaring, enzymatic digestion, alcohol precipitation, and residue filtration to determine fiber content.

2.2.1.2 Experimental Design

In the investigation of precooked pasta, six distinct pasta formulations were developed, with exclusive variations in the base flour while maintaining a consistent composition of 1% salt and 1% monoglyceride. The variations encompassed formulations with wheat flour, IWG flour, sorghum flour, and a combination of each (wheat flour/IWG flour, IWG flour/sorghum flour, wheat flour/sorghum flour). as summarized in Table 2-2.

2.2.1.3 Moisture Content

The moisture content of the raw materials prior to extrusion and extrudates were dried for 2 hours at 135 °C according to AACC Method 44-19.01 (AACC, 2009). Extruded products were ground prior to moisture determination. The moisture content of all samples is presented in Table 2-3. The moisture content values presented in Tables 2-3 were used as reference for hydrating the samples prior to analysis.

2.2.2 Raw Material Analysis

2.2.2.1 Water Absorption Index (WAI) & Water Solubility Index (WSI)

This method was adapted from the method utilized by Anderson, et al. (1970). A known mass (2.5 g) of raw materials and ground extrudates were mixed and suspended in 30 mL of distilled water using a vortex. Extrudates were ground to a particle size of approximately 300 microns using a Moongiantgo Electric High-Speed Grinder to ensure uniformity for analysis. Each sample tested was done in triplicate. The samples were then mixed using a shaker table for 30 minutes. After mixing the samples were placed in a centrifuge at 3,000 g for 15 min using a Centrifuge 5810 R 15 Amp Version (Eppendorf, Hauppauge, NY, USA). The supernatant was separated and placed in trays in the oven for 3 hours at 100 ℃ to evaporate the water. The dried trays were then weighed to determine the mass of dry solids. The leftover precipitate gel left in the test tubes was also weighed and the mass was recorded. Equation 2-1 was used to calculate the WAI.

$$\boldsymbol{WAI\ (g/g) = \frac{Gel\ weight}{Sample\ weight}} \qquad \textbf{2-1}$$

The WSI was determined from the amount of dry solids recovered by evaporating the supernatant at 100℃ for 5 hours and calculated using Equation 2-2. Where W_{dsuper} is the weight of dry solids from the supernatant and $W_{dsample}$ is the weight of the dry sample.

$$WSI = \frac{W_{dsuper}}{W_{dsample}} \, x \, 100$$

2-2

2.2.2.2 Phase Transition Analysis

Phase Transition analyses of the samples were conducted on a Phase Transition Analyzer (PTA™, Wenger Mfg., Sabetha, KS), to determine the softening and flow temperatures (Ts and Tf, respectively). A small amount of raw material (1.5-2.5 g) was hydrated to a target moisture of 18%. The material was compressed in a test chamber at 100 bars of pressure and subject to heating at a constant rate of 10°C/min from 7°C until 120°C or higher until the material starts to flow out of a capillary at the bottom of the chamber (Karkle et al., 2012). The flow temperature (Tf) is an indirect measure of resistance to flow or viscosity (Webb et al., 2023).

2.2.2.3 Rapid Visco Analysis (RVA)

The pasting properties of each raw material and ground product were evaluated using a Rapid Visco Analyzer (RVA) (RVA 4, Newport Scientific Pvt. Ltd., Warriewood, NSW, Australia) and methodology from Webb et al (2023). Extrudates were ground to a particle size of approximately 300 microns using a Moongiantgo Electric High-Speed Grinder to ensure uniformity for analysis. For the analysis, 3.5 g of sample was mixed with 25.0 ml of water. The pasting characteristics, including peak viscosity (PV), pasting temperature (PT), peak viscosity (PV), and final viscosity (FV) were measured. The RVA profile followed a standard protocol, beginning with the sample held at 50°C for 1 minute. The temperature was then increased to 95°C at a rate of 12.2°C/min, maintained for 2.5 minutes, followed by cooling to 50°C at a rate of 11.8°C/min and held for 2 minutes. Viscosity was recorded in centipoise (cP) units. All tests were conducted in duplicate for both raw material and extruded products.

2.2.2.4 Differential Scanning Calorimetry (DSC)

To understand the physicochemical transformation known as starch gelatinization, calorimetric measurements were conducted on raw material blends and extruded products using methodology from Webb et al (2023). Extrudates were ground to a particle size of approximately 300 microns using a Moongiantgo Electric High-Speed Grinder to ensure uniformity for analysis. Samples (8-10 mg) were placed in stainless steel DSC pans with a 1:2 solid-to-water ratio and sealed. After overnight equilibration, the Q100 Differential Scanning Calorimeter (TA Instruments, New Castle, DE) was used, following a program involving heating from 10°C to 140°C at 10°C/min. Transition temperatures (onset, peak, endpoint) and enthalpy (ΔH) were analyzed using TA Instruments Universal Analysis Software (version 5.4.0). Duplicate measurements were performed for all reported data. Enthalpy values were adjusted based on the starch content percentage of each sample to accurately reflect the contribution of starch to gelatinization and amylose-lipid complexation. The presence of amylose-lipid complexes was identified through endothermic peaks above the gelatinization temperature range, which indicate their formation. Total cook (%) was calculated based on the ratio of total enthalpy transition differences between raw and extruded samples where, ΔHT_{raw} = total enthalpy of raw material, and $\Delta HT_{extruded}$ = total enthalpy of ground extrudate. $Total\ cook\ \% = \frac{\Delta HT_{raw} - \Delta HT_{extruded}}{\Delta HT_{raw}} x\ 100$ **2-3**

2.2.3 Extrusion Process

2.2.3.1 Extrusion Parameters

Before extrusion, the raw material mixes were prepared using a batch double-ribbon mixer (Wenger Manufacturing, Sabetha, KS). The mixed materials were extruded through a pilot-scale TX-52 twin-screw extruder (Wenger Manufacturing, Sabetha, KS), which had a

differential diameter cylinder preconditioner (DDC2, Wenger Manufacturing, Sabetha, KS) with a screw diameter of 52 mm and a length-to-diameter (L/D) ratio of 25.5:1. The screw profile is shown in Figure 2-1. The barrel temperatures were set across five zones: 60°C in zone-1, 70°C in zone-2, 95°C in zone-3, 60°C in zone-4, and 50°C in zone-5. A Wenger Vacuum System (Wenger Manufacturing, Sabetha, KS) was used at the 3rd barrel head, operating at approximately 450 PSI, to reduce excess heat and prevent product bubbling or deformation.

Material was fed into the preconditioner using a loss-in-weight single-screw feeder, adjusted to deliver 55 kg per hour. To maintain the target in-barrel moisture level of 40-42%, steam (10-12 kg/h) and water (5-7 kg/h) were added into the preconditioner. The preconditioner shaft speed was kept constant at 339 RPM. The in-barrel moisture content was regulated based on the initial moisture content, with additional water injected at 14 kg/h into the extruder barrel. The extruder screw speed was maintained at 244 RPM. Thermocouples positioned in each zone of the extruder barrel tracked both set and actual temperatures, while die temperature and pressure were monitored using a thermocouple and pressure gauge, respectively.

At the exit end of the extruder, a rotini pasta die, fitted with a vertical elbow attachment and 19 face openings, was used. Each insert had a die open area of 0.01796 square inches. A dual-blade air-pressure face cutter, running at 108 PSI, cut the pasta into rotini shapes. The cut pieces were pneumatically conveyed to a Wenger Double Pass Dryer/Cooler (Series 4800, Wenger Manufacturing, Sabetha, KS). The dryer operated at 160°C with steam injection to ensure gentle drying and reduce the risk of cracks in the fragile product. The total retention time in the dryer was 48 minutes—8 minutes on the top belt and 40 minutes on the bottom belt. Cooling was achieved using ambient air, with an 11-minute retention time on the cooling belt. Dimensions were recorded for 15 samples of each treatment post-drying.

2.2.3.2 Specific Mechanical Energy

The specific mechanical energy (SME) was read out by a wattmeter in kilowatts and converted to kJ/kg as shown in Equation 2-4:

$$\frac{W - W_0}{m/3600} \quad \textbf{2-4}$$

Where W is the wattmeter reading in kW, Wo is the wattmeter reading at no load, and m is the feed rate.

2.2.4 Extrudate Analysis

2.2.4.1 Cooking

The optimum cooking time for wheat pasta was determined using AACC Approved Method 66–50 (AACC, 2000), which checks for the disappearance of the opaque central core of the noodle when gently squeezed between two glass plates. This method was adapted for precooked pasta made from wheat, sorghum, and IWG. This approach allowed the standardization of the assessment of cooking times across the different types of pasta. Commercial pasta was cooked as directed on packaging.

2.2.4.2 Cooking Loss & Water Holding Capacity

Dry matter losses during cooking were determined by AACC Approved Method 66–50 (AACC, 2000). Pasta samples (25 g) were cooked to optimum time in 300 mL of distilled water, rinsed with cold water for 30 seconds, and drained. The cooking water was collected, diluted to 500 mL to allow for thorough rinsing of the pasta and collection of any additional residue, and then evaporated to dryness at 105°C. Drying time was approximately 24 hours. Once dry, the beakers were weighed. Duplicate samples were analyzed for each treatment. Commercial

samples were analyzed using the same methods. The formula used to calculate cooking loss is given in Equation 2-5.

$$Cooking\ loss = \frac{Dried\ weight\ of\ residue}{Weight\ of\ sample}\ x\ 100 \quad \textbf{2-5}$$

Water holding capacity was measured during the cooking loss analysis. Equation 2-6 was used to calculate water absorption.

$$Water\ Holding\ \% = \frac{(Cooked\ product\ weight - Dry\ product\ weight)}{Dry\ product\ weight}\ x\ 100 \quad \textbf{2-6}$$

2.2.4.3 Texture Profile Analysis

Texture profile analysis measured hardness, springiness, cohesiveness, gumminess, and chewiness using a TA-XT2 Texture Analyzer (Texture Technologies Corp., Scarsdale, NY). Single, fully cooked, and hydrated extrudates were compressed twice by a 2-inch circular aluminum probe, adapted from Texture Technology's standards, with a trigger force of 5 g, a pre-test speed of 5 mm/sec, a test speed of 5 mm/sec, and a post-test speed of 5 mm/sec. The probe compressed the samples to 8 mm past the first impact, mimicking a two-bite compression with a pause in between to allow the sample to recover and measure springiness as an adapted method from Webb et al (2023). Compression force data were collected by the texture analyzer software, and hardness, springiness, and chewiness were calculated. Hardness (g) was defined as the peak force during the first compression cycle. Springiness (mm/mm) was measured as the ratio of the distances between the first and second compressions. Chewiness (g) was calculated as the product of hardness, cohesiveness (Area 2/Area 1), and springiness. Commercial pasta was

analyzed for hardness, using the same methods, adjusting the probe height for the size of the pasta.

2.2.5 Statistical Analysis

All data were analyzed using SAS software (SAS Institute Inc., Cary, NC). One-way analysis of variance (ANOVA) was employed to determine significant differences among sample means. Post-hoc comparisons were conducted using Tukey's Honest Significant Difference (HSD) test to evaluate pairwise differences. A significance level of $p < 0.05$ was used for all statistical tests.

2.3 Results & Discussion

2.3.1 Raw Material Analysis

2.3.1.1 Water Absorption Index & Water Solubility Index

The Water Absorption Index (WAI) and Water Solubility Index (WSI) for each raw material and extrudate are shown in Table 2-5. The pasta water absorptions are much higher than the raw materials' due to the starch degradation allowing them to take in more water. Conversely, the WSI for pasta is much lower than the raw materials' for a similar reason, because the starch is cooked and less of it is leaching out and soluble.

Sorghum pasta exhibited the greatest WAI and lowest WSI, suggesting that its starch is well-gelatinized but not excessively degraded. This high gelatinization quality indicates that the pasta can absorb more water without excessive leaching, reflecting high-quality pasta (Benhur et al., 2015). The gelatinization data in Table 2-9 support this observation, showing that sorghum's starch has a higher degree of gelatinization compared to wheat. This means sorghum's starch is more resistant to degradation at cooking temperatures, allowing it to maintain better water

absorption and reduced solubility. In contrast, wheat, with lower gelatinization temperatures, shows higher starch degradation, leading to lower WAI and higher WSI.

The gelatinization data reveal that sorghum's starch maintains its structural integrity at higher temperatures, correlating with its higher WAI and lower WSI. This is supported by the fact that sorghum's starch has longer amylopectin chains, which contribute to its stability and ability to absorb water without significant leaching (Srichuwong et al., 2017). Other treatments containing sorghum also demonstrated similar characteristics of higher WAIs and lower WSIs in comparison to wheat-containing treatments, attributed to the hydrophilic polysaccharides in sorghum flour (Benhur et al., 2015; Srichuwong et al., 2017).

To compare the results with those of Benhur et al. (2015), their study also observed increased WAI with higher sorghum content in the blends, which aligns with the finding that sorghum pasta exhibited the greatest WAI. Their lower WSI values for extrudates are consistent with the observation that sorghum pasta had a lower WSI compared to other flours, suggesting similar trends in starch behavior. While their study presented a higher range of WAI values (up to 38.79), this difference may be attributed to variations in formulations or processing conditions. Overall, both studies demonstrate that sorghum-based pasta tends to have higher water absorption and lower solubility, confirming the consistency of the results.

2.3.1.2 Phase Transition Analysis

Table 2-6 shows the flow temperatures and specific mechanical energy (SME) for each raw material blend. Among the treatments, the Wheat/Sorghum blend has a notably higher flow temperature at 121°C, significantly higher than the other blends. This difference highlights its extreme flow properties. In contrast, other treatments like Wheat, IWG, and Sorghum have flow temperatures ranging from 68°C to 86°C.

The specific mechanical energy (SME) values align closely with flow temperature trends, as seen in Figure 2-2. Higher flow temperatures generally correlate with higher SME values. For example, the Wheat/Sorghum blend, which has the highest flow temperature, also shows the highest SME. This trend supports findings from Webb (2023), which suggest that raw material thermal properties, including flow temperature, often correlate directly with SME.

2.3.1.3 Rapid Visco Analysis

The pasting properties of the raw materials and ground extrudates reveal differences influenced by starch content and the gelatinization process. As shown in Figure 2-3 and Table 2-7, treatments containing IWG exhibited lower peak viscosities and flatter trend lines compared to sorghum-containing treatments, which showed higher peak viscosities. This variation is attributed to sorghum's higher starch content, which typically results in greater viscosities (Liu et al., 2019). This trend was also noted by Boakye et al. (2023), who found that extrusion leads to a decrease in viscosity due to starch breakdown. Similarly, extruded pastas in this study showed lower peak and final viscosities than their raw materials, indicating starch gelatinization during extrusion (Berski et al., 2016).

In the extrudates, pastas demonstrated significantly lower peak and final viscosities compared to their raw material counterparts, as shown in Figure 2-4 and Table 2-8. This reduction is a direct result of starch gelatinization during extrusion, where starches are transformed into a more gelatinized state, absorbing water and reducing viscosity (Berski et al., 2016). For instance, wheat treatment extrudates exhibited higher viscosities, suggesting less gelatinization compared to sorghum treatments. This reflects wheat's lower starch content and highlights how sorghum's higher starch content contributes to greater viscosity reductions in extrudates. Wheat treatments had slightly higher viscosities than sorghum, suggesting less starch

degradation in wheat. This is consistent with Boakye's finding that higher shear (screw speed) leads to greater starch breakdown. Overall, these results highlight how starch content and the extrusion process impact viscosity and pasta quality.

The pasting temperatures of raw materials also play a crucial role in determining pasta quality. Higher pasting temperatures generally improve quality by reducing cooking loss and enhancing water holding capacity, as they allow starch granules to bind and gelatinize more effectively. Conversely, lower pasting temperatures lead to earlier starch granule fracturing, increasing degradation. These findings emphasize the relationship between starch content, pasting behavior, and the gelatinization process in influencing the textural and functional properties of pasta products.

2.3.1.4 Differential Scanning Calorimetry

Table 2-9 shows the gelatinization and amylose-lipid complexation temperatures and enthalpy values for each raw material and ground extrudate. The raw materials exhibited a gelatinization peak around 65-70°C, typical for starches during cooking, indicating that starch gelatinization occurs within this range.

In contrast, the extrudates did not show a gelatinization peak at 65-70°C, suggesting that their starches were already fully gelatinized during extrusion. Instead, a peak around 101-102°C was observed, corresponding to amylose-lipid complexation, which occurs when amylose interacts with lipids during high shear and temperature conditions, such as in extrusion (Srichuwong et al., 2017).

The enthalpy values for gelatinization ranged from 5.5455 to 8.787 J/g, while amylose-lipid complexation enthalpies ranged from 2.126 to 4.245 J/g. Statistical analysis revealed no significant differences between the raw materials and extrudates in either gelatinization or

amylose-lipid complexation temperatures and enthalpy values. These findings suggest that while raw materials gelatinize at 65-70°C, the extrudates are fully gelatinized by the time of analysis, with amylose-lipid complexation influencing their final properties.

2.3.2 Extrusion Processing

2.3.2.1 Process Energy

In extrusion processes, specific mechanical energy (SME), specific thermal energy (STE), and steam loss are crucial factors affecting both efficiency and sustainability. SME is essential as it directly influences the mechanical forces applied during extrusion, impacting product quality and energy consumption. STE plays a significant role in maintaining the optimal temperature for extrusion, which affects the material's flow properties and overall process efficiency. Managing steam loss is important for sustainability, as minimizing energy waste contributes to a more environmentally friendly and cost-effective extrusion process (Hejna et al., 2021). Figures 2-5, 2-6, & 2-7 present results for SME, STE, and steam loss in various extruded products. IWG demonstrates the lowest steam loss among individual grains at 51%, while the Wheat/Sorghum combination shows the lowest overall steam loss at 49.5%. SME varies across products, with Wheat/Sorghum exhibiting the highest SME at 262 kJ/kg. IWG and Wheat/IWG also show lower steam loss. Low steam loss in extrusion cooking is beneficial because it helps in destroying antinutritional factors in sorghum, gelatinizing starch, increasing soluble dietary fiber, and reducing lipid oxidation, which improves nutritional quality (Singh et al., 2007).

The relationship between SME and specific thermal energy (STE) is significant, as higher SME can be associated with higher viscosity and increased flow temperature. Additionally, low steam loss indicates higher water absorption, which is characteristic of the material and can be

related to WAI and WSI. This suggests that materials with lower steam loss are likely to have better water absorption and flow properties, which could impact their overall texture and quality.

2.3.2.2 Extrudate Characteristics

The mean physical parameters of each extrudate are given in Table 2-10 and shown in Figure 2-8. The piece length of the Wheat/Sorghum treatment is significantly longer compared to that of the other varieties. Treatments containing solely wheat, IWG, sorghum, and the Wheat/IWG treatment exhibited shorter and similar lengths, ranging from 30.1 mm to 34.3 mm. Although screw speed and knife speed were held constant during production, the Wheat/Sorghum pieces were nearly twice as long.

This difference in piece length suggests a greater specific mechanical energy (SME) input, which correlates with the flow temperature and material viscosity, playing a crucial role in determining the physical characteristics of the extrudates. In this case, the Wheat/Sorghum treatment had an SME of 261.82 kJ/kg, significantly higher than the other treatments, which ranged from 229.09 to 255.27 kJ/kg, as shown in Figure 2-5.

Higher SME can lead to increased melt viscosity and elasticity, allowing the extrudate to maintain its structure and extend longer before being cut (Ondo et al, 2013). The higher SME for the Wheat/Sorghum treatment indicates more energy was used during extrusion, contributing to its significantly longer piece length.

2.3.3 Extrudate Analysis

2.3.3.1 Cooking Process

The cooking times and characteristics of each pasta formulation are shown in Table 2-11. The cooking times for each pasta formulation varied significantly, influencing the resulting texture. Wheat-based pasta required the longest cooking time of approximately 5:00 minutes,

leading to a persistently gummy texture and inconsistent cooking. IWG-based pasta, with a shorter cooking time of 2:00 minutes, tended to fall apart quickly and was described as somewhat doughy, but had a more consistent texture overall. Sorghum-based pasta, which cooked for around 4:30 minutes, showed inconsistent piece sizes, contributing to uneven cooking.

The combination of IWG and Wheat cooked for 4:00 minutes, resulting in a pasta with a balanced texture—less mushy than IWG alone but not as firm as wheat. In contrast, combining IWG and Sorghum, which cooked for 3:00 minutes, led to an optimal texture with spirals falling off, indicating a desirable consistency. The combination of Wheat and Sorghum faced challenges due to irregular piece sizes, requiring a longer cooking time of 4:30 minutes and resulting in a texture that was intermediate between the firmness of wheat and the softness of sorghum.

2.3.3.2 Cooking Loss & Water Holding Capacity

The cooking quality of the pasta products was evaluated using optimized cook times, WAI & WSI, water holding capacity, and cooking loss, as shown in Table 2-12. Figures 2-9 and 2-10 illustrate the cooking loss and water holding capacity, including a commercial pasta product for comparison. The cooking times for each blend ranged from 2 to 5 minutes, with wheat-based pasta having the longest cook time (5 minutes) and IWG-based pasta the shortest (2 minutes). The variations in cooking times can be attributed to the differing degrees of starch gelatinization and gelatinization temperatures of the starch combinations (Liu et al., 2019). Treatments containing wheat demonstrated longer cooking times, which could be due to the particular starch quality and the gelatinization properties of wheat (Benhur et al., 2015).

Cooking loss measures the pasta's ability to retain structural integrity during cooking. High cooking loss indicates increased starch solubility, leading to cloudy cooking water, reduced

cooking tolerance, and a sticky mouthfeel (Benhur et al., 2015). Precooked pasta formulations with only wheat flour exhibited the highest cooking loss percentage at 5.6%, contrasting with IWG flour at 3.9% and sorghum flour at 1.9%. The Wheat/IWG combination also had a high cooking loss of 5.6%, whereas other formulations ranged from 1.4-3.9%. This can be attributed to wheat being less processed and showing a lower binding capacity (Berski et al., 2016). The higher peak viscosity of wheat extrudate (1064 cP) compared to sorghum (979 cP) and IWG (443 cP) demonstrates this. Similar results were observed in a study by Alavi et al. (2018), where cooking losses in sorghum-based pasta and semolina-based pasta ranged from 4.3% to 5.9%, indicating that the cooking losses in this study fall within a comparable range.

Sorghum indicated more desirable WAI and WSI characteristics, aligning with its lower cooking loss. The Wheat/Sorghum blend had the lowest cooking loss but showed similar WAI and WSI results to sorghum, suggesting strong water absorption without excessive starch leaching. The high cooking loss in wheat is likely due to its longer cooking time, starch quality, and the natural susceptibility of wheat starch to degradation and gelatinization (Benhur et al., 2015; Liu et al., 2019).

Water holding capacity measures how much water the pasta absorbs during cooking, relating to textural properties such as hardness and cohesiveness. Wheat and Wheat/IWG formulations exhibited both high water holding and high cooking loss, which could be due to degraded starch leaching into the water (cooking loss) and the breakage allowing it to absorb more water (Berski et al., 2016).

The relationship between WAI of the raw materials and the cooking loss of the final pasta product is crucial. Sorghum's high WAI (3.53) and low WSI (0.035) indicate its ability to absorb water effectively without leaching out significant amounts of soluble components. This

corresponds to the lower cooking loss observed in sorghum-based pasta, indicating better structural integrity during cooking (Benhur et al., 2015).

2.3.3.3 Texture Profile Analysis

The texture analysis of the pasta formulations revealed distinct differences in hardness (Figure 2-11), springiness (Figure 2-12), cohesiveness (Figure 2-13), gumminess (Figure 2-14), and chewiness (Figure 2-15), with wheat-based pasta exhibiting the hardest and gummiest texture. Wheat also had the lowest springiness and the highest chewiness, which is consistent with its high cooking loss (5.6%) and long cooking time. This suggests significant starch degradation and leaching of soluble materials during cooking. Despite this, wheat displayed high water holding capacity and low water solubility, likely due to incomplete gelatinization that traps water but contributes to its dense, less cohesive structure (Benhur et al., 2015).

In contrast, sorghum-based pasta had the lowest hardness, gumminess, and chewiness, paired with the highest springiness. Sorghum's low cooking loss (1.9%) and high WAI with low WSI suggest effective water absorption without excessive leaching, which aligns with its softer and more cohesive texture. Previous research indicates that sorghum's starch-protein interactions can protect starch from degradation, reducing fracture formation and preventing excessive water infiltration or the formation of dense bonds that increase hardness (Svihus, 2005).

The blends and IWG-based pasta consistently displayed intermediate traits. IWG pasta had lower chewiness and resilience compared to other formulations. It also had the highest water solubility and the lowest water holding capacity, likely contributing to its softer texture. IWG's moderate cooking loss (3.9%) reflects its limited starch content, which may have prevented the formation of sufficient structural bonds for higher hardness (Berski et al., 2016).

The texture properties of the pasta formulations in this study align with findings from Wójtowicz et al. (2020). Like Wójtowicz's results, sorghum-based pasta in this study had lower hardness compared to wheat, which was harder and had higher chewiness. In Wójtowicz's study, wholegrain wheat (WGW) pasta also had lower hardness and expansion than conventional wheat pasta. The softer texture of sorghum pasta in both studies can be attributed to its starch-protein interactions, which help protect starch from excessive degradation. The study by Wójtowicz also noted that processing conditions like dough moisture content and extrusion speed affect pasta texture, a factor that could explain some of the textural differences seen in this study as well, though this was not directly tested here.

The hypothesis that higher water holding capacity would correspond to lower hardness (softer pasta) was not supported by the data. Correlation graphs (Figure 2-17) indicate that water holding does not directly control hardness; instead, starch degradation plays a more significant role. Wheat, for instance, had the highest water-holding capacity but also the highest hardness. This can be explained by its degraded starch, which fractures during cooking and absorbs more water. The cooking process then binds the degraded starch, resulting in a harder structure.

Conversely, IWG's lower starch content likely limited its ability to form bonds, resulting in lower hardness. Sorghum had the lowest hardness and water-holding capacity despite its higher starch content compared to IWG. This is likely due to sorghum's starch-protein interactions, which protect starch granules from degradation and fracture, preventing water infiltration and limiting the formation of dense, hard bonds (Svihus, 2005). These findings highlight that both starch quantity and starch quality are critical factors in determining pasta hardness, with water-holding capacity playing a secondary role.

2.4 Conclusion

This study demonstrates the potential of IWG, wheat, and sorghum as viable ingredients for extruded precooked pasta. Sorghum flour emerged as the most promising ingredient, exhibiting superior cooking performance. It achieved high water absorption without excessive leaching, attributed to its intact starch structure and protein-starch interactions. This protective starch structure also contributed to lower hardness and water-holding capacity, indicating desirable textural properties and sustainable potential as a high-quality pasta ingredient.

Wheat, in contrast, exhibited high cooking loss and hardness, likely due to its low pasting temperature and significant starch degradation. IWG, with its lower starch content, showed moderate cooking loss despite a higher pasting temperature, showing the influence of starch quantity and quality on cooking performance. These findings highlight that starch degradation during cooking had a greater effect on hardness than water-holding capacity alone.

The inclusion of IWG and sorghum flour presents opportunities for improving sustainability in pasta production. IWG's and sorghum's environmental benefits, combined with their unique cooking and textural properties, position them as strong alternatives to conventional wheat. Additionally, the variability observed in extrudate dimensions across formulations suggests that further refinement of processing parameters and ingredient ratios could enhance consistency in product quality.

Future research should explore life cycle assessments and consumer acceptance to understand the broader implications of incorporating these innovative grains into pasta production. This study contributes to the growing focus on sustainable food systems and

emphasizes the importance of diversifying grain sources to reduce the ecological footprint of food manufacturing.

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2.6 Figures & Tables

Have to redo figure numbering and organization after we are done with the "track changes" because it is not working

Figure 2-1 Extruder Screw Profile

TX-52																			
L	1	1	2	2	3	4	2	2	2	5	4	4	1	1	2	2	5	5	6
R	1*	1*	2	2	3	4	2	2	2	5	4	4	1	1	2	2	5	5	6

1	Full pitch double flighted uncut forward
1*	Full pitch single flighted uncut forward
2	3/4 pitch double flighted 9u uncut forward
3	3/4 pitch double flighted 6u uncut forward
4	Kneading block reverse, 3 set
5	1/2 pitch double flighted 9u cut forward
6	3/4 pitch screw double flighted cut cone forward

Figure 2-2 Correlation of Flow Point and Specific Mechanical Energy

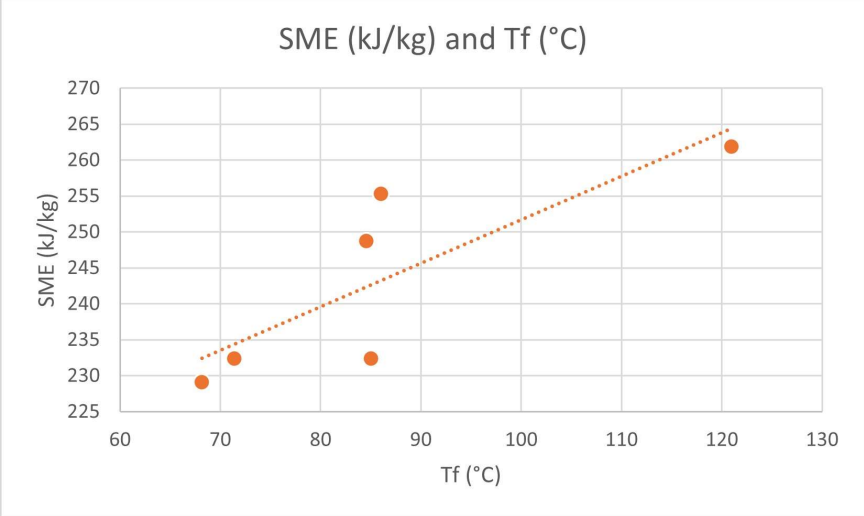

Figure 2-3 Viscosity Curve of Raw Materials

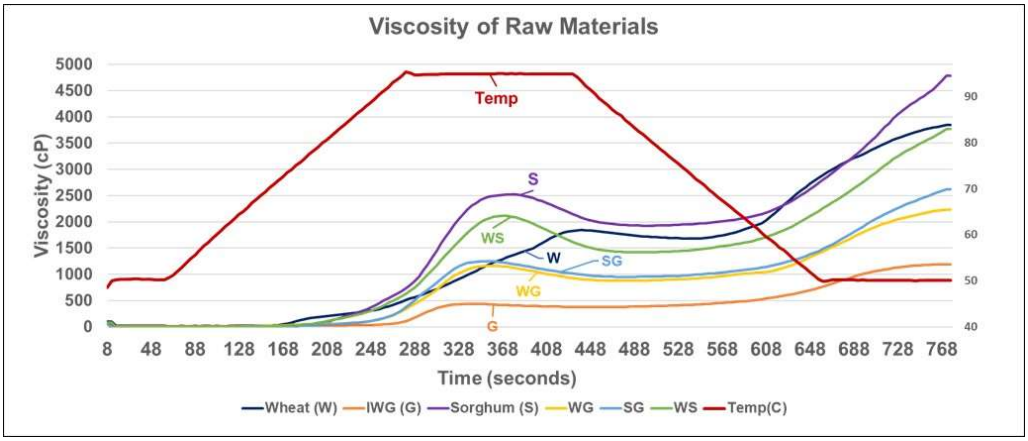

Figure 2-4 Viscosity Curve of Ground Extrudates

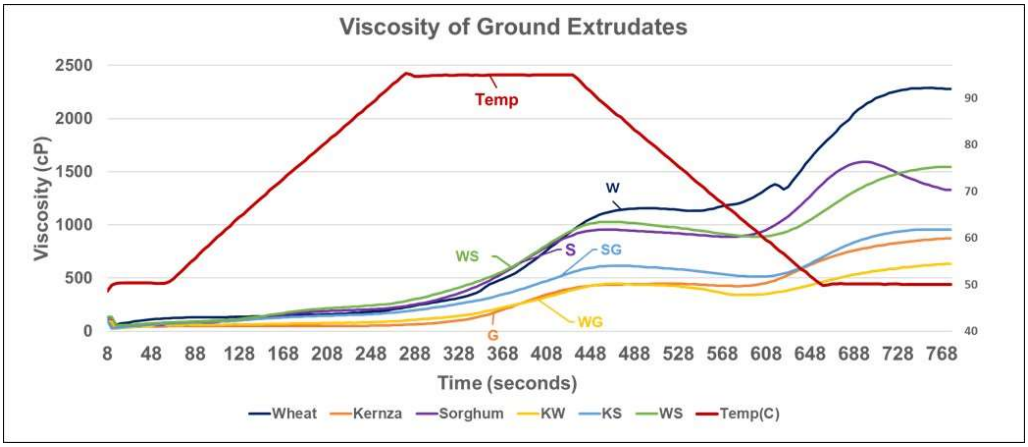

Figure 2-5 Specific Mechanical Energy

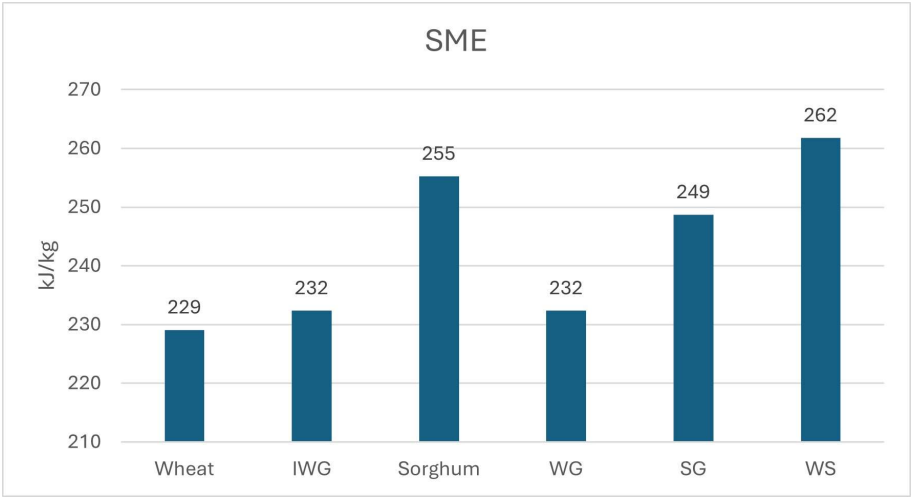

Figure 2-6 Specific Thermal Energy

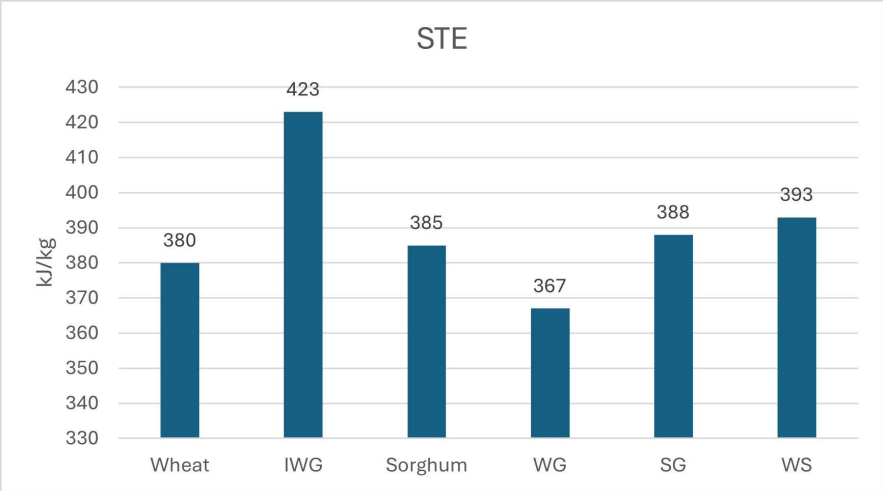

Figure 2-7 Steam Loss Percentage

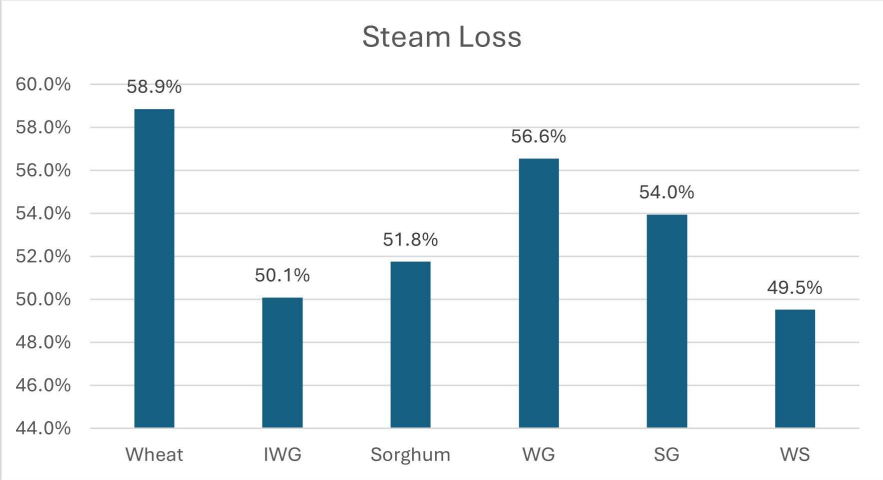

Figure 2-8 Piece Length

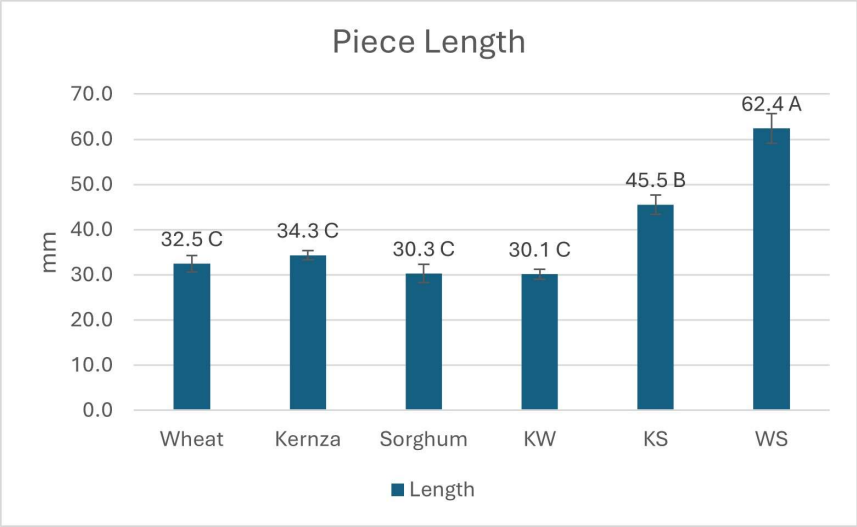

Figure 2-9 Cooking Loss Percentage

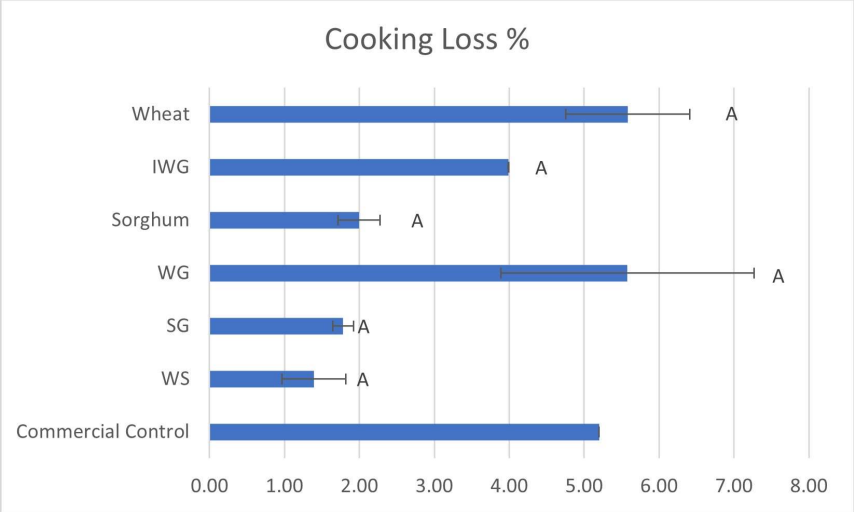

Figure 2-10 Water Holding Capacity of Pasta

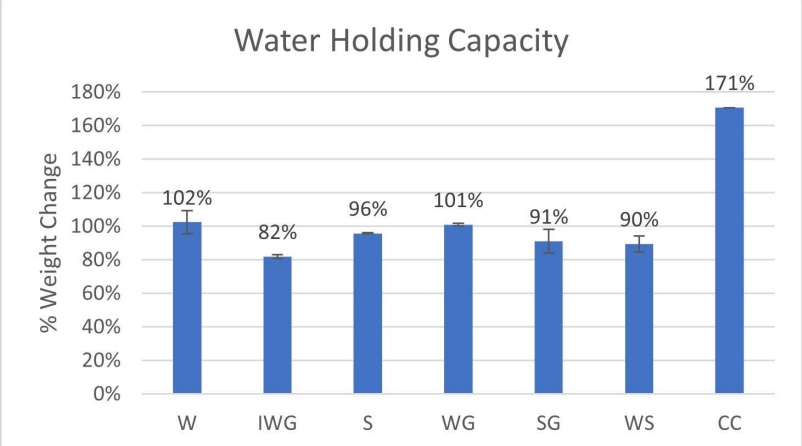

Figure 2-?

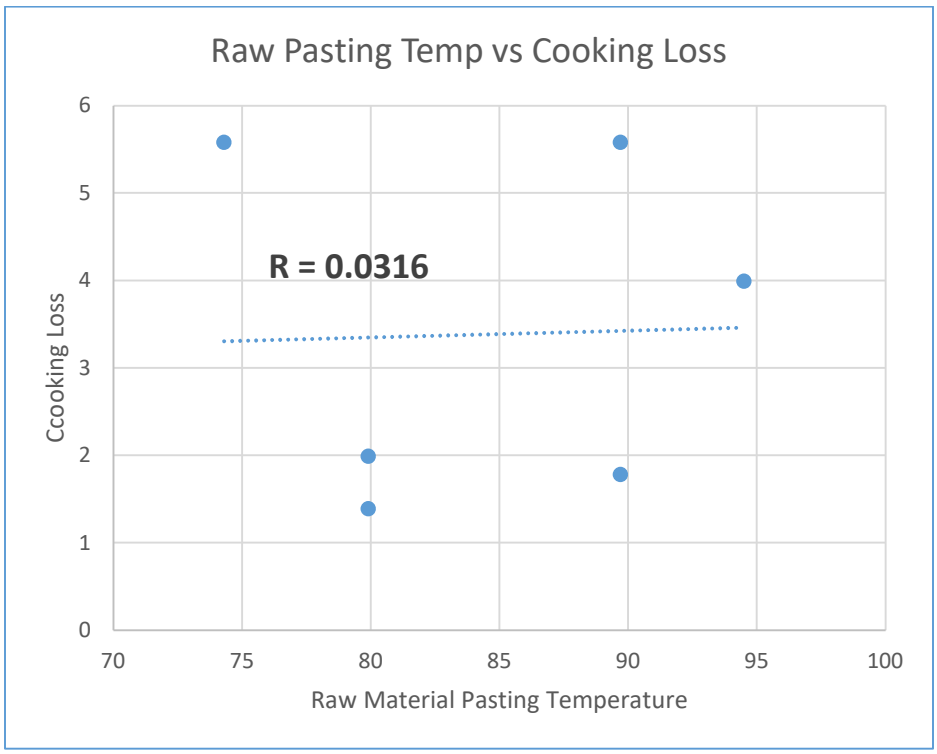

Figure 2-?

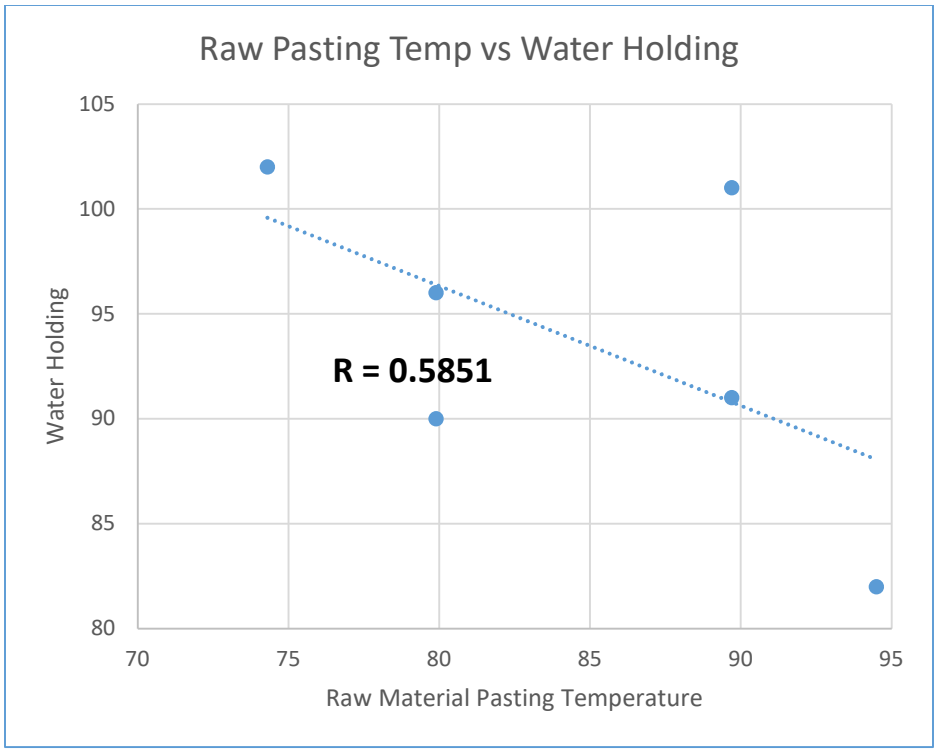

Figure 2-11 Hardness of Pasta

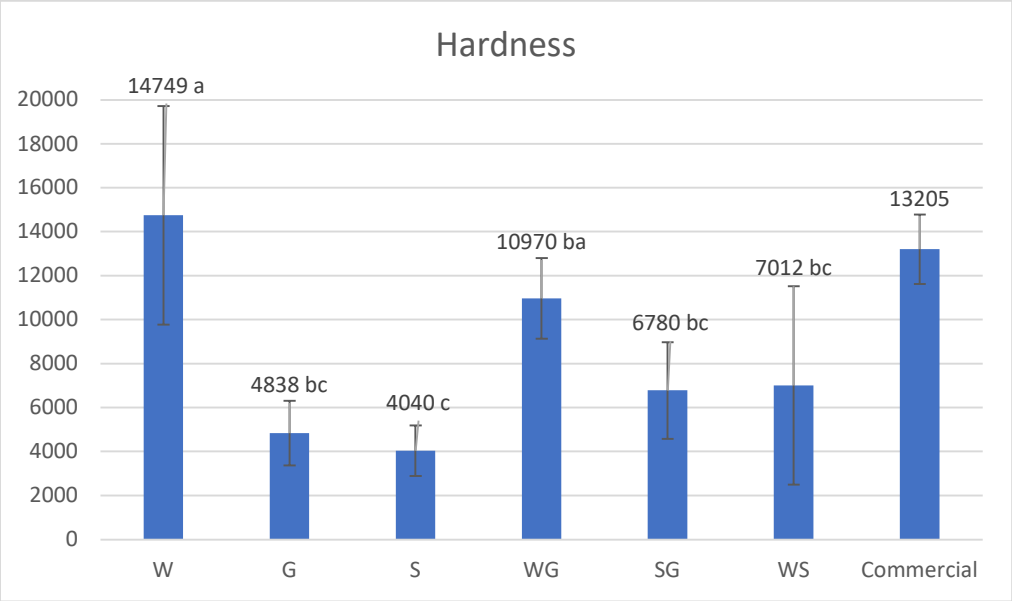

Figure 2-12 Springiness of Pasta

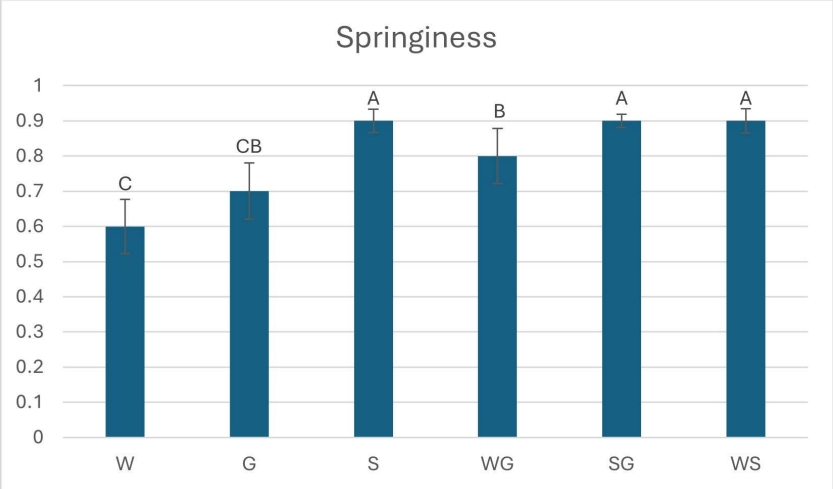

Figure 2-13 Cohesiveness of Pasta

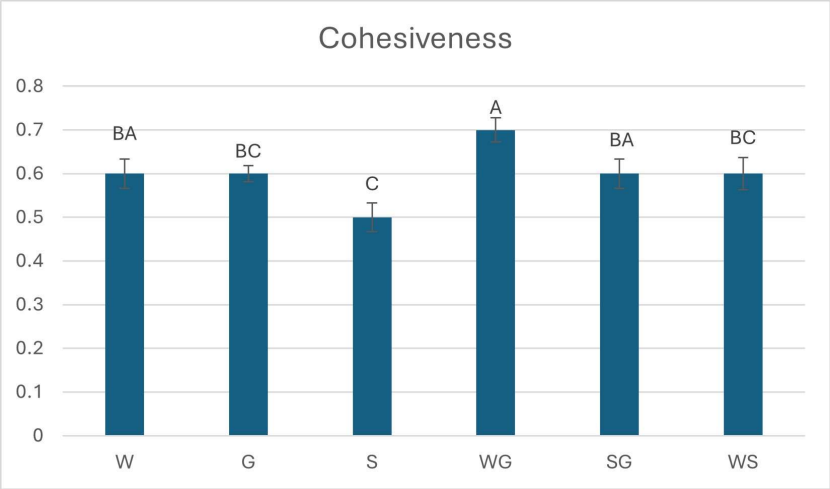

Figure 2-14 Gumminess of Pasta

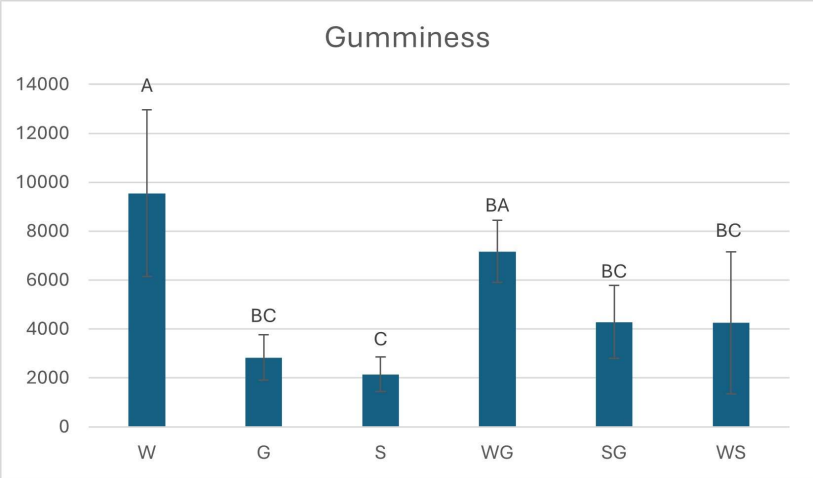

Figure 2-15 Chewiness of Pasta

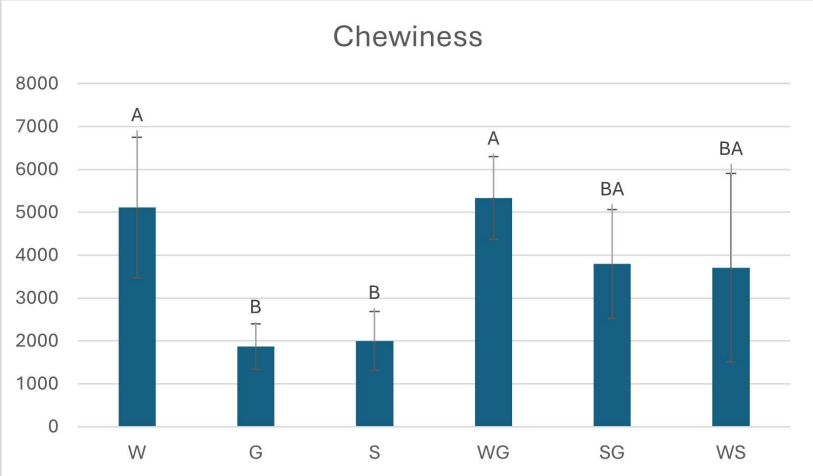

Table 2-1 Proximate Analysis of Raw Materials

	Moisture %	Protein %	Fat %	Ash %	Carbohydrates %	Calories (Cal)	Total Dietary Fiber %	Starch % *
Wheat Flour	10.1	10.9	2.2	0.7	76.2	368.0	4.9	71.3
IWG Flour	10.1	18.3	3.5	2.2	66.0	368.0	16.0	50.0
Sorghum Flour	11.1	9.0	2.4	0.8	76.4	364.5	3.9	72.5

Table 2-2 Formulation Composition

	Wheat Flour	**IWG Flour**	**Sorghum Flour**	**Salt**	**Mono-glyceride**
Wheat (W)	98%			1%	1%
IWG (G)		98%		1%	1%
Sorghum (S)			98%	1%	1%
Wheat/IWG (WG)	49%	49%		1%	1%
Sorghum/IWG (SG)		49%	49%	1%	1%
Wheat/Sorghum (WS)	49%		49%	1%	1%

Table 2-3 Moisture Content of Raw Materials

Raw Material	**Moisture**
Wheat Flour	7.19%
Sorghum Flour	6.51%
IWG Flour	6.22%
Wheat Mix	6.43%
Sorghum Mix	6.00%
IWG Mix	5.84%
Wheat + IWG Mix	6.12%
IWG + Sorghum Mix	5.72%
Wheat + Sorghum Mix	6.17%

Table 2-4 Moisture Content of Ground Extrudates

Ground Extrudate	Moisture
Wheat	10.59%
Sorghum	10.41%
IWG	8.88%
Wheat + IWG	9.52%
Sorghum + IWG	9.73%
Wheat + Sorghum	10.50%

Table 2-5 Water Absorption Index & Water Solubility Index of Raw Materials and Ground Extrudates (Statistical Significance Applied Across Rows)

	Wheat	Std Dev +/-	IWG	Std Dev +/-	Sorghum	Std Dev +/-	IWG/ Wheat	Std Dev +/-	IWG/ Sorghum	Std Dev +/-	Wheat/ Sorghum	Std Dev +/-
Raw Material WAI	0.832 ^{c}	0.02	1.311 ^{a}	0.03	1.21 ^{b}	0.04	0.751 ^{c}	0.01	0.826 ^{c}	0.05	0.816 ^{c}	0.01
Pasta WAI	2.929 ^{b}	0.14	2.28 ^{c}	0.03	3.532 ^{a}	0.12	2.542 ^{cb}	0.03	2.781 ^{b}	0.05	3.42 ^{a}	0.30
Raw Material WSI	0.078 ^{a}	0.001	0.099 ^{a}	0.001	0.067 ^{a}	0.002	0.079 ^{a}	0.001	0.081 ^{a}	0.001	0.068 ^{a}	0.00
Pasta WSI	0.041 ^{dc}	0.001	0.075 ^{a}	0.001	0.035 ^{d}	0.001	0.059 ^{ba}	0.001	0.057 ^{bc}	0.002	0.039 ^{d}	0.001

Table 2-6 Flow Temperature of Raw Materials and Specific Mechanical Energy

Treatment	T_f (°C)	Std Dev +/-	SME (kJ/kg)
Wheat	68.15 ^{c}	1.05	229.09
IWG	71.40 ^{cb}	0.0	232.36
Sorghum	86.05 ^{b}	5.85	255.27
WG	85.05 ^{b}	1.75	232.36
SG	84.55 ^{b}	1.05	248.73
WS	121.00 ^{a}	0.0	261.82

Table 2-7 Pasting Properties of Raw Materials

Raw Material	Pasting Temperature (°C)	Std Dev +/-	Peak Viscosity (cP)	Std Dev +/-	Final Viscosity (cP)	Std Dev +/-
Wheat	92.7 [b]	0.6	1908 [ba]	95	4031 [b]	351
IWG	94.5 [a]	0.0	437 [c]	16	1189 [d]	40
Sorghum	79.9 [d]	0.0	2525 [a]	0	4786 [a]	0
WG	89.7 [c]	0.1	1163 [c]	33	2236 [c]	2
SG	89.7 [c]	0.0	1250 [bc]	1	2620 [c]	59
WS	79.9 [d]	0.0	2119 [ba]	5	3764 [b]	56

Table 2-8 Pasting Properties of Ground Extrudates

Extrudate	Pasting Temperature (°C)	Std Dev +/-	Peak Viscosity (cP)	Std Dev +/-	Final Viscosity (cP)	Std Dev +/-
Wheat	80.8 [ba]	2.3	1110 [a]	65	2330 [a]	71
IWG	77.4 [b]	1.7	446 [c]	4	873 [cd]	13
Sorghum	89.0 [a]	0.1	956 [ba]	33	1329 [cb]	42
WG	83.3 [ba]	5.7	449 [c]	233	632 [d]	315
SG	86.5 [ba]	1.1	616 [bc]	15	954 [cd]	44
WS	86.8 [ba]	0.5	1030 [a]	9	1547 [b]	13

Table 2-9 Gelatinization Characteristics of Raw Materials and Ground Extrudates

	Raw		Pasta	
	Gelatinization (C)	**Enthalpy J/g**	**Amylose Lipid (C)**	**Enthalpy J/g**
Wheat	68.705	8.787 [a]	102.405	3.8435 [a]
IWG	65.905	6.877 [a]	101.715	2.7495 [a]
Sorghum	69.680	8.4325 [a]	101.7	2.2835 [a]
WG	68.635	5.5455 [a]	101.985	4.245 [a]
SG	67.465	6.7115 [a]	101.84	2.126 [a]
WS	71.685	6.891 [a]	101.075	2.653 [a]

Table 2-10 Piece Dimensions

	Length (mm)	Diameter 1 (mm)	Diameter 2 (mm)
Wheat	32.5 ± 1.8	7.5 ± 0.3	6.4 ± 0.4

IWG	34.3 ± 1.0	9.1 ± 0.4	5.8 ± 0.5
Sorghum	30.3 ± 2.0	9.6 ± 0.4	5.2 ± 0.6
WG	30.1 ± 1.1	8.3 ± 0.2	6.4 ± 0.5
SG	45.5 ± 2.1	9.1 ± 0.6	6.1 ± 0.8
WS	62.4 ± 3.3	8.8 ± 0.3	6.7 ± 0.4

Table 2-11 Cooking Observations & Optimal Cooking Time

Treatment	Cooking Time (minutes)	Observations
Wheat	5:00	Gummy texture, inconsistent cooking
IWG	2:00	Falls apart quickly, somewhat doughy texture, consistent
Sorghum	4:30	Inconsistent piece sizes, uneven cooking
Wheat/IWG	4:00	Balanced texture, less mushy than IWG, not as firm as wheat
IWG/Sorghum	3:00	Optimal texture, spirals falling off
Wheat/Sorghum	4:30	Irregular piece sizes, longer cooking time, intermediate texture

Table 2-12 Cooking Quality Characteristics

Sample	Cooking Time (mins)	Water Absorption Index	Water Holding (%)	Cooking Loss (%)	Water Solubility Index
Wheat	5:00	2.93	102%	5.58%	.041
IWG	2:00	2.28	82%	3.99%	.075
Sorghum	4:30	3.53	96%	1.99%	.035
Wheat/IWG	4:00	2.54	101%	5.58%	.059
Sorghum/IWG	3:00	2.78	91%	1.78%	.057
Wheat/Sorghum	4:30	3.42	90%	1.39%	.039

Chapter 3 - Intermediate Wheatgrass (*Thinopyrum intermedium*) and Sorghum as Sustainable Ingredients in Extruded Expanded Snacks

Abstract

The increasing reliance on conventional grains like wheat poses significant environmental challenges, including soil erosion and carbon emissions. This study investigates Intermediate Wheatgrass (IWG) and sorghum, corn, and their 50/50 blend as alternative grains for expanded snack production and investigates how to balance sustainability with favorable textural properties. RVA analysis showed that sorghum had a peak viscosity of 1496 cP, compared to 525 cP for IWG, suggesting differences in starch behavior that impact expansion. Regarding physical characteristics, IWG alone exhibited the highest density (0.24 g/cm³) and hardness (22.95 kg), with a limited expansion ratio (5.8). In comparison, sorghum demonstrated a lower density (0.14 g/cm³), softer texture (hardness 12.96 kg), and a superior expansion ratio of 10.22. Corn, as a conventional comparison, showed a density of 0.12 g/cm³, an expansion ratio of 10.58, and a hardness of 15.54 kg, representing the typical properties targeted in expanded snacks. The 50/50 blend of IWG and sorghum achieved a moderate expansion ratio of 7.38, though density (0.22 g/cm³) and hardness (22.45 kg) were closer to IWG's values, suggesting that blending improved expansion but had limited effects on density and hardness. This research shows the need for innovative solutions to leverage the benefits of these alternative grains and contribute to sustainable food systems.

3.1 Introduction

Challenges and Opportunities in Grain Production

The reliance on traditional grains such as wheat, rice, and corn present significant challenges to food production and sustainability. While these grains account for a substantial portion of global caloric intake, their cultivation often leads to environmental concerns, including soil erosion, nutrient depletion, and increased greenhouse gas emissions (Ross-Ibarra, 2007; Soto-Gómez & Pérez-Rodríguez, 2022). These issues are exacerbated by monoculture practices, which can degrade soil health and reduce biodiversity (Chapman et al., 2022; DeHaan et al., 2018).

In this context, innovative grains like IWG and sorghum offer promising alternatives. IWG's perennial growth habit enhances soil health and carbon sequestration, while its deep root system helps reduce erosion and improve water retention (Tang et al., 2023). Sorghum, known for its drought resistance, provides an environmentally friendly option, particularly in water-scarce regions (Ruiz-Giralt et al., 2023). Incorporating these grains into food products could mitigate some of the environmental impacts associated with conventional grain farming.

Innovations in Expanded Snacks

Expanded snacks are commonly made using extrusion, a process where heat and mechanical forces transform raw materials, typically flours, into light and airy snack products. This process heavily relies on starch content and gelatinization properties, affecting the final product's expansion ratio, bulk density, and overall texture (Hussain et al., 2022). Traditionally, degermed corn flour is preferred due to its high starch content, which helps achieve better expansion and a crispy texture by producing a uniform structure (Robin et al. 2012). However,

whole grain flours are being increasingly explored to improve the nutritional profile of extruded snacks.

Whole corn flour retains the bran and germ, provides more fiber, vitamins, and minerals than degermed flour, but this comes with challenges in extrusion. The bran and germ can interfere with expansion, leading to denser snacks with lower volume (Robin et al., 2012). However, research shows that adjustments in processing parameters, such as temperature and moisture content, can help optimize expansion even when using whole corn flour (Serna-Saldivar & Perez Carrillo, 2019).

Sorghum, a gluten-free and drought-resistant grain, has also been used in extrusion for snack production. The high starch content in sorghum flour makes it suitable for expansion, but the presence of bran can affect the final product's texture. Studies have shown that sorghum-based extruded products exhibit desirable texture characteristics, such as lower bulk density and improved crispness when processed under optimal conditions (Pachigolla et al., 2016). This highlights sorghum's potential as a whole grain alternative in snack production, offering nutritional and sustainable benefits.

While not as commonly used as corn or sorghum, IWG has been incorporated into extruded products with promising results. The unique properties of IWG, including its higher protein and fiber content, can influence the expansion process. Research has demonstrated that IWG-based extrudates can achieve good expansion and texture characteristics, similar to traditional grains when processing conditions are optimized (Boakye et al., 2022, 2023). This suggests that IWG could be a viable alternative for developing sustainable, high-quality expanded snacks.

This study hypothesizes low pasting temperatures will increase starch degradation, which may support film formation in snacks, enhance expansion, and produce a softer texture. Additionally, sorghum's high starch content is expected to improve expansion compared to IWG, whose lower starch content may limit its expansion capacity. Blends of IWG and sorghum, IWG and corn, or corn and sorghum in a 50/50 ratio, are expected to balance sustainable ingredients with desired textural properties, potentially mitigating the expansion limitations associated with IWG. Furthermore, higher specific mechanical energy (SME) is anticipated to reduce hardness in extrudates, contributing to an improved texture.

The primary objectives of this study are to evaluate the expansion and textural characteristics of expanded snacks made using corn, sorghum, IWG, and combinations of these grains. By looking at factors such as bulk density, expansion ratio, and hardness, this research aims to identify effective formulations that use these alternative grain-based snacks' functional and sensory properties.

3.2 Materials & Methods

3.2.1 Ingredients & Formulation

3.2.1.1 Raw Materials

Whole corn flour and degermed corn flour was obtained from Bunge (St. Louis, MO), IWG flour was obtained from Sustain-a-Grain (McPherson, KS), and Sorghum flour was obtained from Nu-Life Market (Scott City, KS). Proximate analysis on protein content, starch content, and total dietary fiber of each flour was done at Midwest Labs (Omaha, NE). Protein analysis followed MWL FO 014, based on AOAC 992.15, USDA/FSIS CLG-PRO04.04, and ISO 14891:2002 (E), IDF 185:2002 (E), where a homogenous sample was combusted in a nitrogen analyzer, and nitrogen gas was measured to calculate protein content. Starch analysis

followed WC 047, based on AOAC 996.11 and YSI Application Note 319, using enzymatic hydrolysis with alpha amylase and amyloglucosidase to convert starch to glucose, quantified using a glucometer. Total dietary fiber analysis followed MWL FO 027, based on AOAC 991.43, involving defatting, de-sugaring, enzymatic digestion, alcohol precipitation, and residue filtration to determine fiber content.

3.2.1.2 Experimental Design

Seven formulations of flour for expanded snacks were developed, exclusively variating the flour with no other added ingredients. Table 3-1 shows the composition of each treatment.

3.2.2 Raw Material Analysis

3.2.2.1 Moisture

The moisture content of the raw materials prior to extrusion and extrudates were dried for 2 hours at 135 °C according to AACC Method 44-19.01 (AACC, 2009). Extruded products were ground prior to moisture determination.

3.2.2.2 Rapid Visco Analysis

The pasting properties of each raw material and ground product were evaluated using a Rapid Visco Analyzer (RVA) (RVA 4, Newport Scientific Pvt. Ltd., Warriewood, NSW, Australia) and methodology from Webb et al (2023) For the analysis, 3.5 g of sample was mixed with 25.0 ml of water. The pasting characteristics, including peak viscosity (PV), pasting temperature (PT), peak viscosity (PV), and final viscosity (FV) were measured. The RVA profile followed a standard protocol, beginning with the sample held at 50°C for 1 minute. The temperature was then increased to 95°C at a rate of 12.2°C/min, maintained for 2.5 minutes, followed by cooling to 50°C at a rate of 11.8°C/min and held for 2 minutes. Viscosity was

recorded in centipoise (cP) units. All tests were conducted in duplicate for both raw material and extruded products.

3.2.2.3 Differential Scanning Calorimetry (DSC)

To understand the physicochemical transformation known as starch gelatinization, calorimetric measurements were conducted on raw material blends and extruded products using methodology from Webb et al (2023). Samples (8-10 mg) were placed in stainless steel DSC pans with a 1:2 solid-to-water ratio and sealed. After overnight equilibration, the Q100 Differential Scanning Calorimeter (TA Instruments, New Castle, DE) was used, following a program involving heating from 10°C to 140°C at 10°C/min. Transition temperatures (onset, peak, endpoint) and enthalpy (ΔH) were analyzed using TA Instruments Universal Analysis Software (version 5.4.0). Enthalpy values were adjusted based on the starch content percentage of each sample to accurately reflect the contribution of starch to gelatinization. Duplicate measurements were performed for all reported data.

3.2.2.4 Phase Transition Analysis

Phase Transition analysis of the samples were analyzed on a Phase Transition Analyzer (PTA™, Wenger Mfg., Sabetha, KS), to determine the softening and flow temperatures (Ts and Tf, respectively). A small amount of raw material (1.5-2.5 g) was hydrated to a target moisture of 18%. The material was compressed in a test chamber at 100 bars of pressure and subject to heating at a constant rate of 10°C/min from 7°C until 120°C or higher until the material starts to flow out of a capillary at the bottom of the chamber (Karkle et al., 2012). The flow temperature (Tf) is an indirect measure of resistance to flow or viscosity (Webb et al., 2023).

3.2.3 Extrusion Process

3.2.3.1 Extrusion Parameters

Raw materials were extruded using a pilot-scale TX-52 twin-screw extruder (Wenger Manufacturing, Sabetha, KS) equipped with a differential diameter cylinder preconditioner (DDC2, Wenger Manufacturing Inc., Sabetha, KS), with a screw diameter of 52 mm and 5 independent zones with an L/D ratio of 25.5:1. The screw profile can be seen in Figure 3-1. The barrel temperatures were 40°C in zone-1, 60°C in zone-2, 80°C in zone-3, 110°C in zone-4, and 130°C in zone-5. The loss-in-weight single screw feeder was adjusted to feed 55 kg per hour into the preconditioner. Water was injected into the extruder barrel at a rate of 2.5 to 3.7 kg/h to maintain appropriate moisture levels in the material. The extruder screw speed was set to 450 RPM. Thermocouples mounted at each zone of the extruder barrel recorded the respective (set and actual) zone temperatures from the control panel. The die temperature and pressure were also recorded using a thermocouple and pressure gauge, respectively. The die used was a 4.12 mm circular die. A rotating knife assembly with 6 hard knives was used to cut the extrudates, operating at a speed of 602 RPM. The extrudates were pneumatically conveyed to a Wenger Double Pass Dryer/Cooler (Series 4800, Wenger Manufacturing Inc., Sabetha, KS), which operated at 220°F. The retention time in the dryer was 8 minutes on the top belt and 6.5 minutes on the bottom belt, followed by 3 minutes of cooling using room temperature air on the cooling belt.

3.2.3.2 Specific Mechanical Energy

The specific mechanical energy (SME) was read out by a wattmeter in kilowatts and converted to kJ/kg using the equation:

$$\frac{W - W_0}{m/3600} \qquad \textbf{3-1}$$

Where W is the wattmeter reading in kW, Wo is the wattmeter reading at no load, and m is the feed rate.

3.2.4 Extrudate Analysis

3.2.4.1 Product Dimensions

For each treatment, 10 extrudates were measured and length (l), diameter (de), and mass (m) were used to calculate piece density (PD), section expansion index (SEI), and specific length (SL). For commercial samples, 2 replicates were recorded in batches of 10 pieces each. Equations are shown below.

$$PD\ (g/cm^3) = \frac{m}{\pi(\frac{d}{2})^2 l} \quad \textbf{3-2}$$

$$SEI = \frac{{d_e}^2}{{d_d}^2} \quad \textbf{3-3}$$

$$SL\ (cm/g) = \frac{l}{m} \quad \textbf{3-4}$$

3.2.4.2 Texture Analysis

Mechanical properties of the extrudates were evaluated using a texture analyzer (TA-XT2) and Texture Exponent software (Stable Micro Systems, United Kingdom). Twenty pieces from each treatment were tested at room temperature. A compression test was performed using a 38 mm compression plate to compress the samples to 80% of their original diameter and measure hardness, expressed as the force required to compress the extrudates. Hardness values were recorded in kilograms of force (Karkle, Keller, et al., 2012). The same methods were used for commercial samples

3.2.5 Statistical Analysis

All data were analyzed using SAS software (SAS Institute Inc., Cary, NC). One-way analysis of variance (ANOVA) was employed to determine significant differences among sample means. Post-hoc comparisons were conducted using Tukey's Honest Significant Difference (HSD) test to evaluate pairwise differences. A significance level of $p < 0.05$ was used for all statistical tests.

3.3 Results & Discussion

3.3.1 Raw Material Analysis

3.3.1.1 Rapid Visco Analysis

The pasting properties of the raw materials (Table 3-4 and Figure 3-2) provide insight into the starch content and gelatinization behavior of the grains used in the extruded snacks. IWG had the highest pasting temperature at 95°C, followed by sorghum at 92°C and corn at 83°C. Degermed corn flour (DGCF), which contained the highest starch content (78.5%, Table 3-2), showed the lowest pasting temperature among the raw materials. This suggests that IWG requires more thermal energy for the starch granules to swell and rupture (Rahardjo et al., 2018).

In terms of peak viscosity, the degermed corn flour (DGCF) exhibited the highest peak and final viscosities (3911 cP and 6597 cP, respectively), , aligning with its high starch content and lower protein and fiber levels. Sorghum also displayed higher peak and final viscosities (1496 cP and 2420 cP), compared to IWG, which had the lowest values (525 cP and 1201 cP). These differences highlight the role of starch in influencing viscosity and pasting behavior. The combination of sorghum and IWG (SG) had a slightly higher peak viscosity (1007 cP) compared to the corn and IWG blend (CG), indicating a more synergistic interaction between sorghum and IWG starches (Rooney & Pflugfelder, 1986a). .

These results demonstrate how starch content influences pasting properties, with higher starch levels in DGCF and sorghum correlating with increased viscosity (Liu et al., 2019). IWG's lower starch and higher protein and fiber contents reduced viscosity, potentially limiting its ability to contribute to thickening in formulations. While pasting temperature differences highlight material-specific behaviors, they may not directly reflect processing conditions during extrusion (Liu et al., 2019).

3.3.1.2 Differential Scanning Calorimetry

The Differential Scanning Calorimetry (DSC) results in Table 3-6 provide insight into how the starches from the different grains and their blends behave when heated. The onset and gelatinization temperatures are key factors that help us understand how each grain's starch reacts to heat, which can affect the processing and texture of the snacks.

For instance, sorghum had a gelatinization temperature of 75.27 °C, which is a bit lower than corn at 76.36 °C but higher than IWG at 65.99 °C. This lower temperature for IWG means it can start to gelatinize earlier, potentially making processing easier and quicker during extrusion. This characteristic could lead to different textures in snacks made with IWG.

When we look at the blends, like corn/Intermediate Wheatgrass (CG) and sorghum/Intermediate Wheatgrass (SG), their thermal properties show interesting results. The CG blend had a gelatinization temperature of 77.005 °C, while SG was lower at 71.37 °C. This suggests that mixing IWG into these blends lowers the temperature at which the starches gelatinize, making the blends more efficient to process (Ma et al., 2017).

Sorghum and corn had higher enthalpy (3.99 J/g and 4.75 J/g, respectively), indicating that their starches are more stable and organized. In contrast, IWG's lower enthalpy (3.24 J/g) suggests its starches might be less organized, which could affect the texture of the final products.

Linking these DSC results to the RVA findings reveals more connections. Sorghum had a higher peak viscosity of 1496 cP compared to IWG at 525 cP. This matches with sorghum's higher gelatinization temperature and enthalpy, indicating that its starch structure holds together better, contributing to a firmer texture in the final snack. On the other hand, while corn had a peak viscosity of 1149 cP, its higher gelatinization temperature means it takes more energy to reach those textural properties (Ma et al., 2017). This could impact how efficiently we can process it during extrusion.

Overall, these DSC results give us a clearer picture of how different starches and their blends interact when heated, affecting the processing and quality of extruded snacks. Understanding these temperature relationships is important for selecting the right grains and optimizing the blends for the textures we want in our snacks.

3.3.1.3 Phase Transition Analysis

The flow point data highlights differences in the thermal behavior of the raw materials, reflecting variations in their starch composition and structure. IWG exhibited the highest flow point (181°C), suggesting its starch requires more thermal energy to soften. This aligns with the higher pasting temperature observed in the RVA analysis. This indicates a more resistant starch structure that could influence extrusion efficiency (Liu et al., 2019).

Sorghum (177°C) and DGCF (170°C) had slightly lower flow points than IWG, which could reflect their higher starch content and differing levels of starch organization. These intermediate values may explain their relatively higher viscosities and gelatinization behavior in the RVA data than IWG. Corn, with the lowest flow point (144°C), demonstrated the least thermal resistance, consistent with its low pasting temperature and tendency for rapid gelatinization during heating.

The relationship between flow point and pasting behavior reinforces the role of starch properties in determining thermal and processing characteristics, which can influence extrusion performance and product texture (Webb et al., 2023).

3.3.2 Extrusion Processing

3.3.2.1 Specific Mechanical Energy

Specific mechanical energy (SME) is important for understanding the energy efficiency of the extrusion process, reflecting the energy needed to transform raw materials into extrudates, as shown in Figure 3-4. The SME data indicates that IWG and DGCF required the highest SME at 425 kJ/kg, while corn had the lowest at 353 kJ/kg. This difference is related to the starch content and pasting properties of the materials, as discussed in the RVA analysis. Higher SME values for IWG and DGCF suggest that more energy was needed for expansion and viscosity, likely due to their higher fiber content, which can hinder starch gelatinization (Masli et al., 2018).

Conversely, the lower SME for corn aligns with its favorable pasting characteristics, which support efficient extrusion with less energy. Blending corn with IWG or sorghum resulted in mid-range SME values (CG: 347 kJ/kg; SG: 373 kJ/kg; CS: 406 kJ/kg), indicating the influence of the ingredients' properties.

Flow temperature and SME were strongly correlated, with higher flow temperatures corresponding to increased SME requirements, as demonstrated in Figure 3-6. IWG and DGCF, which had the highest flow points (181.6°C and 170.4°C), also exhibited the highest SME values (422 kJ/kg), indicating their greater energy demands during extrusion. This relationship is likely influenced by factors such as starch resistance and fiber content, which can hinder gelatinization and require more energy for processing (Masli et al., 2018). In contrast, corn, with the lowest

flow point (144.3°C), had the lowest SME (353 kJ/kg), reflecting its lower resistance to thermal and mechanical disruption. These findings demonstrate that raw material thermal properties directly impact energy inputs during extrusion, linking flow behavior with mechanical processing energy.

However, SME did not strongly correlate with expansion in the samples. The correlation between SME and piece density was low (r = 0.1685), as shown in Figure 3-8, while the correlation between SME and the specific expansion index (SEI) was moderate (r = 0.3997), illustrated in Figure 3-11. For example, despite IWG having the highest SME, it did not yield the expected levels of expansion. This suggests that expansion in these blends depends more on the film-forming abilities of the starches rather than just the mechanical energy input (Aussanasuwannakul et al., 2022).

The low pasting temperatures for IWG (92°C) and sorghum (95°C) support this idea, indicating limited starch swelling during extrusion. As a result, the starches may form denser films that trap less air, leading to harder products (Aussanasuwannakul et al., 2022). For instance, blends like CG and SG had moderate SME values but only achieved intermediate expansion, reinforcing that starch film formation is crucial for expansion.

These findings show that while SME relates to the physical properties of the extrudates, it also highlights the link between raw material composition, energy input, and product characteristics (Gu et al., 2021). While SME typically correlates with product expansion, this study indicates that the relationship between starch properties and processing conditions is complex and requires further investigation.

3.3.3 Extrudate Analysis

3.3.3.1 Viscosity of Extrudates

The pasting properties of the extruded samples (Table 3-5, Figure 3-3) differed from their raw material counterparts. All extrudates recorded a pasting temperature of 50°C, the starting point of the test, due to the extensive starch modification that occurs during extrusion. This uniformity indicates that starch granules were largely gelatinized and structurally damaged during extrusion, consistent with findings from prior studies (Espinosa-Ramírez et al., 2021).

Peak viscosities were much lower in the extrudates compared to the raw materials, as expected from extrusion-induced starch breakdown (Ozcan & Jackson, 2005). DGCF retained the highest peak viscosity (532 cP), though this was greatly reduced from its raw material value. Sorghum extrudates followed with a peak viscosity of 322 cP, higher than IWG (242 cP) and whole corn (151 cP). Final viscosities showed a similar trend, reflecting significant structural changes in starch caused by the high shear and heat of extrusion. These observations align with prior studies, which reported substantial reductions in peak and final viscosities in extruded starches due to the loss of granular integrity and molecular rearrangement during processing (Ozcan & Jackson, 2005) The reduced viscosity of extrudates is linked to their expansion properties. DGCF and sorghum, which had higher starch contents and viscosities, demonstrated better expansion and more porous structures. In contrast, IWG, with its lower starch content, exhibited limited expansion, resulting in denser and harder extrudates. The blends provided additional insights, with SG achieving higher viscosities and potentially better expansion than CG, suggesting that sorghum and IWG complement each other in extruded formulations. These findings confirm that extrusion alters the pasting properties of the materials, reducing their ability to form viscous gels. However, the changes support desired functional outcomes, such as improved expansion and textural properties in snacks, particularly for high-starch materials like DGCF and sorghum (Muñoz-Pabon et al., 2022).

3.3.3.2 Bulk Density & Expansion Ratio

Understanding the relationship between expansion and density (both bulk and piece densities) is crucial for analyzing how starch content and pasting properties of raw materials influence the final extrudates. As illustrated in Figure 3-7, higher expansion ratios are generally linked to lower densities, confirming the inverse relationship between these properties during extrusion. This connection is closely associated with starch content and its gelatinization potential, as reflected in the RVA data.

A clear inverse relationship exists between bulk density and expansion ratio across all samples. The off-dryer (OD) bulk densities ranged from 56 g/L for DGCF, which exhibited the highest expansion ratio, to 173 g/L for IWG, which showed limited expansion. For instance, corn extrudates had a moderate peak viscosity of 1149 cP and a final viscosity of 2310 cP, resulting in an expansion ratio of 3.23 and a low OE bulk density of 94 g/L. In contrast, IWG, with its low peak viscosity of 525 cP and restricted starch gelatinization, demonstrated less expansion (2.37) and a higher OE bulk density of 173 g/L. This indicates that the ability of starch to swell and gelatinize during extrusion is critical for achieving greater expansion, which in turn reduces bulk density (Hussain et al., 2022).

Similar trends were observed in blended samples. The CG and SG blends exhibited intermediate expansion ratios and bulk densities, with OE values of 157 g/L and 146 g/L, respectively. Their OD values were also moderate at 158 g/L and 152 g/L. The higher starch content from corn likely contributed to more expansion; however, the addition of IWG or sorghum moderated the extent of swelling and overall expansion (Espinosa-Ramírez et al., 2021). Thus, the bulk density data—both OE and OD—emphasize how starch behavior during processing directly impacts expansion and the final characteristics of extruded snacks.

3.3.3.3 Piece Density & Sectional Expansion Ratio

Piece density, as illustrated in Figure 3-6, also displays an inverse relationship with the sectional expansion index (SEI), reflecting the findings for bulk density and further showing the importance of expansion. DGCF extrudates had the highest SEI (19.00) and the lowest piece density (0.08 g/cm³), which aligns with the greater starch gelatinization observed in the RVA. This gelatinization facilitates more air incorporation, leading to enhanced expansion. Conversely, IWG extrudates exhibited the highest piece density (0.28 g/cm³) and the lowest SEI (5.80), demonstrating how limited expansion correlates with more compact structures due to insufficient starch properties (Hussain et al., 2022). For comparison, the commercial Cheetos product had a piece density of 0.16 g/cm³, highlighting how DGCF extrudates achieved greater expansion than the commercial product, while IWG extrudates were denser and less expanded.

3.3.3.4 Specific Length

Specific length, a measure of longitudinal expansion, is illustrated in Figure 3-8 and follows similar trends. DGCF extrudates, which expanded the most volumetrically, had a specific length of 5.17 cm/g, indicating significant expansion in both longitudinal and radial directions (Karkle et al., 2012). In contrast, IWG extrudates had a much lower specific length of 4.68 cm/g, consistent with their limited overall expansion. This reduced expansion can be attributed to the lower capacity of IWG flour for starch swelling and gelatinization during extrusion. For context, the commercial Cheetos product had a specific length of 3.13 cm/g, reflecting a more compact longitudinal structure compared to the experimental extrudates.

3.3.3.5 Hardness

Hardness is a key indicator of the texture of extrudates, influencing consumer perception and product quality (shown in Figure 3-13). The average hardness values reveal that IWG

extrudates exhibited the highest hardness at 22.95 kg of force, closely followed by the SG extrudates at 22.45 kg of force. This increased hardness can be connected to the lower starch content and structural integrity provided by IWG flour (Rahardjo et al., 2018). The correlation graph (Figure 3-14) between hardness and piece density demonstrates a positive relationship, indicating that as piece density increases, hardness tends to rise as well (Agbisit et al., 2007). This suggests that denser extrudates, such as those made with IWG, exhibit greater hardness compared to lighter, less dense samples, highlighting the influence of density on texture in extruded products.

Conversely, corn and sorghum produced softer extrudates, with hardness values of 15.54 kg and 12.96 kg, respectively. This observation aligns with the peak viscosity data, which indicates that these flours gelatinize more readily during extrusion, resulting in lighter and less dense products (Alavi et al., 2019; Hussain et al., 2022). The blends containing corn, such as CG and CS, demonstrated similar hardness levels, suggesting that incorporating IWG or sorghum does not substantially alter the texture when combined with corn. Commercial “Cheetos Puffy” products had a harness of 15.87, higher than the sorghum and corn products in this study.

The hardness measurements highlight the relationship between raw material selection and processing methods, emphasizing their impact on the final texture of the extrudates (Muñoz-Pabon et al., 2022). Understanding these dynamics is important for assessing product quality and consumer preferences.

3.3.3.6 Correlations Between Properties

The correlations among SME, pasting temperature, expansion, and density provide insights into the relationships between starch properties and extrudate characteristics. There is a strong positive correlation between pasting temperature and expansion ($r = 0.9289$, Figure 3-10),

indicating that higher pasting temperatures lead to greater expansion. A similar correlation exists between pasting temperature and piece density ($r = 0.8016$, Figure 3-7), suggesting that increased temperatures may result in denser extrudates.

The correlation between SME and expansion is weaker ($r = 0.3997$, Figure 3-11), indicating that while SME affects expansion, it is not the only factor. Additionally, SME and piece density have a minimal correlation ($r = 0.1685$, Figure 3-8), showing that SME does not significantly influence piece density. These correlations highlight the complex interactions among the properties of the raw materials during extrusion.

3.4 Conclusion

This study examined the pasting properties, thermal behavior, and extrudate characteristics of corn, sorghum, and IWG as well as their blends, to understand how raw material composition and processing conditions influence the texture and expansion of extruded snacks. The results supported several hypotheses while also revealing complexities in the relationships between starch properties, extrusion conditions, and final product quality.

IWG exhibited the highest pasting temperature and lowest peak viscosity among the raw materials, consistent with the hypothesis that its starch would require more thermal energy for gelatinization. However, the DSC analysis showed that IWG's gelatinization temperature was lower than corn and sorghum, indicating that pasting temperature does not always align with gelatinization temperature. IWG's lower enthalpy values supported the hypothesis of less organized starch structures, contributing to its lower viscosity and limited expansion during extrusion.

Post-extrusion, pasting temperatures and viscosities of all materials were significantly reduced, consistent with prior studies showing extrusion-induced starch degradation. As

hypothesized, sorghum's higher starch content enhanced expansion compared to IWG, which demonstrated limited expansion due to its lower starch content and reduced viscosity. Blends of IWG with sorghum or corn improved expansion and texture, confirming the hypothesis that blending could balance sustainability with desirable physical properties.

SME measurements showed that IWG and DGCF required the highest energy input for extrusion, reflecting their starch content and pasting properties. However, SME did not correlate strongly with expansion, contradicting the hypothesis that higher SME would result in softer, more expanded products. Instead, expansion was more dependent on the starch composition and gelatinization behavior of the grains.

The analysis of bulk density, piece density, and expansion ratios reinforced the inverse relationship between density and expansion, aligning with the hypothesis that starch degradation and gelatinization promote expansion. IWG extrudates showed higher density and hardness, confirming its limited expansion potential compared to corn and sorghum.

This study highlights the importance of raw material selection and processing parameters in optimizing extruded snack characteristics. While many hypotheses held true, the results also showed the complex interactions between ingredient composition, starch properties, and extrusion conditions. Further research should explore additional factors such as nutritional quality and consumer acceptance to refine formulations using sustainable grains like IWG and sorghum

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3.6 Figures & Tables

charts and numbers are not working at all with track changes on

Figure 3-1 Extruder Screw Profile

TX-52																				
L	1	1	1	1	1	1	1	1	1	2	3	4	4	3	3	3	5	5	6	7
R	1*	1*	1	1	1	1	1	1	1	2	3	4	4	3	3	3	5	5	6	7

1	Full pitch double flighted 9u uncut forward
1*	Full pitch single flighted uncut forward
2	3/4 pitch double flighted 6u uncut forward
3	3/4 pitch double flighted 9u uncut forward
4	Kneading block reverse, 3u 3 set
5	1/2 pitch double flighted 9u cut forward
6	1/2 pitch double flighted 6u cut forward
7	3/4 pitch screw double flighted cut cone forward

Figure 3-2 Viscosity of Raw Materials Curve

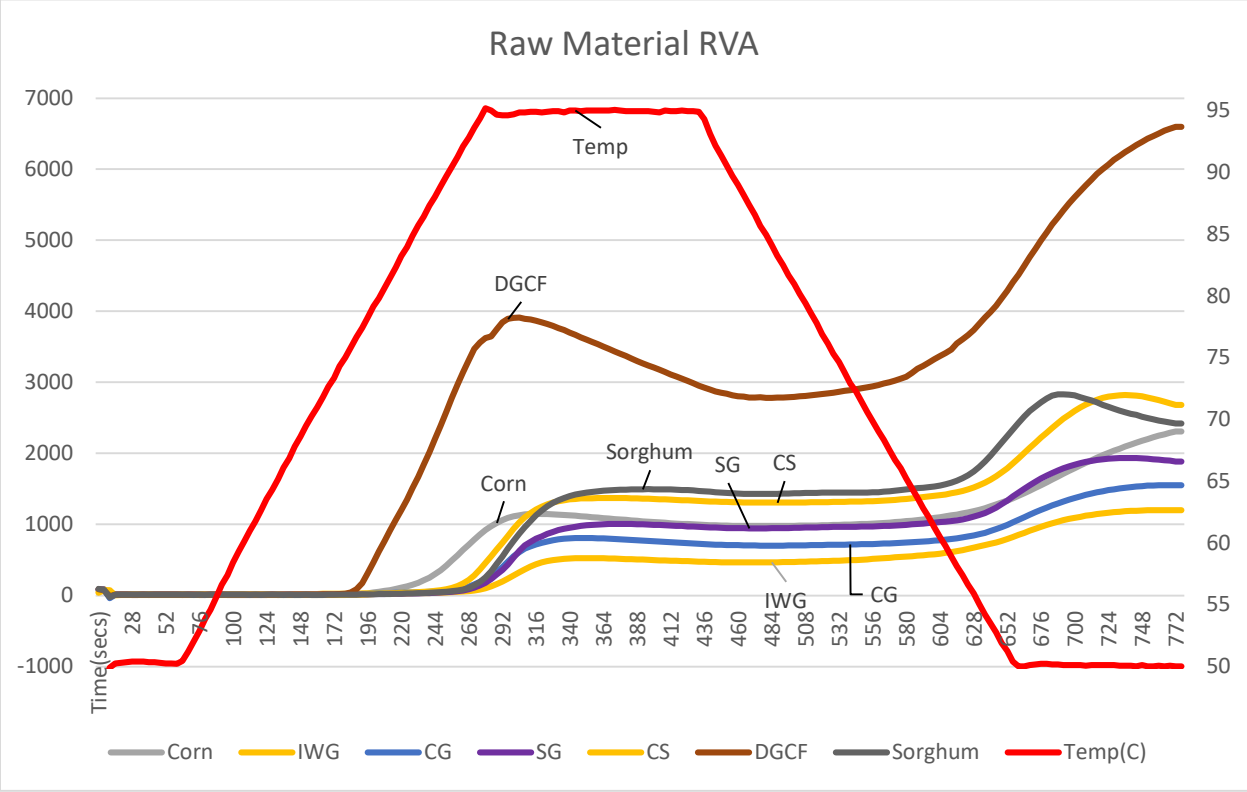

Figure 3-3 Specific Mechanical Energy

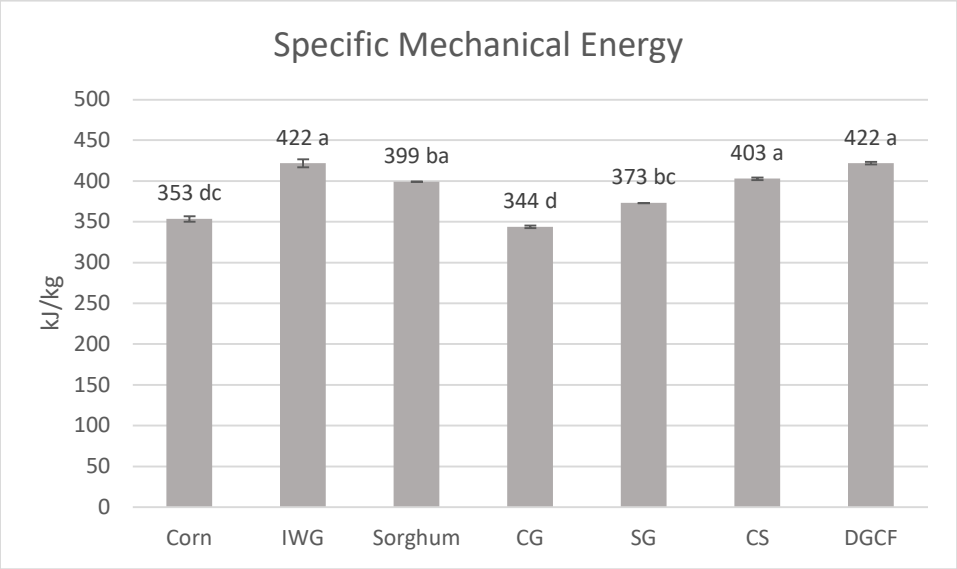

Figure 3-5 Correlation between Flow Point of Raw Material and Specific Mechanical Energy

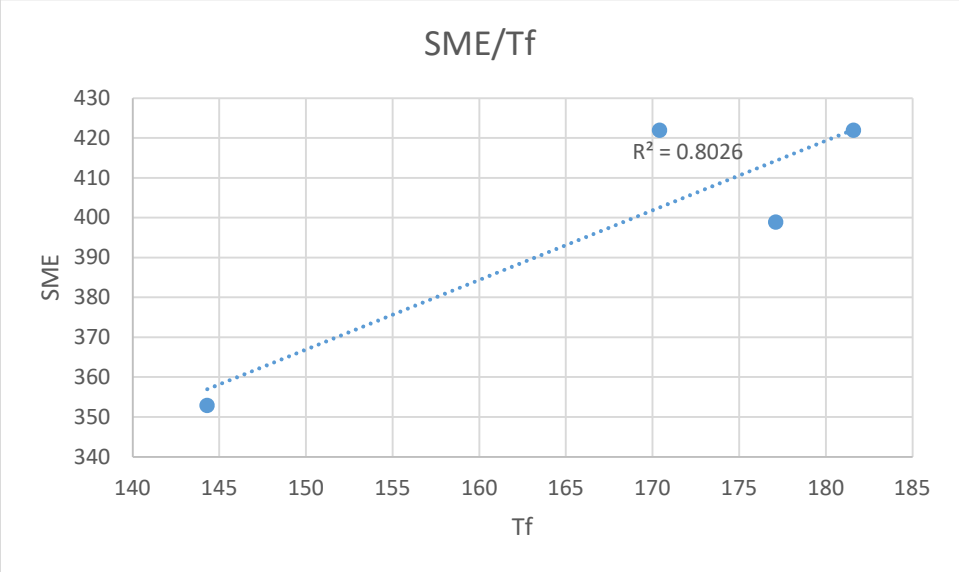

Figure 3-6 Ground Extrudate RVA

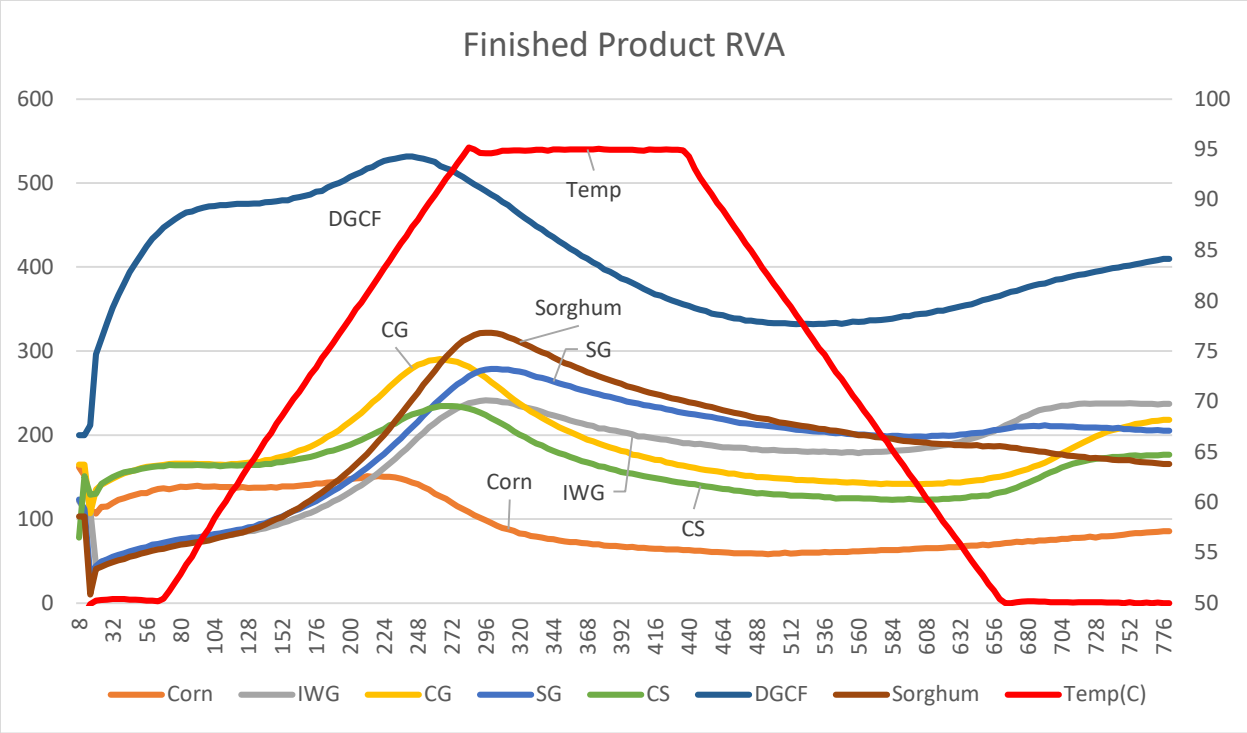

Figure 3-4 Bulk Density of Extrudates off the Extruder and Dryer

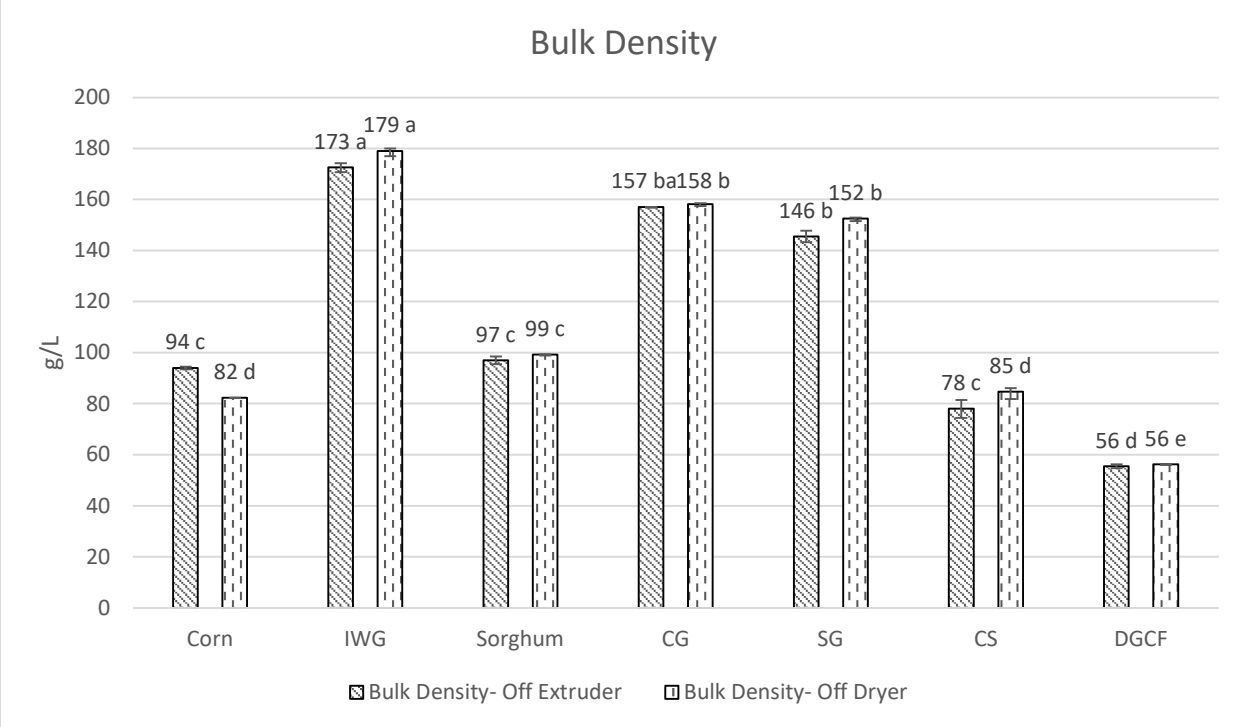

Figure 3-5 Piece Density of Extrudates

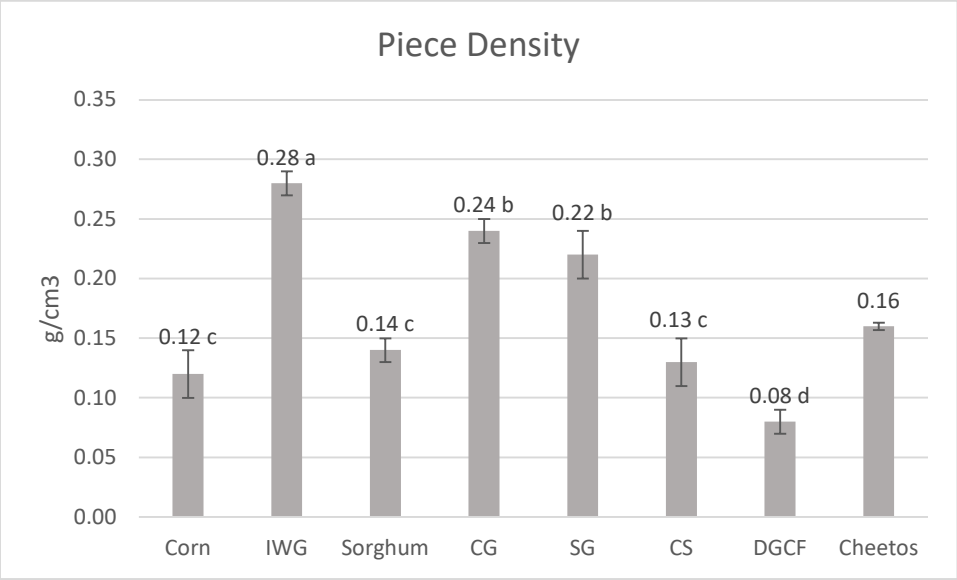

Figure 3-6 Correlation Between the Pasting Temperature of Raw Materials and Piece Density of Extrudates

Figure 3-7 Coorelation Between Pasting Temperature of Raw Materials and Extrudate Piece Density

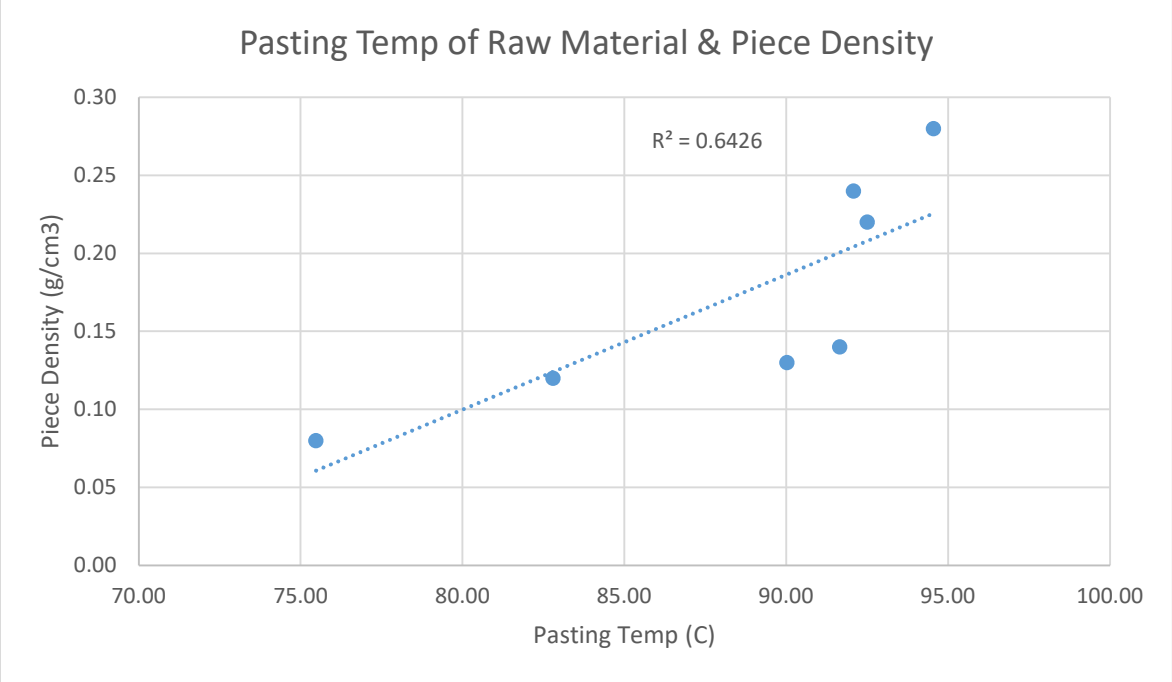

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Figure 3-8 Correlation Between SME and Piece Density

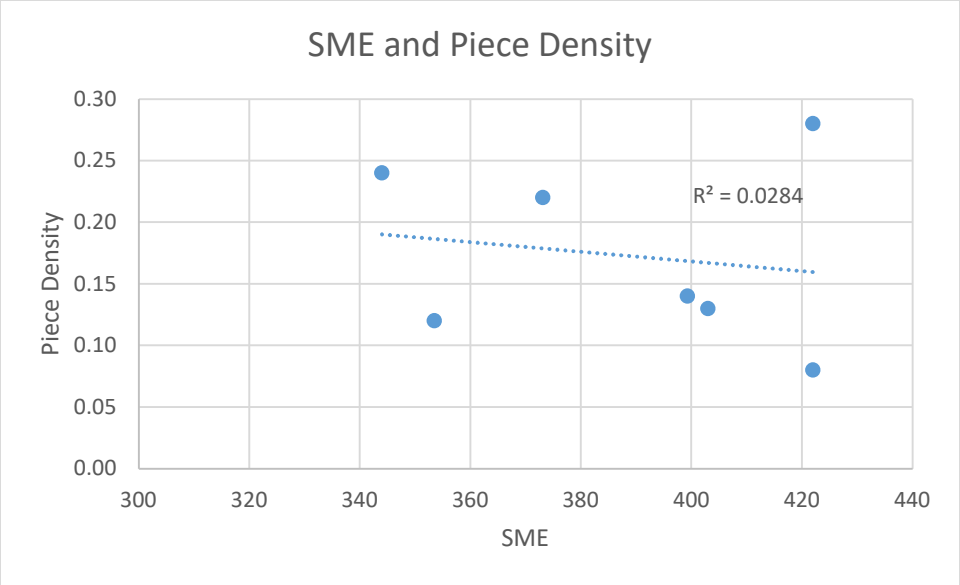

Figure 3-9 Expansion Ratio of Extrudates

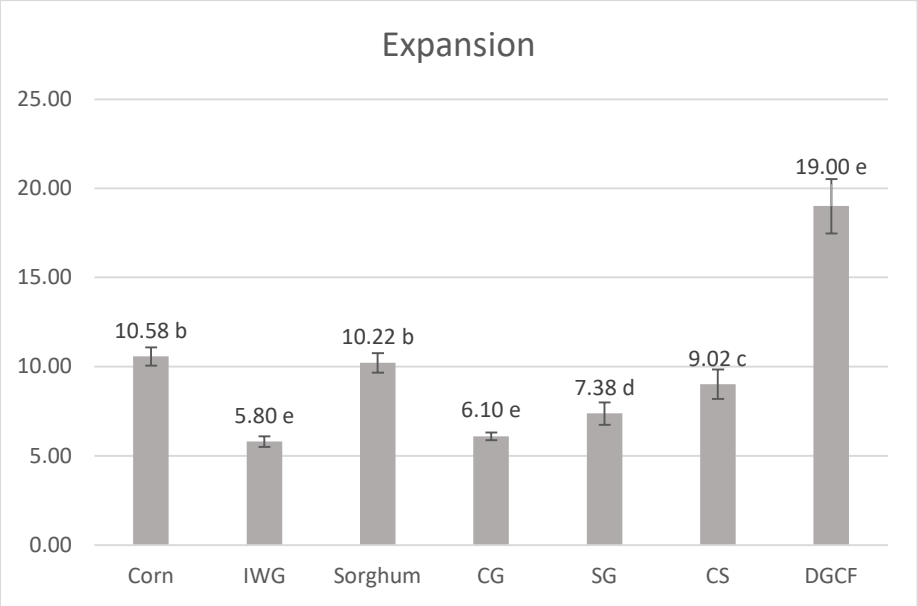

Figure 3-10 Correlation Between the Pasting Temperature of Raw Material and Sectional Expansion of Extrudates

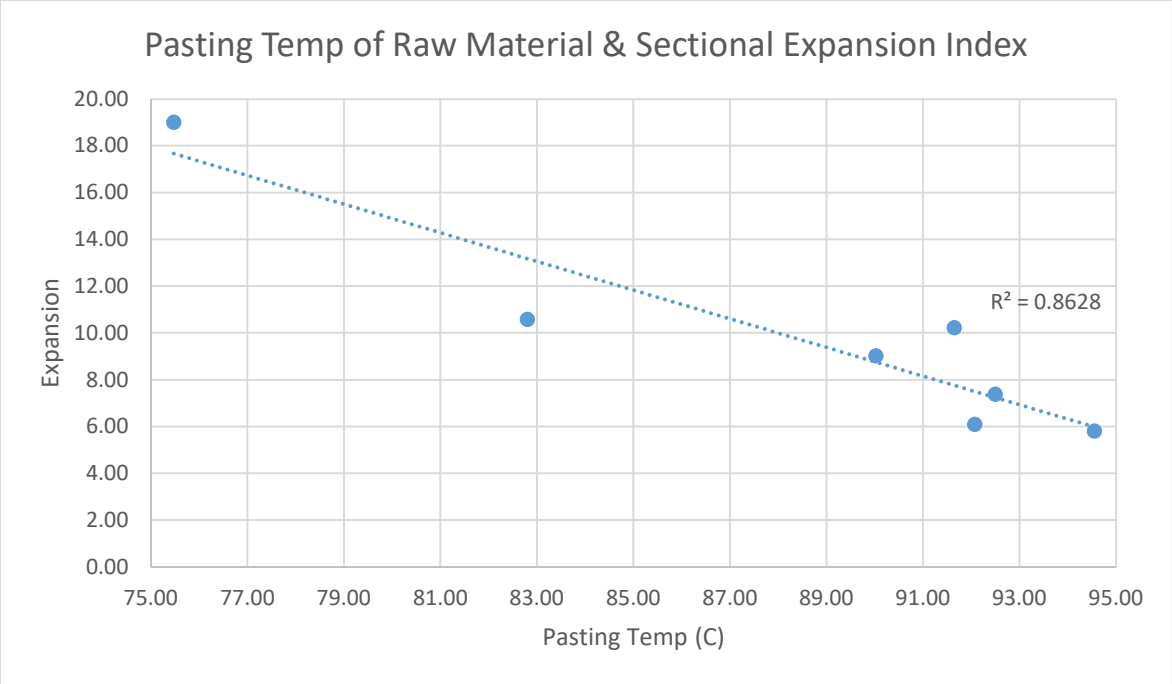

Figure 3-11 Correlation Between SME and Sectional Expansion Index

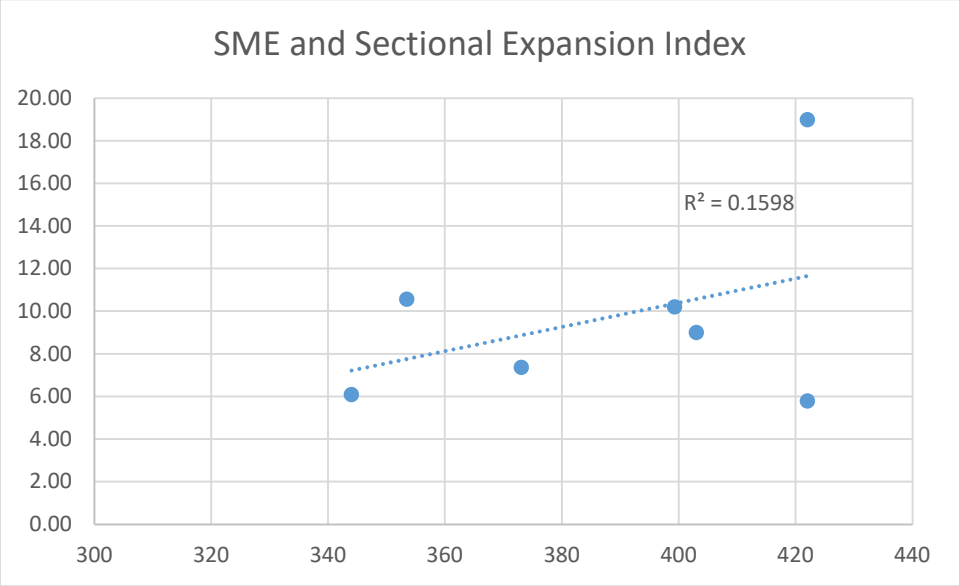

Figure 3-12 Specific Length of Extrudates

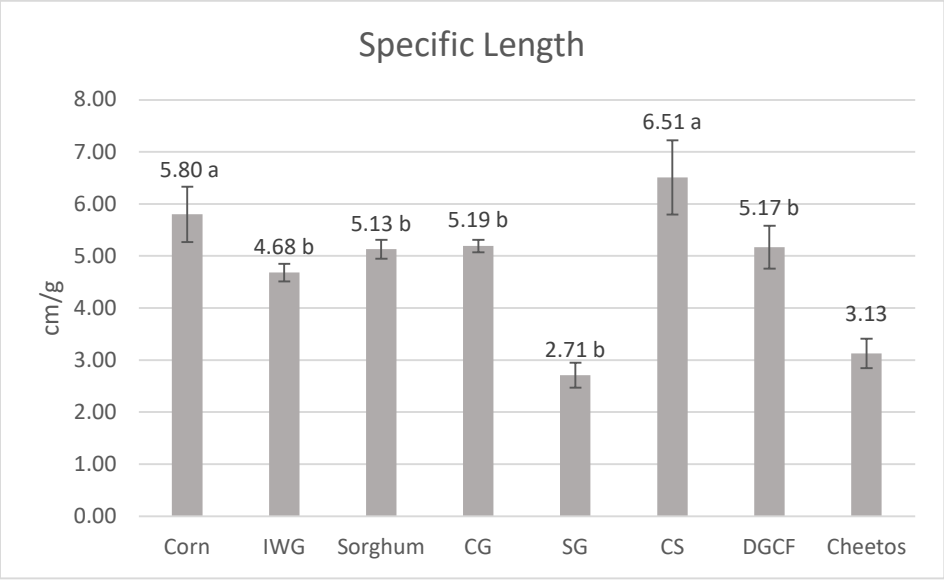

Figure 3-103-13 Hardness of Extrudates

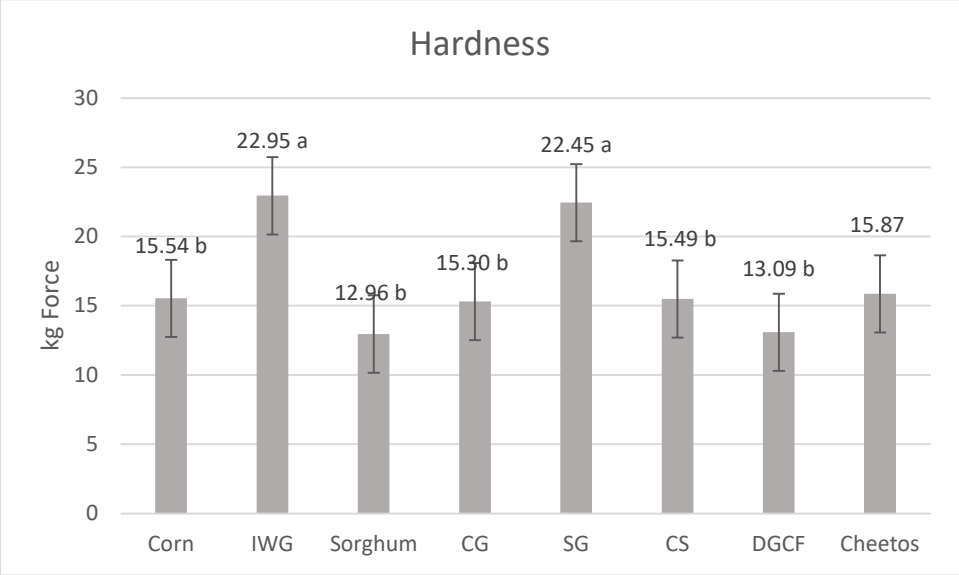

Figure 3-14 Correlation Between Piece Density & Hardness

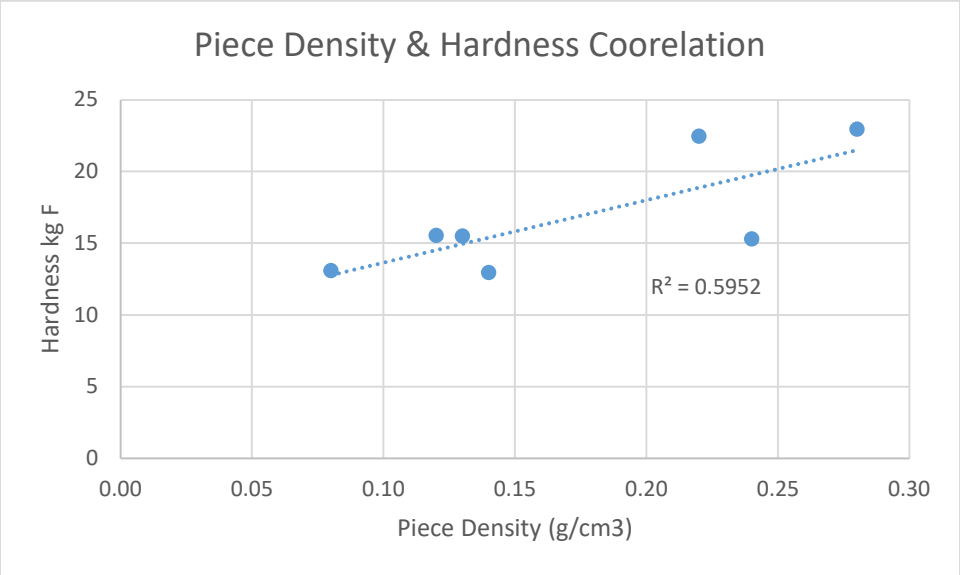

Table 3-1 Formulation Composition

	Corn Flour	IWG Flour	Sorghum Flour	Degermed Corn Flour
Corn (C)	100%			
IWG (G)		100%		
Sorghum (S)			100%	
Corn/IWG (CG)	50%	50%		
Sorghum/IWG (SG)		50%	50%	
Corn/Sorghum (CS)	50%		50%	
Degermed Corn (DGCF)				100%

Table 3-2 Proximate Analysis of Raw Materials

Material	Protein % WB	Total Starch % WB	Total Dietary Fiber % WB	Moisture %
Corn	9.3	58.0	12.5	11.6
IWG	20.3	45.5	17.3	11.9
Sorghum	12.4	61.1	10.0	11.7
CG	-	-	-	11.8
SG	-	-	-	11.8
CS	-	-	-	11.2
DGCF	4.8	78.5	4.4	11.9

Table 3-3 Moisture of Ground Extrudates

Product	Moisture %
Corn	3.8
IWG	3.5
Sorghum	2.1
CG	2.5
SG	2.6
CS	3.0
DGCF	3.1

Table 3-4 Pasting Temperature and Viscosity of Raw Materials

	Pasting Temp (°C)	Std Dev +/-	Peak Viscosity (cP)	Std Dev +/-	Final Viscosity (cP)	Std Dev +/-
Corn	83[c]	1.2	1149[cd]	42.0	2310[c]	22.0
IWG	95[a]	0.0	525[f]	30.0	1201[f]	54.0
Sorghum	92[ba]	0.3	1496[b]	5.5	2420[cb]	58.0
CG	92[ba]	0.0	808[e]	4.0	1553[e]	24.5
SG	93[ba]	0.5	1007[ed]	0.5	1884[d]	21.5
CS	90[b]	0.5	1372[cb]	81.0	2681[b]	98.5
DGCF	75[d]	0.4	3911[a]	45.5	6597[a]	43.5

Table 3-5 Pasting Temperature and Viscosity of Ground Extrudates

	Pasting Temp (°C)	Peak Viscosity (cP)	Std Dev +/-	Final Viscosity (cP)	Std Dev +/-
Corn	50*	151[d]	13.0	86[e]	5.5
IWG	50*	242[c]	12.5	237[b]	11.0

Sorghum	50*	322[b]	3.0	166[d]	2.5
CG	50*	291[b]	4.5	218[b]	2.0
SG	50*	280[cb]	10.5	205[cb]	8.0
CS	50*	235[c]	2.0	177[cd]	3.5
DGCF	50*	532[a]	2.5	410[a]	1.5

*Lowest RVA could read

Table 3-6 Differential Scanning Calorimetry of Raw Materials

	Onset Temp (°C)	**Std Dev +/-**	**Gelatinization Temp (°C)**	**Std Dev +/-**	**Enthalpy (J/g)**	**Std Dev +/-**
Corn	68.77[a]	0.84	76.36[a]	0.16	4.75[ba]	0.79
IWG	58.90[c]	0.26	65.99[b]	0.02	3.24[ba]	0.12
Sorghum	67.55[a]	1.34	75.27[ba]	0.15	3.99[bac]	0.44
CG	60.76[bc]	0.17	77.01[a]	0.59	2.79[bc]	0.90
SG	61.66[bc]	1.14	71.37[ba]	4.38	2.00[c]	0.98
CS	69.47[a]	0.44	76.06[a]	0.02	4.32[ba]	0.18
DGCF	65.29[ba]	1.49	73.37[ba]	0.30	7.58[a]	0.22

Table 3-7 Flow Point of Raw Materials

Grain	**Flow Point (Tf) °C**
Corn	144
Sorghum	177
IWG	181
DGCF	170

Chapter 4 - Evaluating Environmental Impacts of Pasta Production Using Intermediate Wheatgrass (*Thinopyrum intermedium*) and Sorghum in Extruded Precooked Pasta and Expanded Snacks Through LCA

Abstract

This study conducts a life cycle assessment (LCA) of pasta and snack products made with Intermediate Wheatgrass (IWG), wheat, corn, and sorghum to evaluate their environmental focusing on Global Warming Potential (GWP) and the role of carbon sequestration in environmental footprints. Results indicated that, when emissions were attributed solely to the flour, IWG pasta had the highest direct GWP at 0.31 kg CO2 eq/kg, compared to wheat (0.24 kg CO2 eq/kg) and sorghum (0.11 kg CO2 eq/kg). However, after incorporating carbon sequestration, IWG's net GWP significantly improved, reaching -0.50 kg CO2 eq/kg for pasta and -0.52 kg CO2 eq/kg for snacks, further reduced to -0.70 kg CO2 eq/kg and -0.73 kg CO2 eq/kg under physical allocation, respectively. This offset was due to IWG's high soil organic carbon (SOC) sequestration, which reached 41.60 tons C/hectare, transforming it from a high-emission crop into a carbon sink. In contrast, wheat, corn, and sorghum showed net carbon losses. The incorporation of physical allocation for straw also reduced environmental impacts, particularly for IWG formulations. These findings highlight the importance of considering both direct emissions and carbon sequestration potential when evaluating the sustainability of grain-based products. The results demonstrate IWG’s superior environmental profile, offering a more sustainable alternative to conventional grains like wheat and sorghum, with significant

implications for future agricultural and product development strategies aimed at mitigating climate change.

4.1 Introduction

Environmental Challenges of Conventional Grains

Traditional grain cultivation, particularly of wheat, corn, and rice, plays a central role in global food systems but presents significant environmental challenges. These three grains account for approximately 35% of global caloric intake (Ross-Ibarra, 2007), and their production has expanded dramatically over the past several decades due to advancements in agricultural practices. However, the intensification of these systems raises substantial sustainability concerns. In wheat and corn production, frequent soil disturbance caused by annual replanting contributes to soil erosion and decreases carbon sequestration potential. Monoculture systems, common for both crops, rely heavily on synthetic fertilizers, pesticides, and irrigation, which degrade soil health, contaminate water resources, and threaten biodiversity (Soto-Gómez & Pérez-Rodríguez, 2022). The intensive mechanization involved in the cultivation of these grains also increases fossil fuel consumption and greenhouse gas emissions, exacerbating the environmental impact of these staple foods (DeHaan, 2018; Chapman et al., 2022).

Corn production is notorious for its high water demands and pesticide use, placing a strain on water-scarce regions and further impacting ecosystems. Like wheat, corn monoculture depletes soil nutrients and requires significant chemical inputs to maintain yields (Khorramdel et al., 2013). These practices contribute to loss of biodiversity, soil degradation, and increased carbon footprints, highlighting the environmental costs associated with conventional grain production.

Alternative Grains

Alternative grains like IWG and sorghum offer promising solutions to address these environmental concerns. IWG, as a perennial crop, reduces the need for annual replanting, mitigating soil erosion and improving soil health through its deep root system, which enhances carbon sequestration and increases soil organic carbon (SOC) (Tang, 2023). Sorghum, known for its drought tolerance, provides a viable option in water-scarce regions, reducing the strain on water resources (Ruiz-Giralt, 2023). Both grains, when integrated into diversified agricultural systems, have the potential to enhance ecosystem resilience and reduce the environmental impact of grain production.

Carbon Sequestration

Carbon sequestration refers to the process of capturing and storing atmospheric carbon dioxide in soils, plants, and other natural systems (Brandão et al., 2013). In agricultural contexts, perennial crops like IWG are particularly effective at sequestering carbon due to their deep root systems, which allow them to store more carbon in the soil over time compared to annual crops (Tang et al., 2023). This process not only helps mitigate the effects of climate change by reducing the amount of CO2 in the atmosphere but also enhances soil health and long-term productivity (de Oliveira et al., 2020). By incorporating crops that promote carbon sequestration, agricultural systems can potentially offset some of the greenhouse gas emissions associated with crop production, contributing to overall sustainability.

The Role of LCA in Evaluating Grain Cultivation and Food Processing

LCA is an important tool for understanding the environmental impacts of food production, covering everything from raw material extraction to final disposal (Caffery et al., 2014). By analyzing inputs like energy, water, and fertilizers, along with outputs such as emissions and waste, LCA provides a detailed look at sustainability. Studies have shown that

alternative grains like IWG and sorghum offer meaningful environmental advantages over traditional crops like wheat and corn. Law et al. (2020), a study on environmental impacts of IWG using a Farm Energy Analysis tool, highlighted that IWG, as a perennial grain, can reduce carbon footprints due to its deep roots, which improve carbon storage and minimize soil erosion and nutrient runoff. Sorghum, on the other hand, stands out for its drought resistance, making it a strong choice for areas with limited water availability. Recent work by Paolotti (2023) has also shown how incorporating these grains into pasta production can cut energy use and greenhouse gas emissions, further emphasizing their potential to lower the environmental impact of food products.

LCA studies have also been applied to less conventional food sources, showcasing the flexibility of the method. For instance, Ulmer et al. (2020) looked at the use of honeybee drone brood as a protein source in Germany. While not directly connected to grains, it demonstrates the range of LCA applications in evaluating new and traditional food systems. The findings from Ulmer et al. (2020) highlight how the environmental impact of novel protein sources, such as insect-based foods, can be assessed and compared to conventional food systems. By integrating various environmental impact categories like resource use, energy consumption, and land use, this research offers valuable insights into the potential sustainability of alternative protein sources, which can be useful in shaping future food production systems. Roy et al. (2009) further demonstrated how LCA can guide the transition toward more sustainable agriculture by evaluating the environmental benefits of alternative crops. Their study emphasizes the resource efficiency of crops like legumes and other non-cereal plants, which often require fewer inputs such as water, fertilizers, and pesticides, compared to conventional crops like wheat. These benefits are significant when considering the ecological strain imposed by industrial agriculture,

especially in terms of land use and greenhouse gas emissions. Roy et al. (2009) show that LCA can be a powerful tool in identifying the potential of alternative crops to reduce environmental footprints while promoting biodiversity and ecosystem health.

Extrusion Processing in Food Production

Extrusion cooking is a key processing method for both the precooked pasta and expanded snack products evaluated in this study. This high-temperature, short-duration process offers a sustainable approach by reducing energy consumption and minimizing water usage during cooking. Unlike traditional low-shear extrusion for pasta, which typically uses wheat semolina, extrusion cooking results in precooked pasta that requires minimal home preparation time. This not only improves consumer convenience but also contributes to reduced energy use during the cooking phase (Wójtowicz et al., 2020; Vignola et al., 2018).

Innovative Aspects of Precooked Pasta

Precooked pasta represents an alternative from traditional pasta, undergoing extrusion cooking, a method that fully cooks the product during processing. This process has been shown to reduce the environmental impact by lowering the energy and water required for home cooking, addressing both product sustainability and consumer convenience concerns (Wójtowicz et al., 2020). For example, extrusion processes have been found to cut down on the need for boiling water during preparation and shorten cooking times, reducing household energy use. This is a key sustainability advantage of using extruded products that only require minimal rehydration or heating at home, potentially reducing energy use by up to 35% (Wójtowicz & Mościcki, 2009).

Paolotti et al. (2023) assessed the environmental impacts of traditional pasta production, focusing primarily on resource use such as water and energy. Their LCA highlighted significant

contributions from the production and processing stages, suggesting areas where efficiencies could be achieved, particularly in terms of water and energy consumption. Although this study did not explore alternative grains, it indicates that shifts toward more resource-efficient crops could help mitigate some of the environmental impacts associated with conventional pasta production.

Bevilacqua et al. (2007) found that land use and fossil fuel consumption were the most significant environmental impacts in the life cycle of durum wheat pasta. Their analysis indicated that wheat cultivation and semolina production were major contributors, with land use accounting for 80% of the environmental burden. This suggests that crops with lower resource demands, such as IWG and sorghum, might offer an opportunity for reducing land use and fossil fuel consumption in pasta production. Based on these findings, the hypothesis for this study is that IWG and sorghum could result in a reduced environmental footprint compared to conventional wheat pasta, especially in the categories of land use and fossil fuel consumption.

Expanded Snack

The extruded expanded snack product in this study traditionally uses corn as a base, which is known for its favorable expansion properties during extrusion cooking. Corn is commonly used in snack production due to its ability to create light, airy textures, making it an industry standard for extruded snacks (Alavi et al., 2019). However, using LCA to evaluate the environmental trade-offs in expanded snack production allows for a better understanding of how grain choice, processing methods, and end-product convenience can align with sustainability objectives. While studies on alternative grains in snack production are limited, LCA methodologies have been applied to other food systems, demonstrating the potential for more sustainable alternatives. For instance, Ulmer et al. (2020) conducted an LCA on the use of

honeybee drone brood as a protein source for snack production in Germany. This research found that drone brood, a by-product of honey production, could serve as a protein-rich ingredient with significantly lower environmental impacts, particularly in land use and fossil fuel depletion, compared to traditional meat sources. The study also highlighted the potential of insect proteins, such as those derived from drone brood, to offer sustainable alternatives to conventional animal-based proteins in snacks. This study, though focused on insect protein, underscores the importance of evaluating the environmental impact of non-traditional ingredients in food production, including snacks. Despite the growing interest in sustainable food ingredients, there is a noticeable gap in LCA studies specifically focused on snacks. Our study aims to fill this gap by analyzing the environmental impacts of using alternative grains like IWG and sorghum in extruded snack production. By applying LCA to snack products, this research seeks to provide a clearer understanding of how different grains and their associated environmental footprints compare to conventional ingredients like corn.

Objective of the Study

The objective of this study was to perform a comparative LCA of precooked pasta and extruded expanded snack, using novel ingredients, IWG and sorghum, as substitutes for conventional grains like wheat and corn. These products were evaluated within the context of improving sustainability, both environmentally and in production efficiency. By comparing the environmental impacts of using IWG and sorghum in place of conventional grains, the study aims to identify the potential sustainability benefits of these alternatives.

The LCA considers the energy consumption and steam use during the processing and extrusion of the grains, considering the entire supply chain from grain cultivation to product

formation. Differences in yield between the crops were also considered, particularly the higher straw output from IWG, which influences input allocation and environmental impacts.

The hypothesis for this LCA study is that IWG will have higher environmental impacts across most categories compared to sorghum, corn, and wheat due to its lower grain yield. However, because IWG requires fewer inputs during cultivation, applying physical allocation to account for its co-products, such as straw, is expected to reduce its overall impacts. Additionally, it is anticipated that IWG's net positive soil carbon, as a result of its perennial growth habit, will offset its GWP, unlike the other grains, which do not contribute to net soil carbon. It is also hypothesized that cooking time of precooked pasta at the consumer's home can have an influence on the overall environmental impact of the final product, as discussed earlier with the study by Wójtowicz et al. (2009) .

4.2 Materials & Methods

4.2.1 Life Cycle Assessment

The LCA methodology was employed to evaluate the environmental impacts of pasta and expanded snack products made using IWG and sorghum as sustainable alternatives to conventional grains like wheat and corn. This methodology adheres to the principles established by the Society of Environmental Toxicology and Chemistry (SETAC) and follows the standardized ISO 14040 and 14044:2006 guidelines.

According to SETAC, LCA is an objective procedure to assess the energy and environmental loads associated with a product or process (Paolotti et al., 2023). This involves identifying energy and materials used throughout the product's life cycle as well as the waste released into the environment. This study accounts for environmental impacts from raw material

cultivation through production and extrusion processes, as well as looking at consumer energy usage from cooking.

The impact categories evaluated in this study include global warming potential (measured in kg CO2 equivalent), eutrophication (in kg N equivalent), acidification (in kg SO2 equivalent), smog formation (in kg O3 equivalent), ozone depletion (in kg CFC-11 equivalent), and freshwater ecotoxicity (measured in CTUeco). All of these impacts are considered midpoint indicators. The assessment was carried out using the TRACI 2.1 impact assessment method. The analyses were performed in openLCA 2.1.0, utilizing the US LCA Commons database for inventory data. Six formulations of pasta including wheat, IWG, and sorghum, as well as 50/50 blends of each grain were modeled.

These impact categories are calculated using characterization factors provided by the TRACI 2.1 method. Characterization factors allow for the aggregation of emissions into a single metric for each category, enabling clearer comparisons between products. Global warming potential (GWP), for example, is expressed in kg CO2 equivalent and reflects the combined impact of various greenhouse gases like CO2, methane (CH4), and nitrous oxide (N2O), which are weighted according to their ability to trap heat in the atmosphere over a 100-year period.

Eutrophication is assessed by quantifying the release of nutrients such as nitrogen and phosphorus into water bodies, measured in kg N equivalent. These emissions can contribute to excessive algae growth and reduced water quality. Acidification, measured in kg SO2 equivalent, accounts for emissions such as sulfur dioxide (SO2) and nitrogen oxides (NOx), which lead to acid rain, soil acidification, and damage to ecosystems.

Smog formation, reported in kg O3 equivalent, reflects the contribution of emissions such as volatile organic compounds (VOCs) and nitrogen oxides (NOx) to ground-level ozone

formation, which impacts air quality. Ozone depletion, measured in kg CFC-11 equivalent, captures the effects of chemicals like chlorofluorocarbons (CFCs) that damage the ozone layer.

Lastly, freshwater ecotoxicity is represented in comparative toxic units for ecosystems (CTUeco), indicating the potential harm that toxic substances may cause to aquatic life. This calculation aggregates various pollutants based on their impact on freshwater ecosystems.

Together, these characterization factors make it possible to quantify and compare the environmental impacts of different products and formulations, simplifying the interpretation of complex life cycle data.

4.2.2 Goal & Scope Definition

4.2.2.1 Functional Unit

The functional unit chosen for this study is 1 kg of product, either pasta or expanded snacks. This allows for the comparability of environmental impacts between products. The functional unit serves as the basis for attributing input and output flows, enabling a consistent evaluation of both IWG and sorghum as sustainable alternatives.

4.2.2.2 System Boundaries

The system boundaries in this LCA focus on the stages of grain cultivation, processing, and product extrusion and is outlined in Figure 4-1. Processes beyond the factory gate, such as packaging and transportation are excluded from the analysis. Capital goods, infrastructure, and downstream processes such as packaging and distribution were not included due to their minimal impact on the overall results. In this LCA, grain milling was excluded from the system boundaries. Although other pasta and food LCAs often include this step, it was assumed to be the same across grains due to a lack of data specific to IWG milling.

Data were primarily sourced from experimental trials and lab data collected during the production phases, while background data were obtained from the US Commons databases well as research from Caffrey et al., 2014; Law et al., 2022; *Life Cycle Assessment Commons*, 2024. The inventory includes inputs such as fertilizers, fuel, steam, and water for the cultivation and extrusion processes. Outputs include the final products (pasta or expanded snacks) as well as steam lost in production and emissions relevant to selected impact categories.

4.2.3 Inventory Analysis- Data Descriptions & Assumptions

This section outlines the main phases of the production process, and the inventory of inputs and outputs associated with each stage from grain cultivation to extrusion processing.

4.2.3.1 Grain Cultivation

The study considers IWG and sorghum as primary grains, with conventional wheat and corn used for baseline comparison. Yields, fertilizer usage, and emissions (such as CO_2 and nitrous oxide) were measured and averaged over multiple production cycles. IWG data was averaged over a 3-year period, representing one planting cycle, as it is a perennial crop with 3–5 harvests per cycle. Its notably higher straw output was included in the assessment. However, if only the first year's higher yields were considered, this could potentially influence the results (Law et al., 2020).. Data for IWG and wheat cultivation came from an environmental impact study by Law et al (2022), sorghum cultivation came from a study by Caffrey et al (2014), and corn data came from the US openLCA Commons Database. These data were chosen due to being conducted in similar climates and cultivated without irrigation.

4.2.3.2 Extrusion & Energy

The extruded expanded snacks and pasta products underwent similar production processes, with variances in steam input and energy consumption due to differences in moisture

content and grain composition. Detailed records of steam use and losses were included, as this was a critical input/output flow of environmental impact. The energy required for processing was tracked, specifically energy and steam used during extrusion. Steam was treated as both an input and an output, given its function in heating and the need to account for steam loss in the production system.

4.2.3.3 Mass-Energy Balance

The mass-energy balance is a critical aspect of understanding the environmental and energy impacts of pasta production, specifically during the extrusion process. The balance includes specific mechanical energy (SME), thermal energy input for steam, and steam loss (Maichel, 2021). These components are essential inputs for energy, heat, and steam in the LCA and were factored into the environmental impact calculations, as shown in Table 4-1.

Specific Mechanical Energy (SME), measured through wattmeter readings, reflects the energy required for the extrusion of each grain formulation (Maichel, 2021). Formulations like the Wheat/Sorghum combination exhibit the highest SME at 262 kJ/kg, while IWG and Wheat/IWG present lower SME values. These variations are important as higher SME correlates to greater energy consumption, impacting energy use in the LCA.

$$SME\ \left(\frac{kJ}{kg}\right) = \frac{Total\ energy\ input\ (kJ/s)}{Mass\ of\ product\ extruded\ (kg/s)}$$

4-1

Steam Loss was recorded to evaluate how efficiently the process retains moisture, which affects energy efficiency (Maichel, 2021). The lowest steam loss was found in IWG at 50.1%, indicating better moisture retention and therefore reduced energy waste. This efficiency reduces the thermal energy needed to maintain optimal conditions, resulting in lower overall energy consumption when optimized.

$$Steam\ Loss\ (\%) = \left(\frac{Rate\ of\ Steam\ Lost\ (kg/s)}{Rate\ of\ Steam\ Input\ (kg/s)}\right) \times 100$$

4-2

Thermal Energy Input for Steam Usage refers to the total energy required to generate the steam used during the extrusion process, not just what is absorbed by the product (Maichel, 2021). This input is crucial because, regardless of absorption efficiency, all the steam energy supplied contributes to the overall energy demand. While Specific Thermal Energy (STE) measures the efficiency of energy transfer during the process—indicating how much energy is used to manage and maintain processing temperatures—total steam energy input better reflects the energy burden. IWG displayed the highest STE at 423 kJ/kg, suggesting a higher energy demand to maintain processing conditions, but the overall steam input is more indicative of energy usage.

$$Thermal\ Energy\ Input\ (kJ) = Steam\ Flow\ Rate\ (kg/s) \times Enthalpy\ of\ Steam\ (kJ/kg) \times Time\ (s)$$

4-3

$$STE\left(\frac{kJ}{kg}\right) = \frac{(Rate\ of\ Steam\ Input\ (kg/s)\ - Rate\ of\ Steam\ Loss\ (kg/s))\ * Enthalpy\ of\ Steam\ (kJ/kg)}{Mass\ flow\ rate\ of\ material\ (kg/s)}$$

4-4

These energy inputs—SME, steam energy input, and steam loss—were factored into the LCA to assess their contribution to the environmental impacts of pasta production. Efficient energy use and lower steam loss, particularly in formulations like IWG, can lead to reduced carbon emissions and environmental impacts during the extrusion phase, a critical component in the overall LCA results.

In the LCA, these energy inputs are modeled as inputs contributing to the environmental burdens of production, including greenhouse gas emissions, energy use, and resource consumption. The energy efficiency of the extrusion process—such as how much energy is retained in the product versus lost to steam—plays a crucial role in determining the overall sustainability of different formulations. For example, lower SME values (as seen in IWG-based formulations) may lead to a reduction in energy usage during extrusion, potentially lowering the carbon footprint. The efficiency of steam generation and distribution in the boiler system is also important. While we make assumptions about the boiler efficiency due to limited data, we know the steam efficiency, which allows us to more accurately assess the thermal energy requirements. The input for "natural gas combusted in boiler" was calculated based on the thermal energy input required for steam generation, which varied depending on the specific pasta formulation. The thermal energy input values were converted to the corresponding natural gas volume using an assumed boiler efficiency of 80%. For each formulation, the thermal energy input was divided by the boiler efficiency to estimate the total energy required from natural gas combustion. This energy value was then converted to volume using a calorific value of 38 MJ/m^3 for natural gas. The calculated volumes approximated to be 0.015 m^3, reflecting the small-scale nature of the process. Understanding both the thermal efficiency of the boiler and the energy retained in the final product helps to provide a clearer picture of the environmental impact of different grain formulations. Optimizing both energy use and steam loss during production is not often studied, but could have environmental benefits that can be measured in LCA.

4.2.3.4 Allocation Procedures

In this LCA, allocation was based on the physical mass ratio of grain to straw produced by each type of flour, IWG, wheat, corn, and sorghum. Each flour was allocated according to the

proportion of straw yielded by mass, reflecting the significant differences in straw output between these crops. This allocation was applied to the raw materials stage and did not extend to economic or energy-based factors as economic data were not available.

Two allocation methods were used to assess the environmental impacts of both the precooked pasta and expanded snack products. The first method attributed all emissions solely to the flour, treating the grain as the primary product of interest. The second method employed a physical allocation approach, distributing the environmental burden between the grain and straw. This was based on their mass ratio, considering the potential use of straw as a co-product, such as for animal feed. While economic allocation methods, such as the 70/30 split described in studies like Paolotti et al (2023), could offer an alternative, they were not applied here due to insufficient economic data for IWG straw. Physical allocation was therefore chosen as a straightforward method to address the lack of economic information and to capture the influence of co-product allocation. Other methods, such as system boundary expansion, could potentially allocate impacts based on combined product systems, but these approaches were beyond the scope of this study. By comparing the two allocation methods used, this analysis provides a range of potential environmental impacts and demonstrates how co-product treatment affects the overall results.

4.2.3.5 Raw Material

Table 4-2 presents key inputs and outputs for wheat, IWG, sorghum, and corn production. Inputs include diesel, nitrogen, phosphorus, potash fertilizers, quicklime, and transportation by truck and train, reported per kg of grain. Land use is also provided in m^2a. IWG has the highest diesel (0.042 L) and land use (5.128 m^2a) requirements, while sorghum shows the lowest diesel input (0.001 L). Outputs for each grain include whole grain (1 kg) and straw, with

IWG yielding the most straw (4.06 kg), compared to wheat (1.54 kg), sorghum (1.50 kg), and corn (1.00 kg). Inputs were derived from Law et al., 2022, Caffrey et al., 2014, Life Cycle Assessment Commons, 2024.

4.2.3.6 Extruded Products

4.2.3.6.1 Scenario 1: Precooked Pasta

For the precooked pasta products, the inputs vary based on the type of flour used (wheat, IWG, sorghum, or combinations). Each formulation required a consistent amount of flour—either 0.98 kg of wheat, IWG, or sorghum flour, or a 0.49 kg mixture of two flours (wheat + IWG, sorghum + IWG, or wheat + sorghum). Energy usage ranged from 229 kJ for wheat pasta to 262 kJ for the wheat + sorghum blend. Natural gas consumption for the boiler stayed relatively consistent, between 546 and 588 units, while steam input was nearly uniform across formulations (0.20 to 0.22 kg). Water input varied from 0.26 kg (wheat + IWG) to 0.39 kg (wheat pasta). In terms of outputs, each formulation produced 1 kg of pasta, with steam outputs ranging from 0.10 to 0.12 kg. All inflows and outflows for each pasta product can be seen in Table 4-3. Data for cooking precooked pasta in a consumer's home in terms of energy usage based on optimal cook time from Chapter 2 is also included. The electricity input for cooking was calculated based on the total energy consumption over the specific cooking time for each pasta formulation, expressed on a per kilogram of pasta basis. The power required for cooking was estimated by dividing the total energy input by the corresponding cooking time, resulting in the average power consumption in Wh.

4.2.3.6.2 Scenario 2: Expanded Snack

For the extruded expanded snack products, the inputs again differed based on the type of flour used: 1 kg of corn, IWG, or sorghum flour, or 0.50 kg of a combination of two flours (corn

+ IWG, sorghum + IWG, or corn + sorghum). Energy usage was higher for IWG snacks (422 kJ) compared to corn snacks (353 kJ), with sorghum and blended snacks falling in between (344 to 403 kJ). Water input remained consistent at 0.05 to 0.06 kg across all formulations. The output was 1 kg of snack product for each formulation. All inflows and outflows for each snack product can be seen in Table 4-4.

4.2.4 Carbon Sequestration & Carbon Stocks

The estimation of SOC was conducted using the Tier 1 IPCC method, which calculates SOC changes over a 25-year period by considering land use, tillage, and input levels (IPCC, 2003). For this analysis, a reference SOC value (SOC_{REF}) of 38 tons C/hectare was used, representing cropland in Kansas classified as having High Activity Clay (HAC) soil. The SOC was calculated using the following equation:

$$SOC = SOC_{REF} \times F_{LU} \times F_{mg} \times F_I \quad \textbf{4-5}$$

In this formula, SOC_{REF} refers to the initial reference SOC value, and the factors F_{LU} (land use), F_{MG} (tillage), and F_I (input) adjust this value based on agricultural practices. Factor values were obtained from IPCC (2003).

Wheat, corn, and sorghum were classified as being grown on "long-term cultivated land," referring to fields that have been continuously farmed with annual crops for over 20 years (Gautam et al., 2020; *Life Cycle Assessment Commons*, 2024). The land use factor (F_{LU}) for these crops was 0.82. For IWG, the land was categorized as "set aside (< 20 yrs)" because it is a perennial grass, leading to a land use factor of 0.93 to reflect its different management (Law et al., 2022).

For tillage practices, wheat, corn, and sorghum were considered to be under "reduced tillage," which minimizes soil disturbance, resulting in a tillage factor (F_{MG}) of 1.03 for wheat

and corn, and 1.03 for sorghum, reflecting its medium residue retention based on grain-to-residue ratios. IWG, as a perennial grass, was classified under "no-till" (F_{MG} = 1.10) (Law et al., 2022).

The input factor (F_I) varied by crop based on their typical residue return levels. For wheat corn, and sorghum, a "medium input (no manure)" system was assumed, with an input factor of 1.0. While IWG was assigned "high input (no manure)" (F_I = 1.07) because of its higher residue production with a ratio of 1:4.06 which can be found in Table 4-2 (Law et al., 2022). These SOC inputs are presented in Table 4-5.

The inclusion of soil carbon sequestration in this LCA provides a more complete perspective on the GWP of IWG. To evaluate the impact of IWG's carbon sequestration, we scaled down soil carbon data to match the grain yields and system boundaries used in this study. The scaled carbon values were converted from elemental carbon to CO2 equivalents using the appropriate conversion factor (44/12), consistent with IPCC guidelines. This calculation allowed the carbon sequestered to be integrated into the analysis and compared directly to the GWP from production emissions.

The soil carbon sequestration data represent an accumulation over approximately 25 years, as defined by the IPCC methodology. This timescale reflects the long-term nature of carbon storage associated with perennial crops like IWG. To incorporate sequestration into the GWP assessment, a "net GWP" was calculated using the following equation:

$$Net\ GWP = GWP\ from\ LCA\ (kg\ CO_2eq) - Soil\ carbon\ sequestration\ (kg\ CO_2eq) \quad \textbf{4-6}$$

This approach tests the hypothesis that IWG's carbon sequestration can offset its higher GWP due to lower grain yields. By subtracting the sequestration value, the net GWP provides a more balanced view of the environmental impacts of IWG compared to annual grains. Including this calculation highlights the importance of considering soil carbon dynamics in LCA studies,

particularly for perennial crops with unique carbon storage potential. This is especially relevant when evaluating the long-term environmental benefits of transitioning to more sustainable agricultural practices.

4.3 Results & Discussion

4.3.1 Scenario 1: Precooked Pasta

The environmental impacts of the precooked pasta formulations varied depending on the grain type and allocation method used. When all emissions were attributed to the flour (Table 4-6), wheat and IWG formulations had the highest global warming potential (GWP) at 0.24 kg CO2 eq and 0.31 kg CO2 eq, respectively, while sorghum had the lowest at 0.11 kg CO2 eq. In contrast, Paolotti et al. (2023) reported that the production of 1 kg of Pasta Mancini (made from conventional wheat) emitted 1.376 kg CO2 eq. This difference is largely due to scale and scope: Paolotti's study reflects large-scale industrial production, which involves energy-intensive processes like milling and storage, while this study uses a smaller experimental setup with a more limited processing footprint. Freshwater ecotoxicity (FE) followed a similar trend, with IWG having the highest impact at 0.07 CTUeco and sorghum the lowest at 0.0057 CTUeco. Smog formation and acidification impacts also showed wheat and IWG generally having higher values than sorghum. Blended formulations, such as wheat + sorghum, exhibited intermediate values between the individual grain formulations.

Applying physical allocation for straw (Table 4-7) substantially reduced the GWP and FE across all formulations. For instance, wheat's GWP decreased from 0.24 kg CO2 eq to 0.13 kg CO2 eq, and IWG’s GWP dropped from 0.31 kg CO2 eq to 0.11 kg CO2 eq, representing reductions of 46% and 66%, respectively. Similarly, the GWP for sorghum + IWG dropped from 0.21 kg CO2 eq to 0.093 kg CO2 eq (56% lower), while its FE decreased from 0.039 CTUeco to

0.0089 CTUeco (77% lower). These findings demonstrate the significant influence of straw co-product allocation on the environmental profiles, particularly for IWG-based formulations. In contrast, wheat-based pasta showed smaller reductions due to its relatively lower straw output compared to IWG.

Overall, 99.43% of the environmental impacts of the pasta life cycle were attributed to grain cultivation, 0.57% to pasta processing, and less than 0.01% to at-home cooking, disproving our hypothesis that the cooking time would lower the overall environmental impact. These results contrast sharply with those reported by Paolotti et al. (2023), where 76.3% of impacts stemmed from grain cultivation, 6.1% from grain milling and storage, and 17.6% from pasta processing. The differences can be attributed to scale: Paolotti's study examined large-scale industrial pasta production involving thousands of pounds of product sourced from extensive wheat fields, which required energy-intensive processes such as grain milling and storage. In contrast, this study utilized a small-scale experimental setup, where limited planting areas and reduced energy and resource requirements in the processing stages led to lower proportional impacts from processing.

4.3.2 Scenario 2: Expanded Snack

The environmental impacts of expanded snacks varied depending on the allocation method used. Overall 86.55% of GWP came from raw material cultivation and 13.45 % came from extrusion processing, compared to when physically allocated for straw, 66.87 % of GWP came from raw material cultivation and 34.13 % from extrusion. When all emissions were attributed to the flour (Table 4-9), IWG snacks exhibited the highest global warming potential (GWP) at 0.29 kg CO2 eq, while sorghum snacks had the lowest at 0.090 kg CO2 eq. IWG also had higher impacts across other categories, such as freshwater ecotoxicity (FE) at 0.073 CTUeco

and smog formation at 0.066 kg O3 eq, compared to sorghum, which had the lowest impacts at 0.0056 CTUeco and 0.0043 kg O3 eq for these categories.

Using physical allocation for straw (Table 4-10) reduced the impacts across all formulations. For example, corn snacks saw their GWP decrease from 0.14 kg CO2 eq to 0.082 kg CO2 eq, while IWG snacks showed a 71% reduction in GWP, dropping from 0.29 kg CO2 eq to 0.085 kg CO2 eq. FE impacts for IWG also decreased by 80%, from 0.073 CTUeco to 0.015 CTUeco. Sorghum-based snacks had the lowest FE under physical allocation, decreasing from 0.0056 CTUeco to 0.0025 CTUeco. Blended formulations, such as Corn + Sorghum, demonstrated relatively low and consistent impacts regardless of the allocation method.

Across all expanded snack formulations, GWP and FE were consistently the highest impact categories, with IWG generally having the largest values. The physical allocation approach highlighted the environmental advantages of IWG's high straw output, which reduced the environmental burden of its products. However, because straw has less economic value and is not always utilized as a co-product, the results based solely on flour allocation may be more relevant in scenarios where straw remains unused.

By assessing both allocation methods, this analysis provides a comprehensive understanding of the environmental impacts across different scenarios, accounting for variability in potential straw utilization. Figures 4-2 through 4-5 further illustrate these patterns, comparing the impacts of expanded snack formulations across different categories and allocation methods.

4.3.3 Carbon Stock & Sequestration

The calculated SOC values for each crop system reveal significant differences in carbon sequestration potential (Table 4-5). Wheat and corn resulted in an SOC of 32.09 tons C/hectare, reflecting similar management practices. Sorghum exhibited an SOC of 34.34 tons C/hectare,

consistent with its medium residue classification due to a grain-to-residue ratio of 1:1.5. In contrast, IWG showed the highest SOC at 41.60 tons C/hectare, attributed to its status as a perennial grass requiring no tillage and producing greater crop residue, which enhances soil carbon retention (Law et al., 2022).

Tang et al. (2023) further support these findings, reporting that shifting from wheat to IWG increased SOC by 33 g C/m²/year (equivalent to 3.3 tons C/hectare over four years), primarily by restoring particulate organic carbon. Additionally, IWG reduced SOC losses by 38% compared to annual wheat, increased soil microbial biomass, and improved soil respiration.

When SOC sequestration rates are expressed per unit of production, IWG sequestered 0.81 kg CO2 eq/kg annually, making it the only crop evaluated to achieve net carbon storage. In contrast, wheat (-0.10 kg CO2 eq/kg), corn (-0.28 kg CO2 eq/kg), and sorghum (-0.17 kg CO2 eq/kg) all showed net carbon losses from the soil. These findings align with Tang et al. (2023), who observed net SOC gains under IWG systems compared to losses in annual wheat systems. Including deep soil carbon (below 30 cm) in future assessments could further enhance these estimates, as Tang et al. (2023) reported significant carbon storage within the top 2 meters of soil under IWG.

The integration of SOC values into the LCA showcases IWG's remarkable potential to transform its GWP profile. Initially, IWG products demonstrated the highest direct GWP among the crops studied due to elevated energy and input requirements during production. For example, precooked pasta made from IWG had a direct GWP of 0.31 kg CO2 eq/kg, higher than wheat (0.24 kg CO2 eq/kg) and sorghum (0.11 kg CO2 eq/kg). However, when accounting for SOC sequestration (Table 4-8), IWG pasta achieved a net GWP of -0.50 kg CO2 eq/kg, which was further reduced to -0.70 kg CO2 eq/kg under physical allocation. This transition from the highest

direct GWP to a net negative value highlights IWG's ability to offset emissions and even serve as a carbon sink. In comparison, wheat pasta reached 0.34 kg CO2 eq/kg, and sorghum pasta achieved 0.28 kg CO2 eq/kg, both remaining positive.

Similarly, expanded snack formulations demonstrated IWG's significant offsetting capabilities. Corn-based snacks had a direct GWP of 0.14 kg CO2 eq/kg and limited carbon sequestration (-0.28 kg CO2 eq/kg), resulting in a net GWP of 0.42 kg CO2 eq/kg. In contrast, IWG snacks reduced their net GWP from 0.29 kg CO2 eq/kg to -0.52 kg CO2 eq/kg due to high SOC sequestration rates. Under physical allocation (Table 4-11), the net GWP of IWG snacks decreased further to -0.73 kg CO2 eq/kg. Blended formulations, such as Sorghum + IWG, also benefited from IWG's sequestration potential, achieving a net GWP of -0.05 kg CO2 eq/kg.

These results demonstrate that IWG's SOC sequestration not only offsets its direct emissions but also transforms its environmental impact. The ability to turn what initially appears to be a high-emission crop into a net carbon sink is critical for addressing global warming potential in agricultural systems. IWG's capacity to achieve negative GWP values—both for pasta and snack products—sets it apart from annual crops like wheat, corn, and sorghum. Even under physical allocation, where the environmental burdens of co-products like straw are shared, IWG consistently demonstrates its potential to reduce the overall carbon footprint of grain-based products.

The implications of these findings are substantial. By incorporating SOC sequestration into LCAs, IWG's broader environmental benefits become clear. Unlike other crops that either fail to achieve net carbon storage or show minimal reductions in their carbon footprint, IWG offers a pathway to climate-positive agriculture. This ability to offset emissions and achieve

negative GWP values highlights the potential of perennial grains like IWG to contribute to sustainable food systems while mitigating climate change.

4.3.4 Overall Comparative Insights

The sorghum data used in this study comes from a much larger-scale production system with greater plot sizes and higher yields compared to the other grains. This scale difference may have influenced the inputs calculated on a per kg of grain basis. As larger plots and higher yields can spread inputs like fertilizers and fuel across a greater volume of grain, this might result in comparatively lower input values per kg for sorghum than if it were grown at a smaller scale, similar to the other crops in this study. Therefore, the differences in scale and yield could have impacted the overall input-output balance for sorghum.

The results of this study, when considering both environmental and functional properties, show a shift in the performance of different grains. While sorghum-based pasta formulations were previously shown to demonstrate superior pasta quality compared to other grain blends in Chapter 2, the inclusion of net GWP analysis reveals a more nuanced environmental impact. Sorghum's higher energy demands and limited carbon sequestration lead to a higher net GWP compared to IWG, which, despite initially showing a higher direct GWP, achieves a net negative GWP due to its carbon sequestration potential.

Similarly, while corn has been shown to produce better-expanded snacks in earlier chapters, the updated environmental data for corn-based snacks reveals a net positive GWP, with limited carbon sequestration. In contrast, IWG snacks have a much more favorable environmental profile, with a lower net GWP due to its carbon storage capabilities.

These findings highlight the importance of not only selecting grains based on their functional properties for specific products but also considering their environmental impact.

IWG's ability to offset its emissions and achieve a net negative GWP offers a more sustainable alternative in both pasta and snack formulations, challenging the assumption that grains like sorghum and corn, despite their functional advantages, automatically offer the best environmental outcomes. Thus, grain selection should now take into account both product characteristics and carbon sequestration potential to optimize sustainability across product lines.

Additionally, steam input for extrusion processing, which contributes to the energy use in the study, could be improved. Currently, over half of the steam used in processing is lost, suggesting that improvements in steam recovery or adjustments to the processing conditions could reduce energy consumption and overall environmental impacts. Optimizing this aspect of processing could help offset some of the potential environmental impacts associated with grain production and processing, particularly for grains like sorghum and IWG, where energy use is a notable factor in the total impact assessment.

4.3.5 Soil Health & Erosion Control

The advantages of IWG extend beyond carbon sequestration. Its perennial nature improves soil health by reducing erosion and enhancing nutrient cycling, which is not adequately represented in conventional LCA metrics. Unlike annual crops like wheat that require intensive tillage, IWG's deep roots stabilize the soil and promote better water retention, leading to improved soil structure and fertility (Clément et al., 2022). These indirect benefits are essential for sustainable agricultural practices but are challenging to quantify using traditional LCA frameworks.

4.3.6 Limitations & Future Considerations

The current LCA reflects the complexity of assessing the environmental benefits of alternative crops like IWG. Data gaps regarding water usage and soil health metrics hinder a

comprehensive evaluation. For instance, while IWG is known to have lower water needs due to its drought resistance, specific consumption data were not available (Crain et al., 2024). Additionally, the challenges of quantifying soil health benefits and carbon sequestration using standard LCA tools highlight the need for more refined assessment methods.

The focus on land area rather than grain yield complicates comparisons between IWG and wheat. Adjustments made for IWG's lower yield may impact the perceived resource efficiency. This emphasizes the necessity for improved metrics to capture the sustainability advantages of alternative crops more effectively.

4.4 Conclusion

The life cycle assessment of pasta and snack products made with IWG, wheat, corn, and sorghum highlights the potential of these alternative grains to support sustainable agriculture. While sorghum demonstrated the lowest overall GWP across both product categories, making it an attractive option for minimizing immediate environmental impacts, IWG’s ability to sequester carbon offers long-term environmental benefits. The net GWP of IWG, which shifts from a positive to a negative value when accounting for carbon sequestration, emphasizes its potential for offsetting higher production emissions.

Though IWG's grain yield is lower, its perennial growth and contributions to soil health, such as enhancing SOC and preventing erosion, suggest that it could play a role in long-term environmental sustainability. The carbon sequestration potential of IWG, as demonstrated by its high SOC values, helps mitigate the higher energy and input demands required for its production. Furthermore, the substantial amount of straw produced by IWG adds additional environmental value, allowing for resource optimization, such as its use for animal feed or soil improvement.

Sorghum, on the other hand, combines relatively low environmental impacts with functional advantages, particularly for food products such as pasta and snacks. While it doesn't offer the same carbon sequestration potential as IWG, sorghum's lower GWP and good expansion properties for snacks make it a competitive option, especially in large-scale production systems.

In summary, incorporating both IWG and sorghum into agricultural practices can enhance sustainability by providing complementary benefits. Sorghum's immediate environmental advantages and IWG's long-term carbon storage capabilities highlight the importance of balancing short-term impact reductions with long-term soil and ecosystem health. These findings emphasize that advancing sustainable agriculture requires a holistic approach, considering both the functional properties of grains and their environmental impacts over time.

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4.6 Figures & Tables

Figure 4-1A System Boundary Diagram for Precooked Pasta

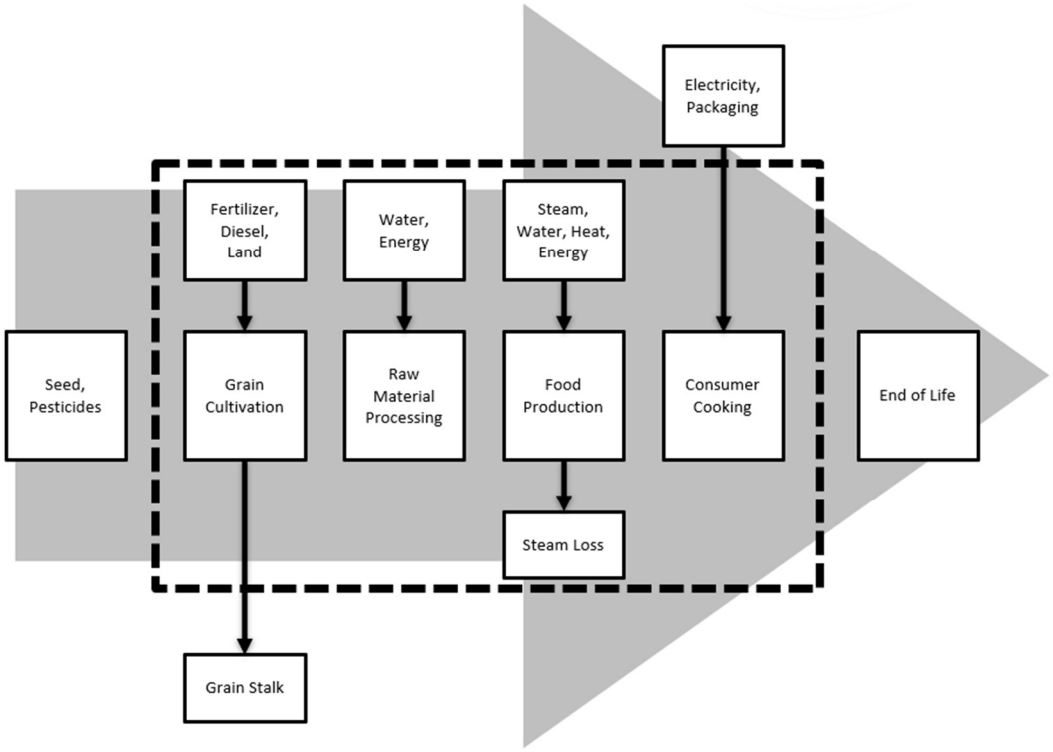


Figure 4-1B System Boundary Diagram for Expanded Snack

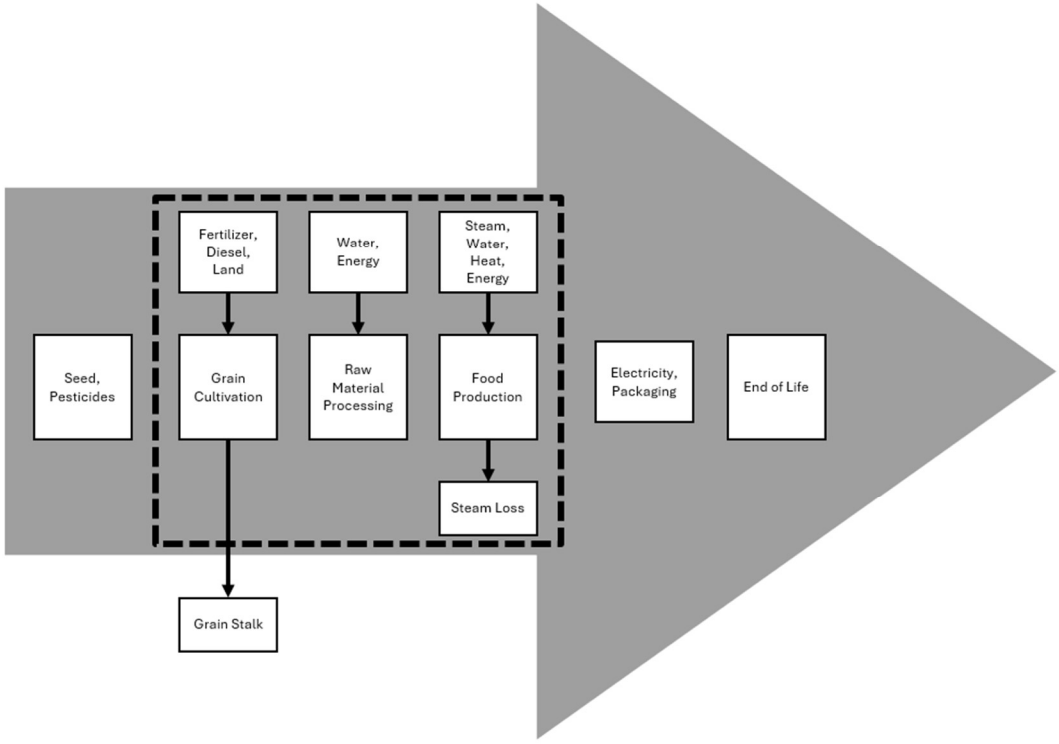


Figure 4-2 Global Warming Potential for Pasta

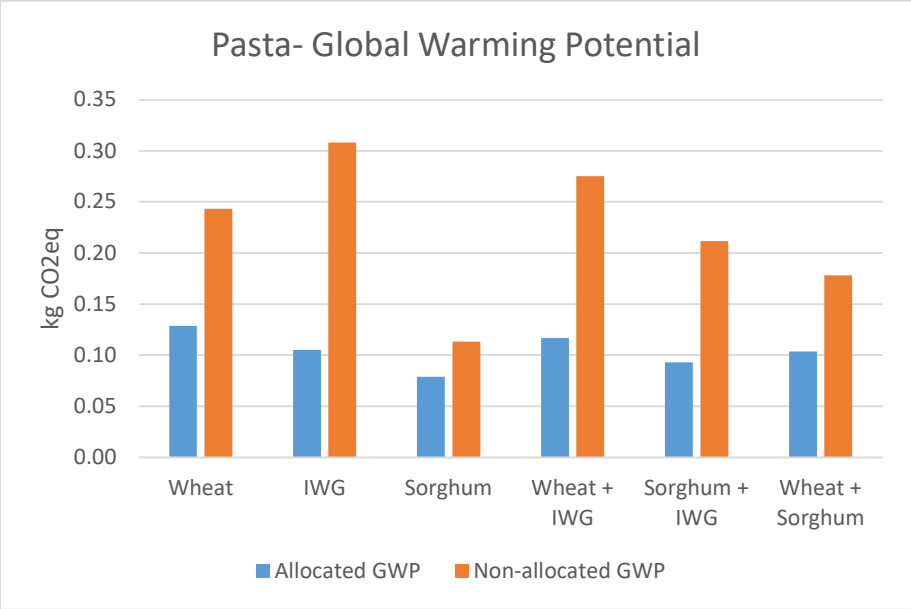


Figure 4-3 Freshwater Ecotoxicity for Pasta

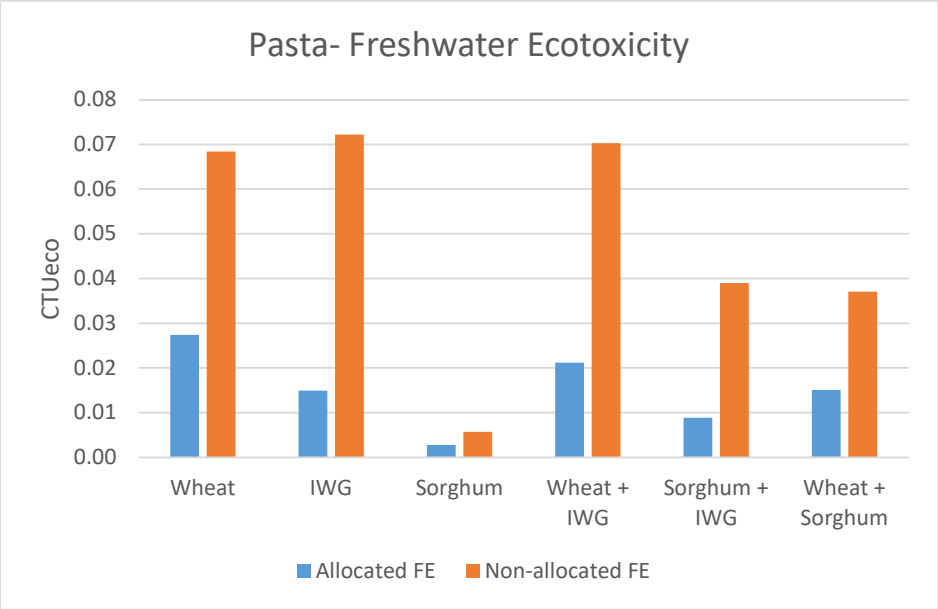


Figure 4-4 Global Warming Potential for Snack

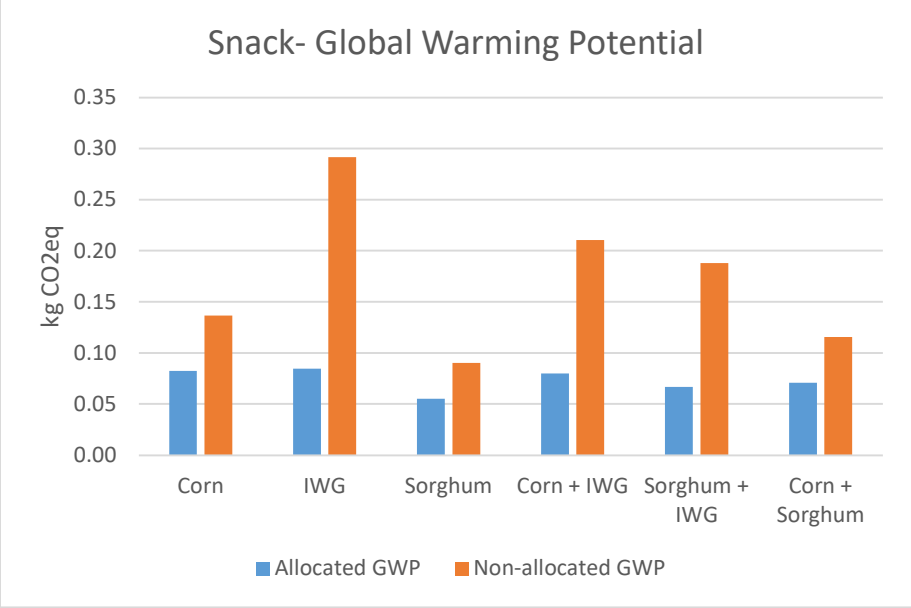


Figure 4-5 Freshwater Ecotoxicity for Snack

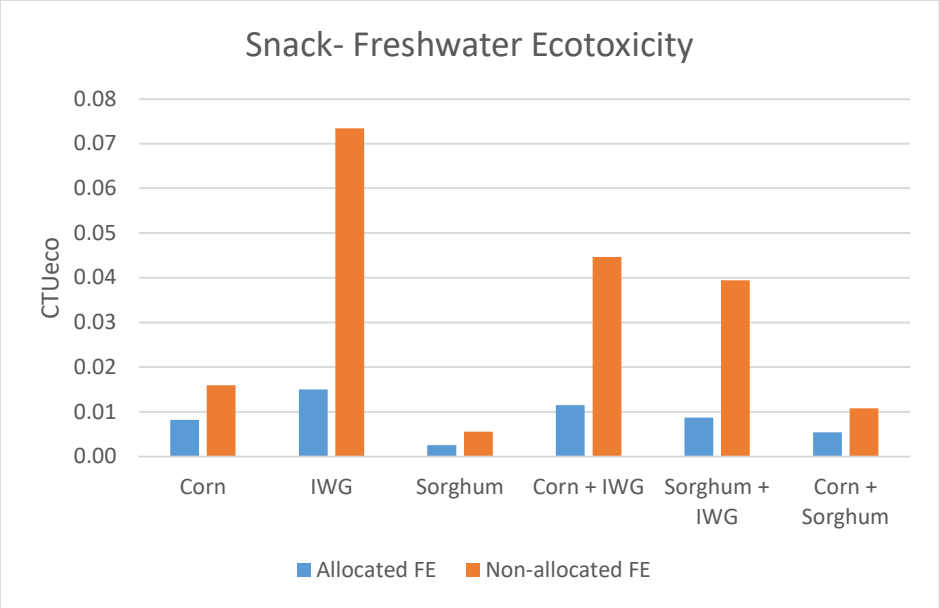


Table 4-1 Energy Balance

Grain Combination	Specific Mechanical Energy (SME) [kJ/kg]	Specific Thermal Energy (STE) [kJ/kg]	Energy to Produce Steam [kJ/kg]	Steam Loss [kg/kg]	Steam Loss Percentage (%)
Wheat	229	380	575	0.21	58.9
IWG	232	423	588	0.21	50.1
Sorghum	255	385	568	0.21	51.8
Wheat + Sorghum	262	393	575	0.21	49.5
Wheat + IWG	232	367	588	0.20	56.6
Sorghum + IWG	249	388	546	0.22	54.0

Table 4-2 Inflow/Outflow Table for Cultivation of 1 kg of Grain Over a 1-year Planting Cycle

Inputs	**Wheat[1]**	**IWG[1]**	**Sorghum[2]**	**Corn[3]**
Diesel (L)	0.02600	0.04169	0.00070	0.00686
Nitrogen Fertilizer (kg)	0.03757	0.04615	0.03080	0.01690
Phosphorous Fertilizer (kg)	0.03005	0.02769	0.00190	0.00584
Potash Fertilizer (kg)	0.02253	0.03690	0.00420	0.00718
Quicklime (kg)	0.01871	0.01817	_	0.03050

Transport- Truck (t*km)	0.02038	0.02038	0.00045	0.01650
Transport- Train (t*km)	0.05429	0.05429	0.00091	0.04400
Land Use (m^2*a)	4.17300	5.12800	3.06300	1.18200
Outputs				
Whole Grain (kg)	1	1	1	1
Straw (kg)	1.54	4.06	1.50	1.00

[1](Law et al 2020), [2](Caffery et al 2015), [3](Life Cycle Assessment Commons, 2024)

Table 4-3 Inflow/Outflow Table for Extrusion Processing of Precooked Pasta

Inputs	**Wheat Pasta**	**IWG Pasta**	**Sorghum Pasta**	**Wheat + IWG Pasta**	**Sorghum + IWG Pasta**	**Wheat + Sorghum Pasta**
Wheat Flour (kg)	0.98	_	_	0.49	_	0.49
IWG Flour (kg)	_	0.98	_	0.49	0.49	_
Sorghum Flour (kg)	_	_	0.98	_	0.49	0.49
Energy from extrusion (kJ)	229	232	255	232	249	262
Natural Gas Combusted in Boiler (m^3)	0.015	0.015	0.015	0.015	0.015	0.014
Steam (kg)	0.21	0.21	0.21	0.21	0.22	0.20
Water (kg)	0.39	0.39	0.35	0.35	0.26	0.34
Electricity at home (Wh)	0.08	0.03	0.07	0.07	0.05	0.07
Outputs						
Pasta (kg)	1	1	1	1	1	1
Steam (kg)	0.12	0.11	0.11	0.12	0.12	0.10

Table 4-4 Inflow/Outflow Table for Extrusion Processing of Expanded Snack

Inputs	Corn Snack	IWG Snack	Sorghum Snack	Corn + IWG Snack	Sorghum + IWG Snack	Corn + Sorghum Snack
Corn Flour (kg)	1.0	_	_	0.50	_	0.50
IWG Flour (kg)	_	1.0	_	0.50	0.50	_

Sorghum Flour (kg)	_	_	1.0	_	0.50	0.50
Energy from extrusion (kJ)	353	422	399	344	373	403
Water (kg)	0.05	0.06	0.06	0.05	0.06	0.06
Outputs						
Snack (kg)	1	1	1	1	1	1

Table 4-5 Carbon Stock Calculation

Crop	**SOC_{ref} (tons C/hectare)**	**F_{lu}**	**F_{mg}**	**F_i**	**SOC (tons C/hectare)**	**Net SOC (tons C/hectare)**	**Functional Carbon Sequestered (kg CO2eq/kg, annually)**
Wheat	38.00	0.82	1.03	1.00	32.09	-5.91	-0.10
Corn	38.00	0.82	1.03	1.00	32.09	-5.91	-0.28
Sorghum	38.00	0.82	1.03	1.07	34.34	-3.66	-0.17
IWG	38.00	0.93	1.10	1.07	41.60	3.60	0.81

Table 4-6 Impact Assessment for Precooked Pasta

Impacts	Wheat	IWG	Sorghum	Wheat + IWG	Sorghum + IWG	Wheat + Sorghum
Global Warming Potential (kg CO2 eq)	0.243	0.308	0.113	0.275	0.212	0.178
Freshwater Ecotoxicity (CTUeco)	0.068	0.072	0.006	0.070	0.039	0.037
Smog Formation (kg O3 eq)	0.043	0.066	0.005	0.055	0.036	0.025
Eutrophication (kg N eq)	0.005	0.004	0.000	0.005	0.002	0.003
Acidification (kg SO2 eq)	0.002	0.003	0.000	0.002	0.001	0.001

Table 4-7 Impact Assessment for Pasta with Physical Allocation for Straw

Impacts	Wheat	IWG	Sorghum	Wheat + IWG	Sorghum + IWG	Wheat + Sorghum
Global Warming Potential (kg CO2 eq)	0.129	0.105	0.079	0.117	0.093	0.104
Freshwater Ecotoxicity (CTUeco)	0.027	0.015	0.003	0.021	0.009	0.015
Smog Formation (kg O3 eq)	0.018	0.015	0.003	0.017	0.009	0.011
Eutrophication (kg N eq)	0.002	0.001	0.000	0.001	0.001	0.001
Acidification (kg SO2 eq)	0.001	0.001	0.000	0.001	0.000	0.001

Table 4-8 Net Global Warming Potential for Precooked Pasta

Formulation	**GWP (kg CO2 eq/kg)**	**GWP with Physical Allocation (kg CO2 eq/kg)**	**Carbon Sequestration (kg CO2 eq/kg)**	**Net GWP (kg CO2 eq/kg)**	**Net GWP with Physical Allocation (kg CO2 eq/kg)**
Wheat	0.24	0.13	-0.10	0.34	0.23
IWG	0.31	0.11	0.81	-0.50	-0.70
Sorghum	0.11	0.08	-0.17	0.28	0.25
Wheat + IWG	0.28	0.12	0.31	-0.03	-0.19
Sorghum + IWG	0.21	0.09	0.24	-0.02	-0.14
Wheat + Sorghum	0.18	0.10	-0.19	0.36	0.29

Table 4-9 Impact Assessment for Expanded Snacks

Impact	Corn	IWG	Sorghum	Corn + IWG	Sorghum + IWG	Corn + Sorghum
Global Warming Potential (kg CO2 eq)	0.136	0.291	0.090	0.210	0.188	0.116
Freshwater Ecotoxicity (CTUeco)	0.016	0.073	0.006	0.045	0.039	0.011
Smog Formation (kg O3 eq)	0.014	0.066	0.004	0.040	0.035	0.009
Eutrophication (kg N eq)	0.001	0.005	0.000	0.003	0.002	0.001
Acidification (kg SO2 eq)	0.001	0.003	0.000	0.002	0.001	0.001

Table 4-10 Impact Assessment for Expanded Snack with Physical Allocation for Straw

Impacts	Corn	IWG	Sorghum	Corn + IWG	Sorghum + IWG	Corn + Sorghum
Global Warming Potential (kg CO2 eq)	0.082	0.085	0.055	0.080	0.067	0.071
Freshwater Ecotoxicity (CTUeco)	0.008	0.015	0.003	0.012	0.009	0.005
Smog Formation (kg O3 eq)	0.008	0.014	0.002	0.011	0.008	0.005
Eutrophication (kg N eq)	0.000	0.001	0.000	0.001	0.001	0.000
Acidification (kg SO2 eq)	0.000	0.001	0.000	0.000	0.000	0.000

Table 4-11 Net Global Warming Potential for Expanded Snack

Formulation	**GWP (kg CO2 eq/kg)**	**GWP with Physical Allocation (kg CO2 eq/kg)**	**Carbon Sequestration (kg CO2 eq/kg)**	**Net GWP (kg CO2 eq/kg)**	**Net GWP with Physical Allocation (kg CO2 eq/kg)**
Corn	0.14	0.08	-0.28	0.42	0.36
IWG	0.29	0.09	0.81	-0.52	-0.73
Sorghum	0.09	0.06	-0.17	0.26	0.23
Corn + IWG	0.21	0.08	0.13	0.09	-0.05
Sorghum + IWG	0.19	0.07	0.24	-0.05	-0.17
Corn + Sorghum	0.12	0.07	-0.37	0.48	0.44

Chapter 5 - Conclusion

5.1 Background

This research addresses the urgent need for sustainable food production methods in response to environmental challenges and consumer demand for healthier options. By investigating the viability of alternative grains—specifically Intermediate Wheatgrass (IWG), and sorghum—in the production of extruded precooked pasta and snacks, this study contributes to the ongoing conversation about sustainable agriculture and food systems. The findings highlight the potential of these alternative grains to enhance sustainability in food production, reduce ecological footprints, and support healthier diets. This research expands the knowledge base surrounding the functional properties of IWG and sorghum, offering insights that can inform future agricultural practices and product development. Overall, this study emphasizes the importance of diversifying grain sources to promote environmental stewardship and improve food quality, paving the way for more resilient and sustainable food systems.

5.2 Chapter 2

This study illustrated the potential of IWG and sorghum as functional ingredients in extruded precooked pasta. The inclusion of IWG flour and sorghum flour enhanced sustainability in pasta production. Although the wheat/IWG combination exhibited a higher cooking loss percentage, sorghum flour displayed the lowest cooking loss, indicating better water absorption and improved pasta quality. Significant differences in texture characteristics were observed, with sorghum pasta achieving the highest water absorption index and lowest water solubility. These findings suggested the need for optimized processing parameters and ingredient ratios to ensure consistent product quality in extruded pasta.

5.3 Chapter 3

The evaluation of extruded snacks made from blends of IWG, sorghum, and corn revealed that the composition of raw materials significantly influenced key properties such as pasting viscosity, bulk density, piece density, expansion ratio, specific length, and hardness. Higher starch content in IWG and sorghum was associated with increased expansion ratios and lower densities, as supported by RVA findings that indicated flours with higher viscosities contributed to a lighter, airier texture. The specific mechanical energy measurements highlighted the effect of energy inputs on texture and structural integrity, emphasizing the potential of IWG and sorghum as alternatives to conventional corn flour in snack production.

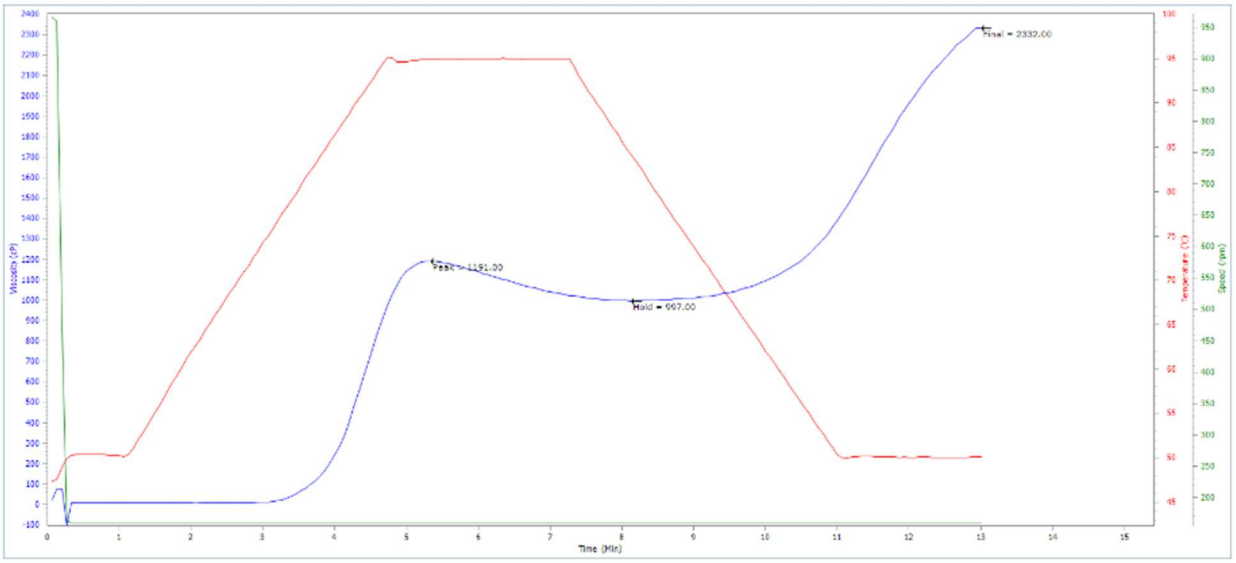
5.4 Chapter 4

The life cycle assessment of pasta and snack products using Intermediate Wheatgrass (IWG), sorghum, wheat, and corn underscores the complementary roles these alternative grains can play in sustainable agriculture. Sorghum's low Global Warming Potential (GWP) across both product categories makes it an attractive option for reducing immediate environmental impacts, while IWG's carbon sequestration ability transforms its net GWP to a negative value, showcasing its potential for long-term environmental benefits. Although IWG's grain yield is lower and production requires higher inputs, its perennial nature enhances soil health, increases soil organic carbon (SOC), and prevents erosion, offering a sustainable solution over time. Sorghum's functional advantages, including low GWP and superior snack expansion properties, position it as a practical choice for large-scale food production. Together, IWG and sorghum provide a balanced approach to sustainable agriculture, combining immediate impact reduction with long-term ecosystem health.

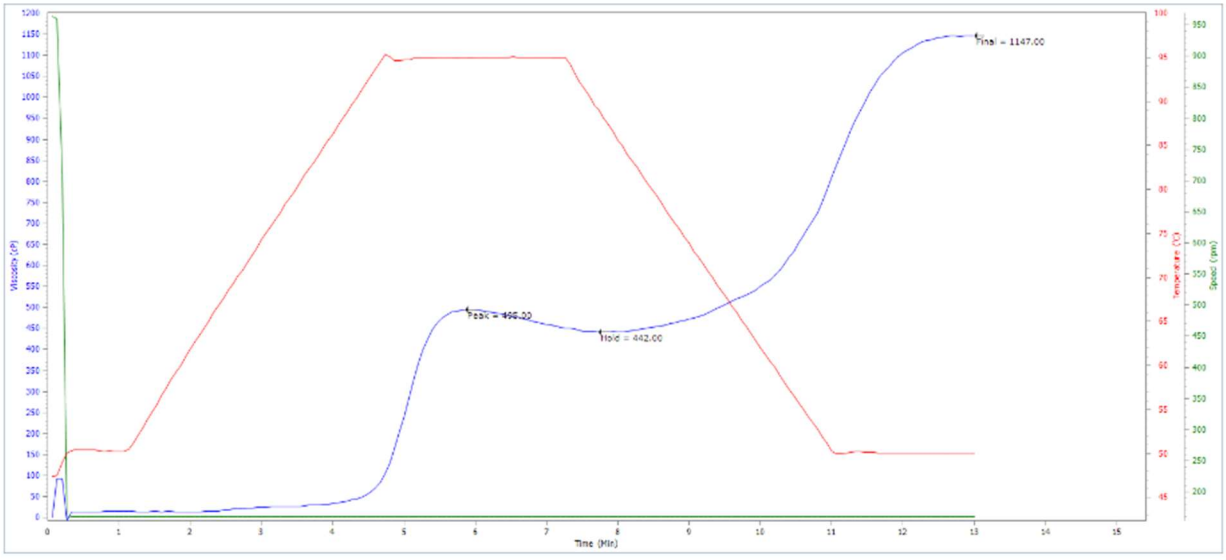
5.5 Future Work

Future research should focus on optimizing processing parameters for extruded pasta and snack products made with IWG and sorghum to enhance texture and quality. Exploring consumer acceptance and sensory attributes of these innovative formulations will be crucial for market viability. Investigating the individual effects of different protein sources and their interactions will further clarify the functional properties of these alternative grains. Expanding the scope of LCA studies to include broader environmental and economic impacts will also be valuable in promoting the adoption of IWG and sorghum in mainstream agriculture. By continuing to build upon this research, there is potential to develop high-quality, nutritious products that meet consumer demands while minimizing environmental impacts.

Appendix A - Chapter 3

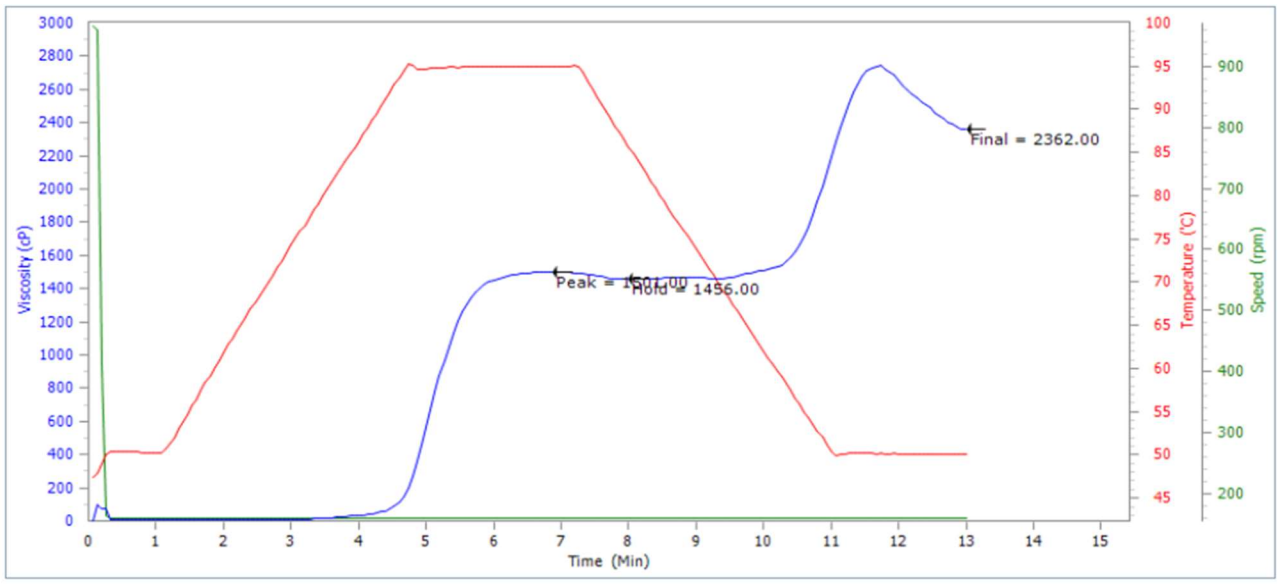


Corn Raw Material

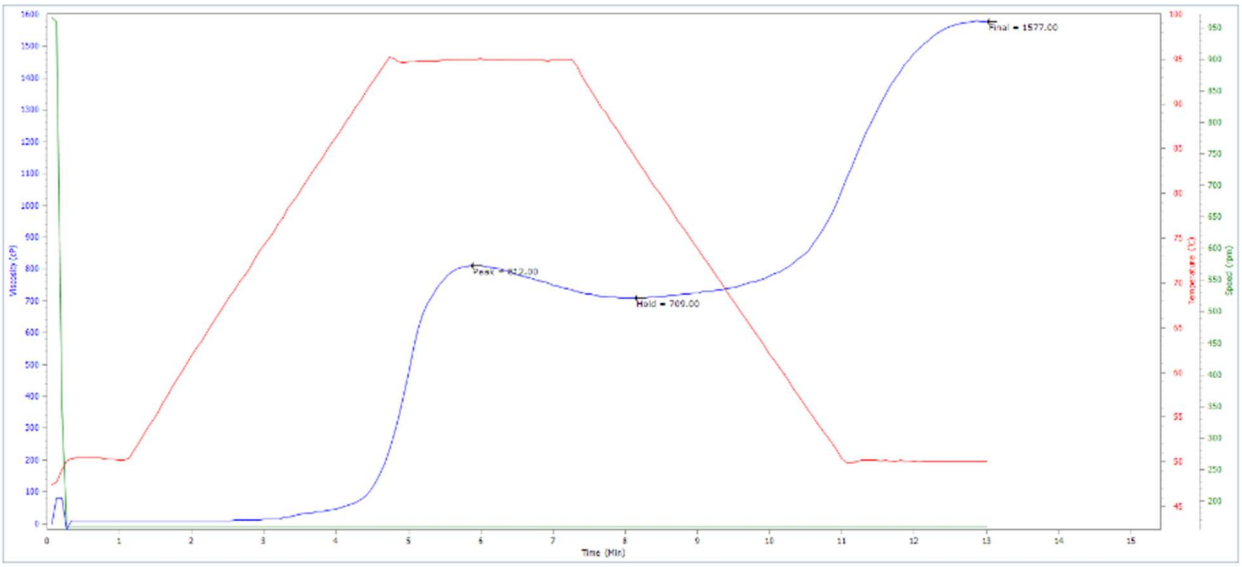


Intermediate Wheat Grass Raw Material

Figure 5-1 RVA Curves for Corn Raw Materials and Intermediate Wheat Grass

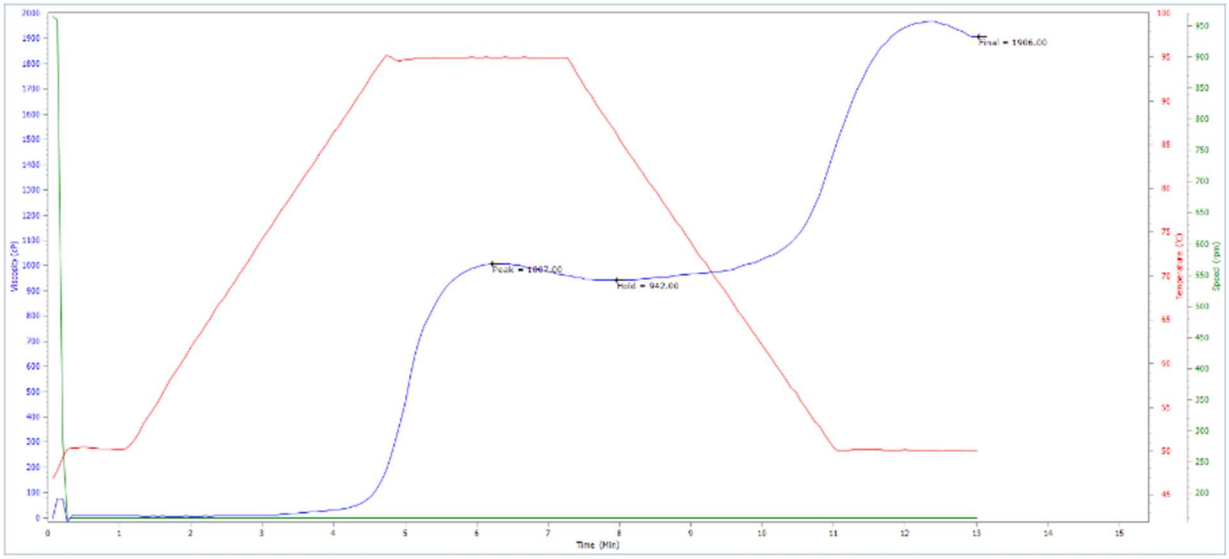


Sorghum Raw Material

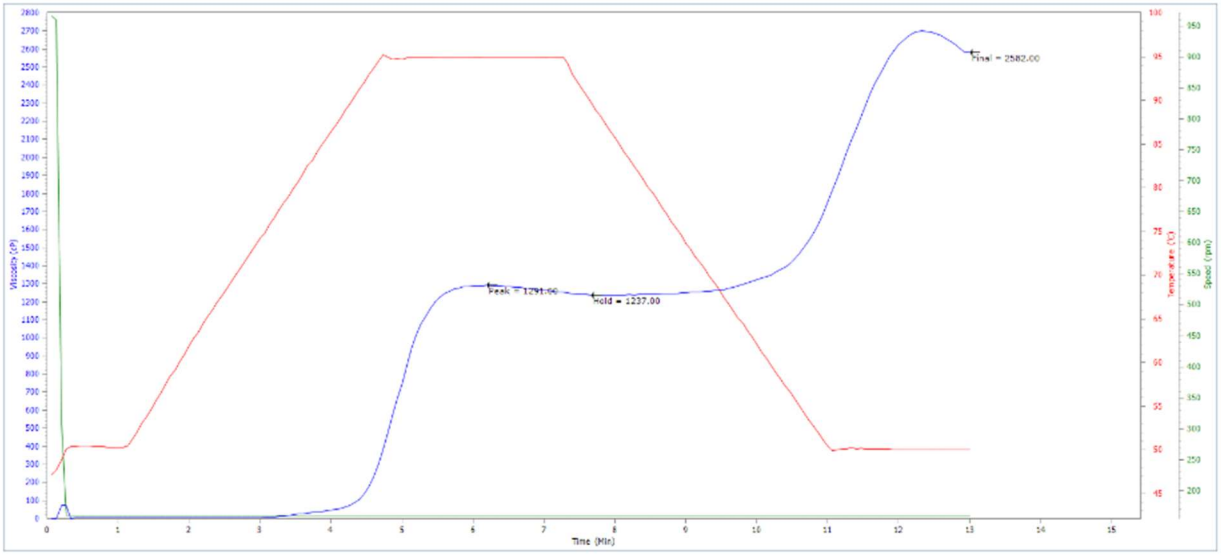


Corn + Intermediate Wheat Grass Raw Blend

Figure 5-2 RVA Curves for Sorghum Raw Materials and Corn + Intermediate Wheat Grass Raw Blend

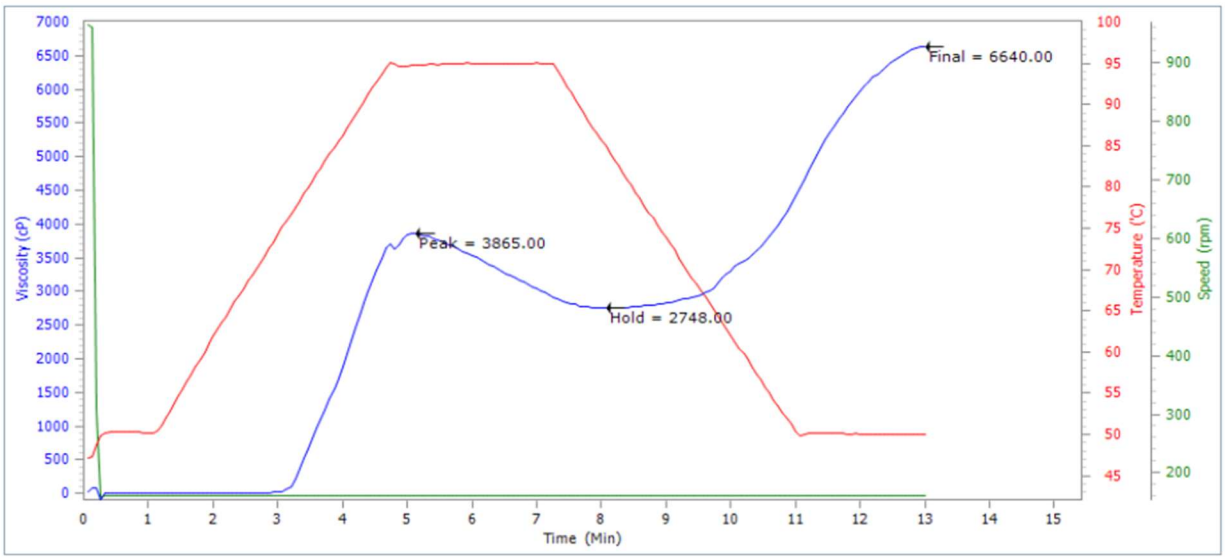


Sorghum + Intermediate Wheat Grass Raw Blend



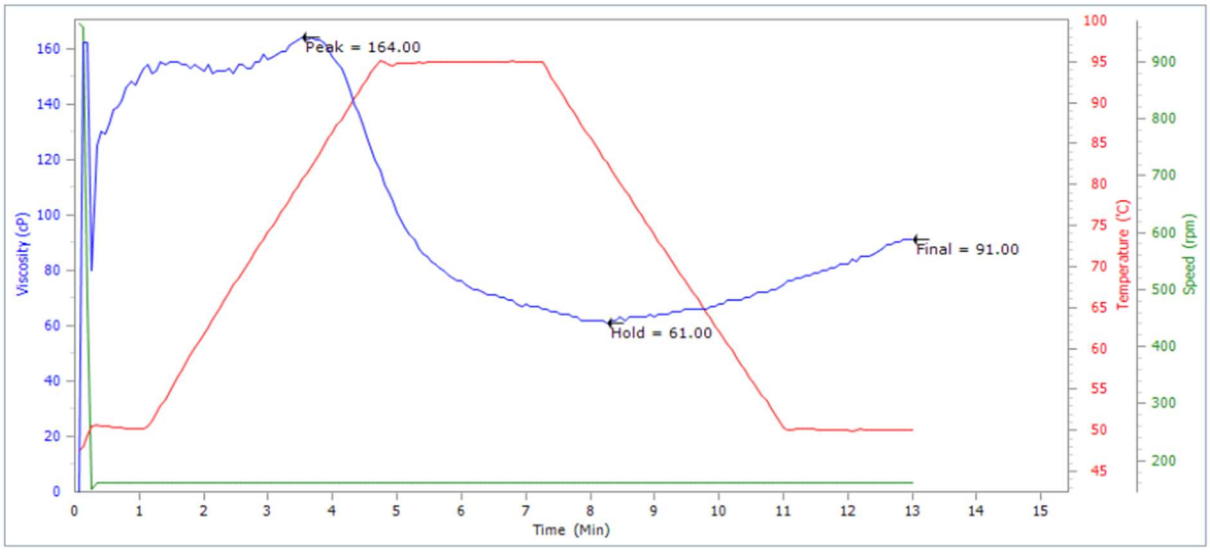
Corn + Sorghum Raw Blend

Figure 5-3 RVA Curve for Sorghum + Intermediate Wheat Grass Raw Blend and Corn + Sorghum Raw Blend



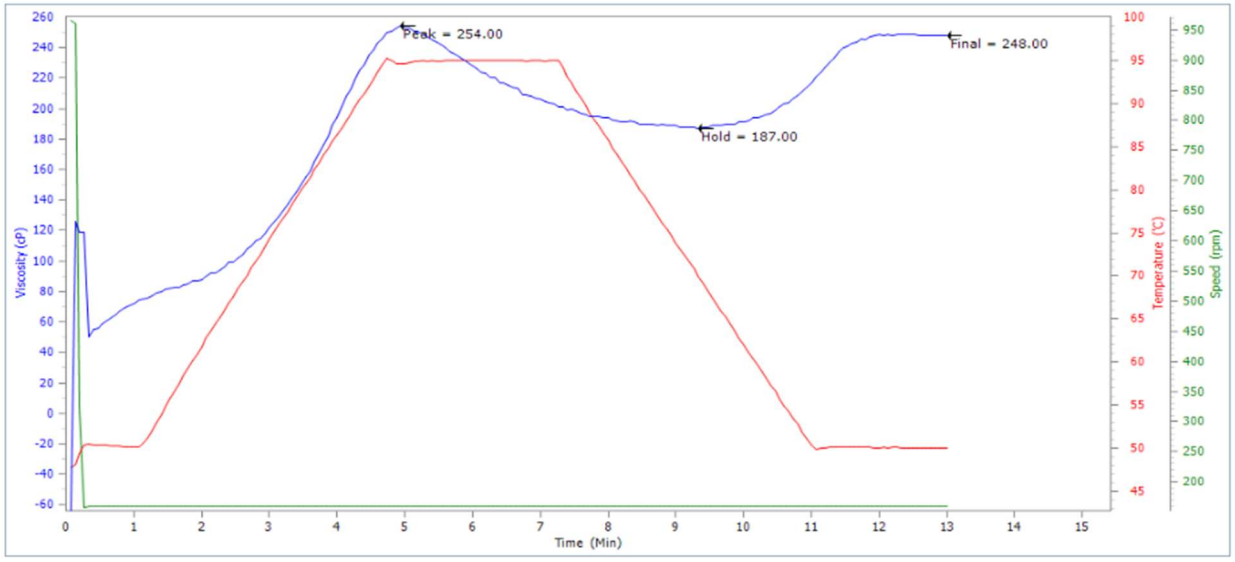
Degermed Corn Flour Raw Blend

Figure 5-4 RVA Curve for Degermed Corn Flour Raw Blend

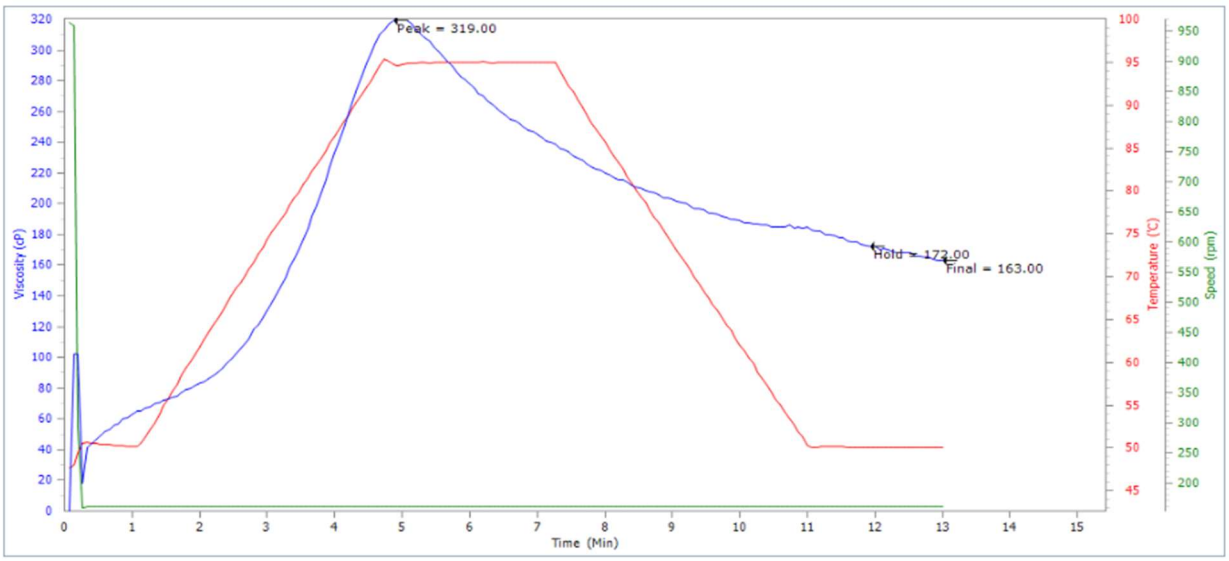


Corn Finished Product

Figure 5-5 RVA Curve for Corn Finished Products

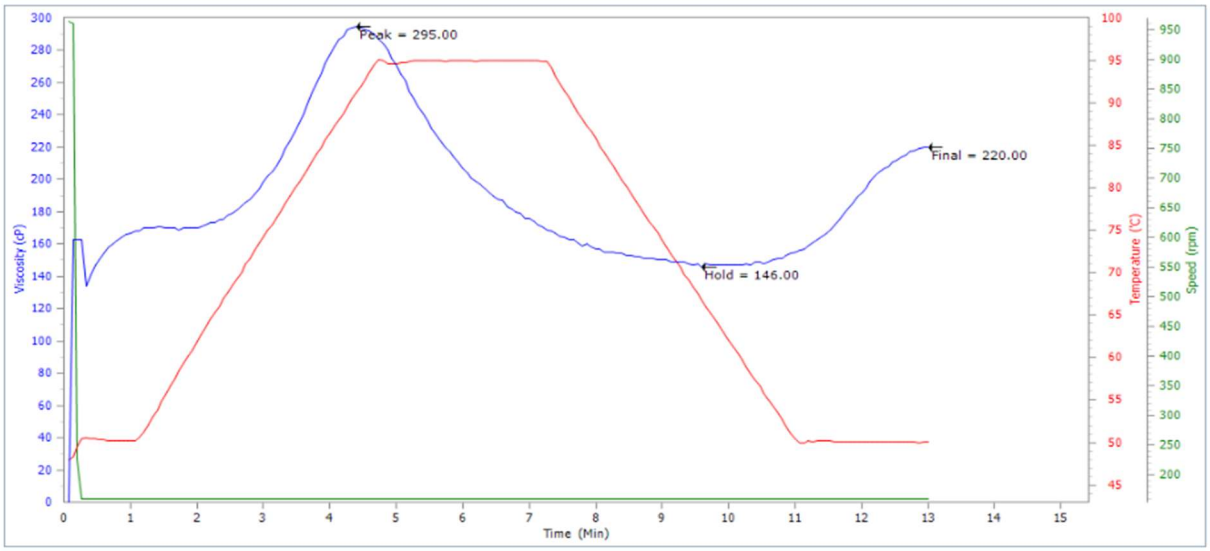


Intermediate Wheat Grass Finished Product

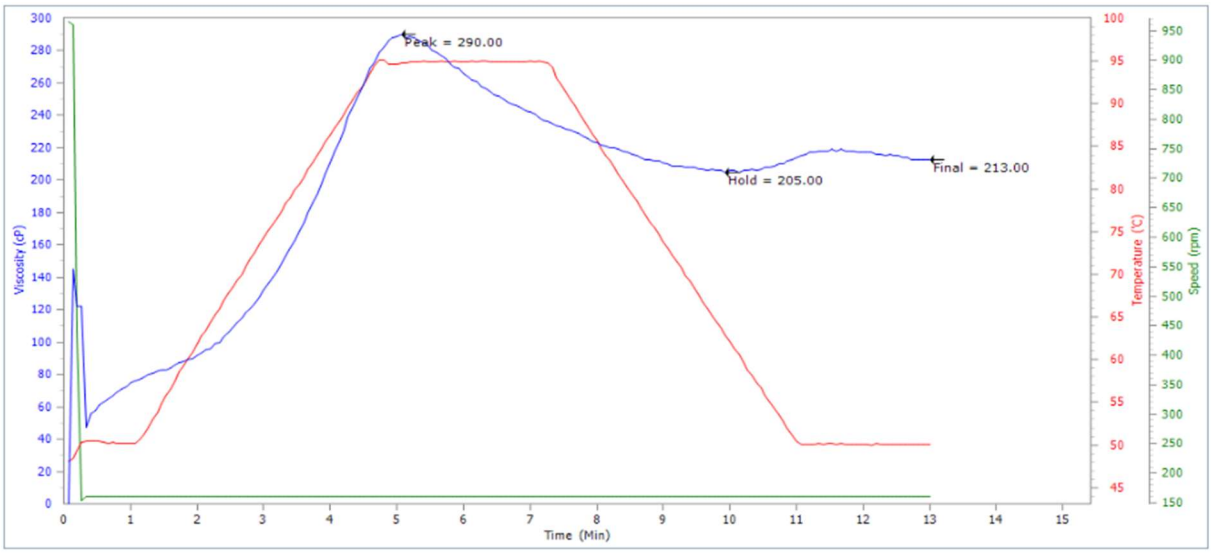


Sorghum Finished Product

Figure 5-6 RVA for Intermediate Wheat Grass Finished Produce and Sorghum Finished Product

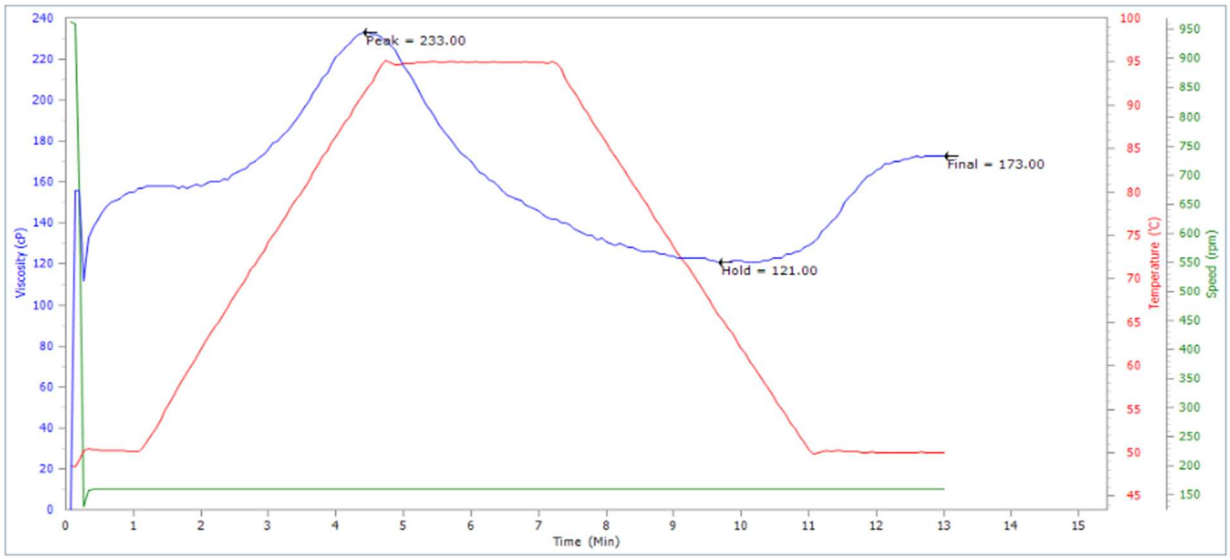


Corn + Intermediate Wheat Grass Finished Product

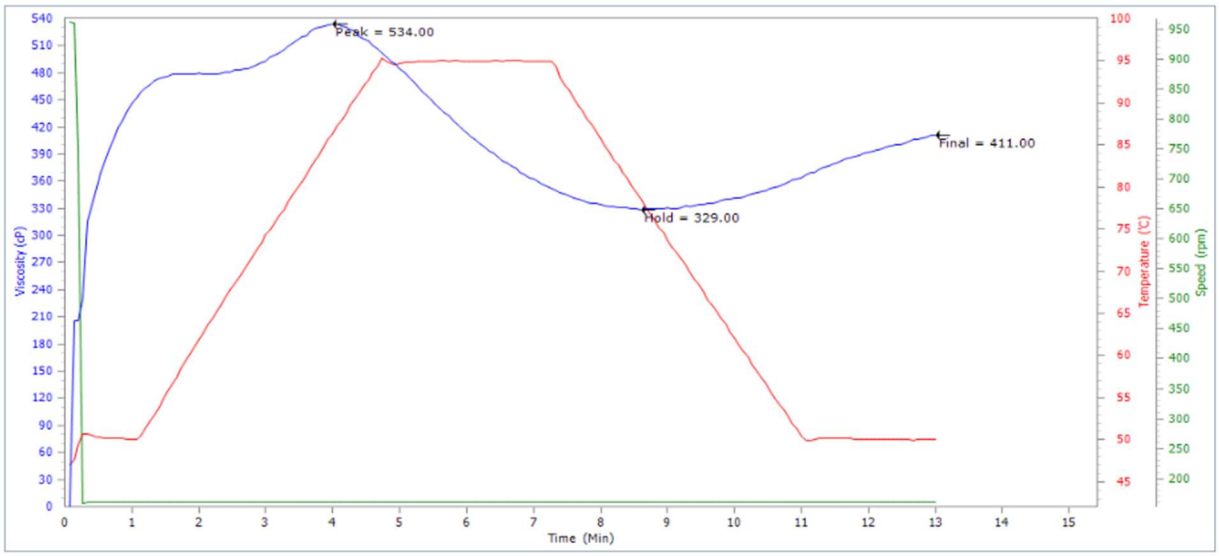


Sorghum + Intermediate Wheat Grass Finished Product

Figure 5-7 RVA Curve for Corn + Intermediate Wheat Grass Finished Product and for Sorghum + Intermediate Wheat Grass Finished Product

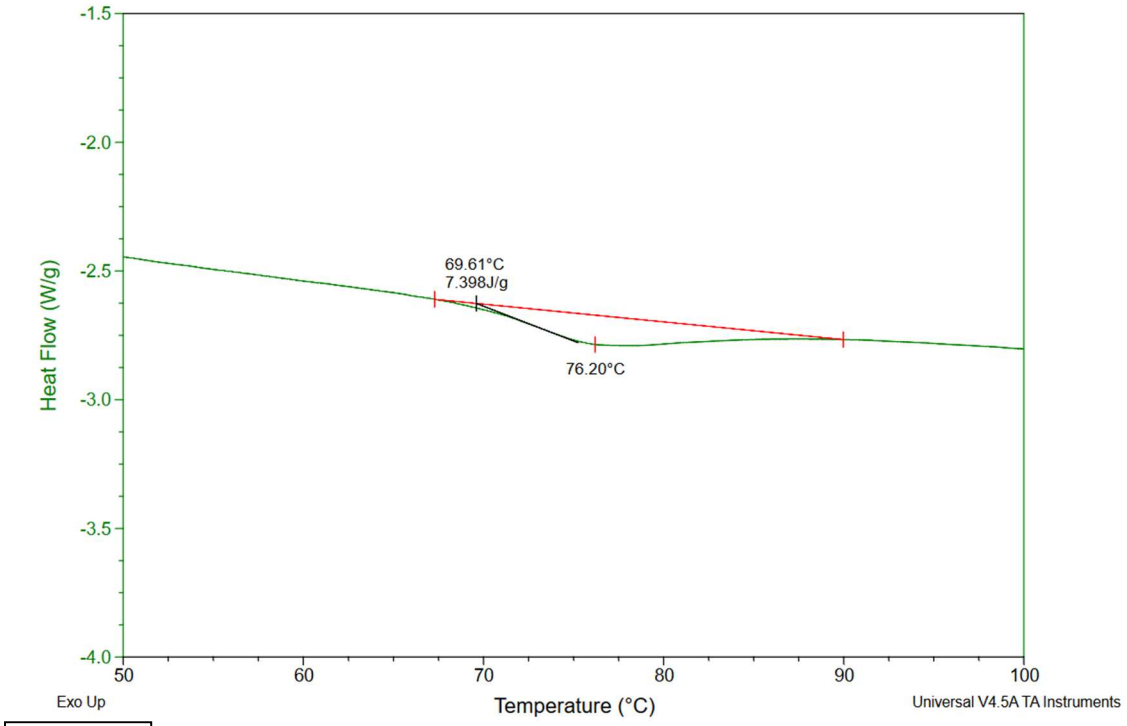


Corn + Sorghum Finished Product

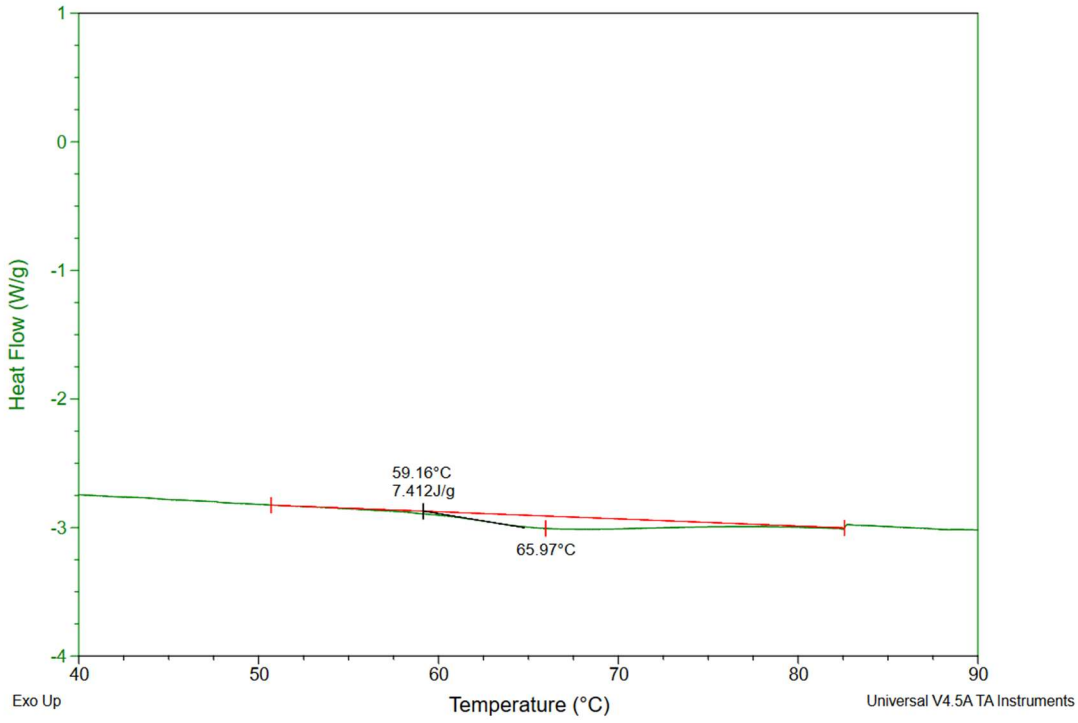


Degermed Corn Flour Finished Product

Figure 5-8 RVA Curve for Corn + Sorghum Finished Product and Degermed Corn Flour Finished Product

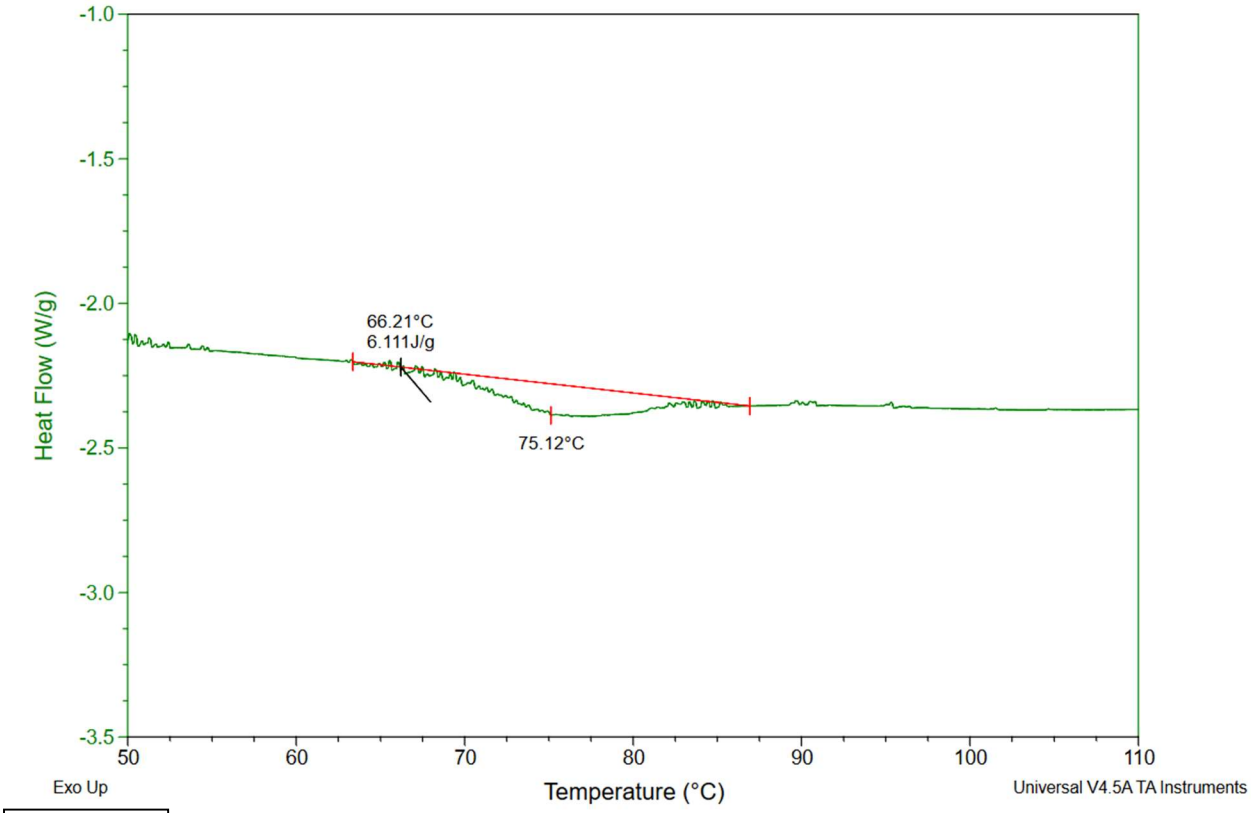


Corn

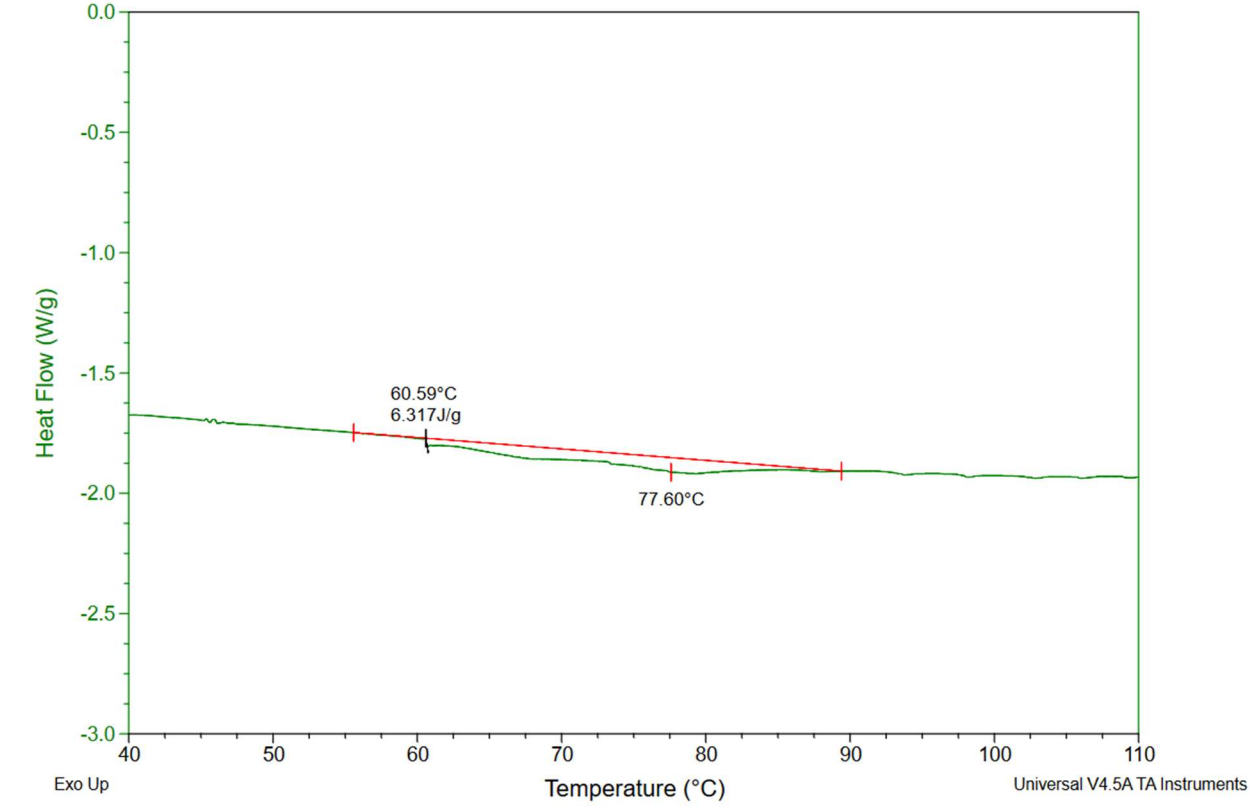


Intermediate Wheat Grass

Figure 5-9 DSC Curve for Corn and Intermediate Wheat Grass

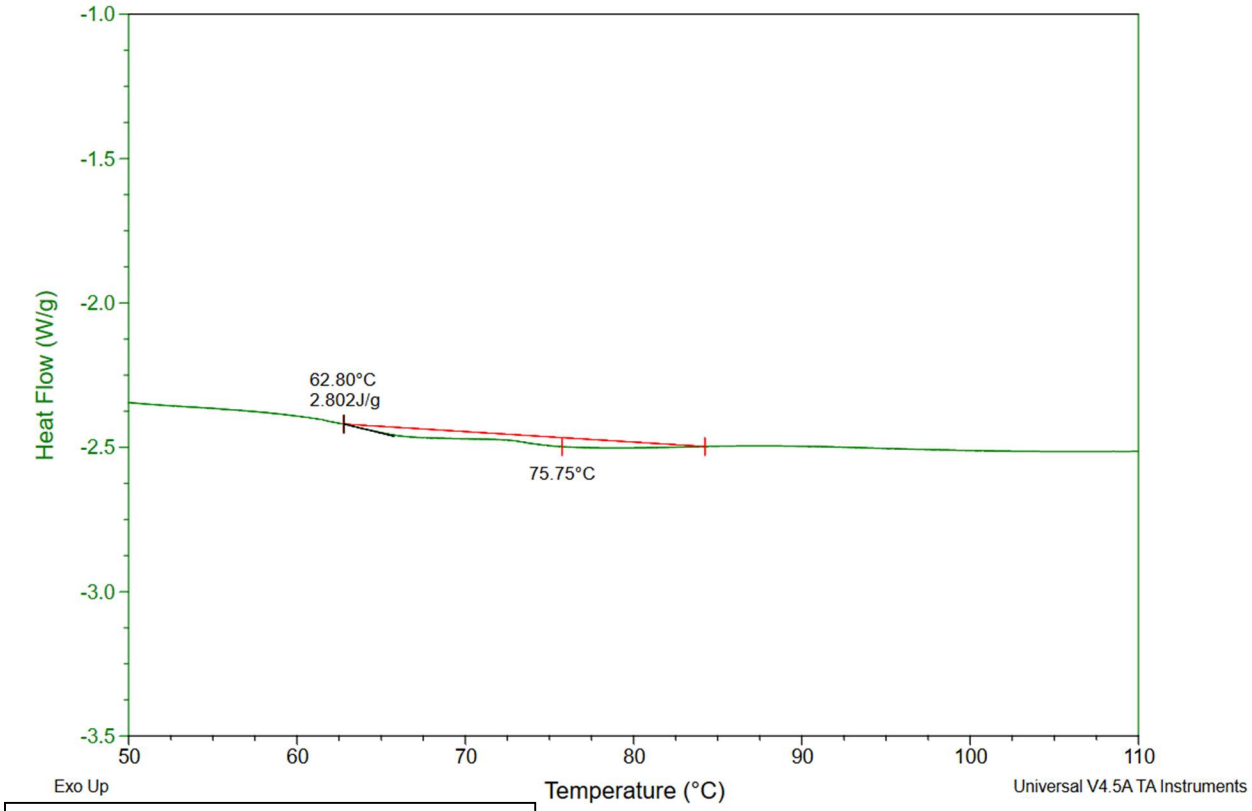


Sorghum

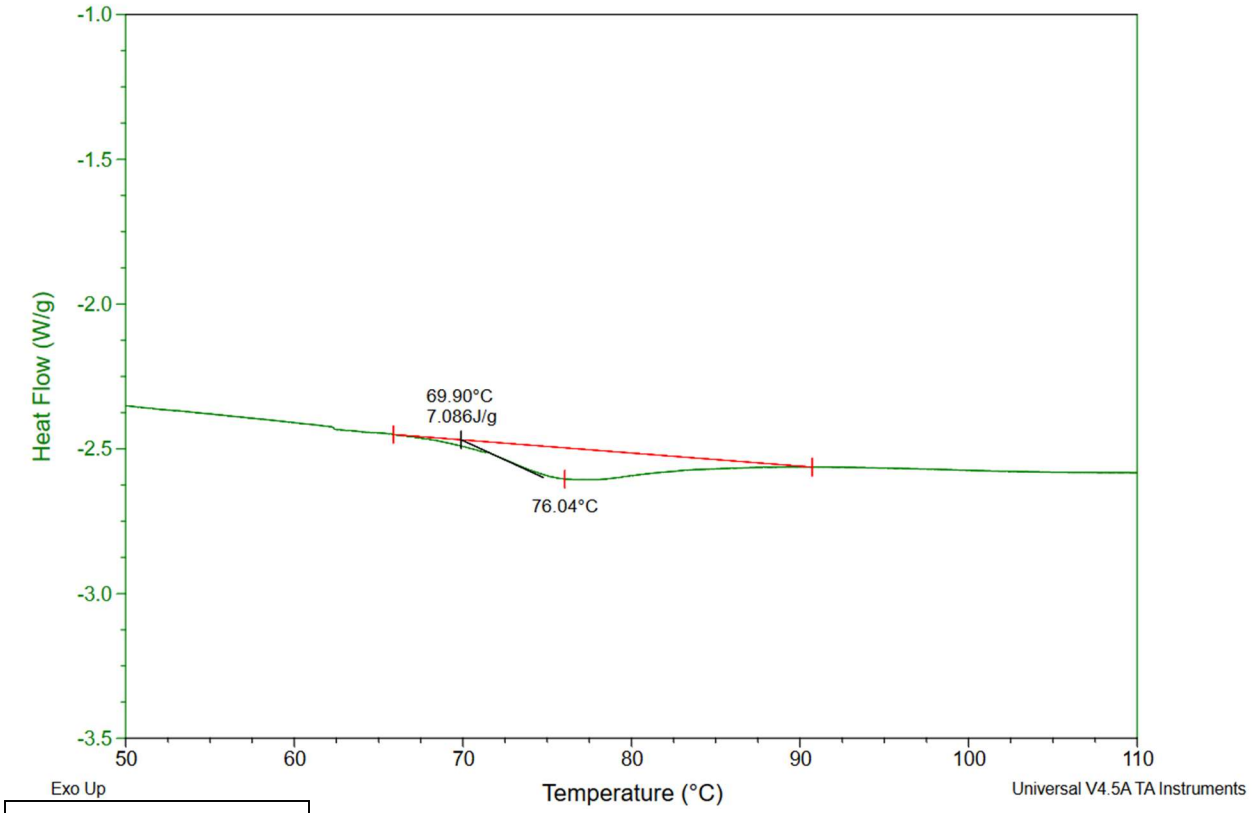


Corn + Intermediate Wheat Grass

Figure 5-10 DSC Curve for Sorghum and Corn + Intermediate Wheat Grass

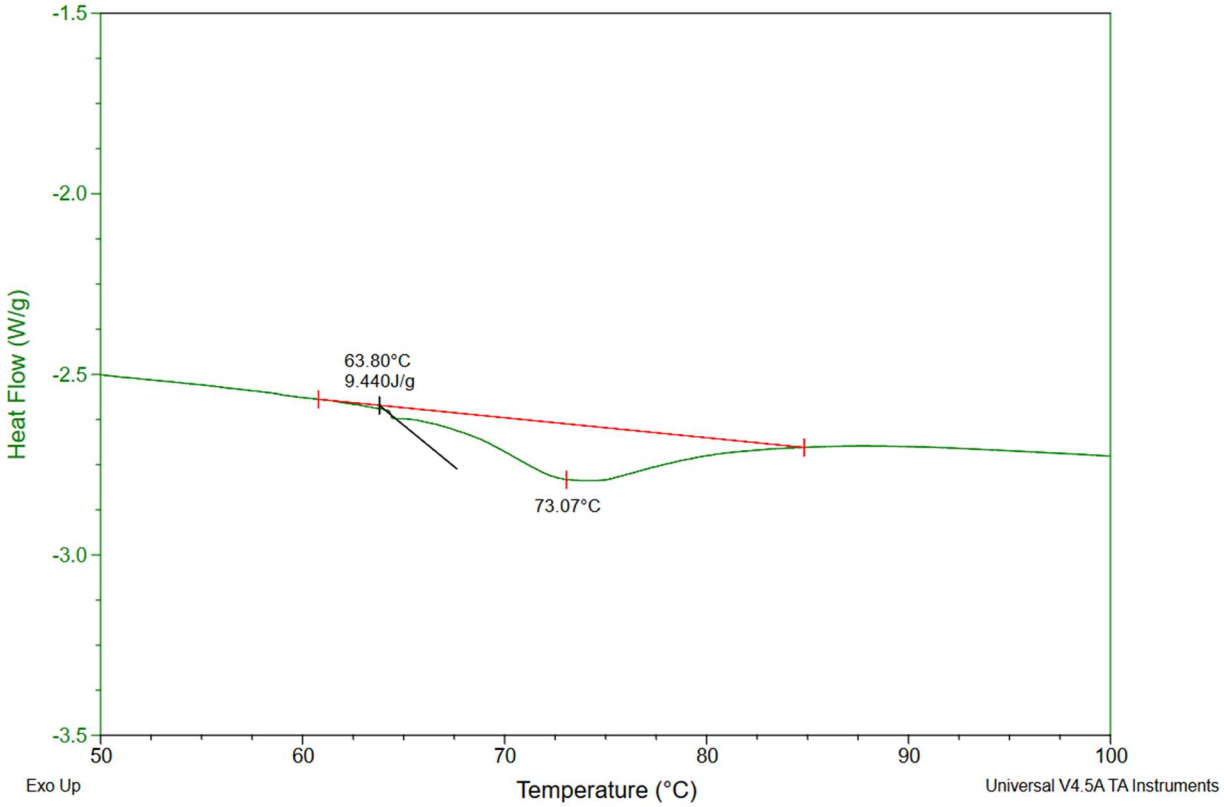


Sorghum + Intermediate Wheat Grass



Corn + Sorghum

Figure 5-11 DSC Curve for Sorghum + Intermediate Wheat Grass and Corn + Sorghum



Degermed Corn Flour

Figure 5-12 DSC Curve for Degermed Corn Flour