



Effect of hydrocolloids on the quality and functional characteristics of banana gluten-free pasta

Siphosethu Richard Dibakoane (201707357)



<https://orcid.org/0000-0001-5132-621>

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Supervisor: Dr O. C. Wokadala

Co-supervisor: Prof. V. Mlambo

Co-supervisor: Dr E. Jooste

Co-supervisor: Dr T.A Anyasi

School of Agricultural Sciences

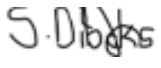
Faculty of Agriculture and Natural Sciences

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DECLARATION

I, Siphosethu Richard Dibakoane, confirm that this MSc thesis has only been submitted to the University of Mpumalanga. This work was done under the supervision of Dr O. C. Wokadala and Prof. V. Mlambo. Sources of information and other material have been fully acknowledged.

Student: Siphosethu Richard Dibakoane (201707357)

Signature:  Date:.....

Main Supervisor: Dr O. C. Wokadala

Signature:  Date:.....

Co-Supervisor: Prof. V. Mlambo

Signature: ...  Date:

Co-supervisor: Dr T.A. Anyasi

Signature: ...  Date:.....

GENERAL ABSTRACT

Unripe banana flour pasta products are not preferred by consumers due to their high cooking losses, darker colour, and stickiness caused by low protein levels in the flour. To address these challenges, this study assessed the combined effect of three types of hydrocolloids, namely egg white (EW), guar gum (GG), and xanthan gum (XG), on the quality and functional characteristics of banana flour-based pasta. The pasta samples were made using distilled water (36.1 – 40.1%), wheat flour (60.6%), banana flour (36.0%) with varying levels of hydrocolloids (18 – 22% and 0.5 – 4.5%). The samples were dried overnight and stored in sealed and airtight plastics pending further analysis. One-way analysis of variance (ANOVA) and response surface regression analysis were used to analyse relationships between inclusion levels of hydrocolloids and the quality and functional characteristics of the pasta.

The cooking time, and hardness of the pasta showed linear and quadratic increases ($p < 0.05$) in response to incremental levels of the hydrocolloids. However, the cooking loss showed a linear decrease ($p < 0.05$) in response to incremental levels of the hydrocolloids. The adhesiveness of the pasta showed linear increase ($p < 0.05$) in response to incremental levels of EW and XG, whilst that of pasta containing GG showed linear decrease ($p < 0.05$). The colour parameters of the uncooked pasta showed linear and quadratic increases ($p < 0.05$) in response to incremental levels of the hydrocolloids. However, the colour of the cooked pasta, except for lightness showed a linear and quadratic decrease ($p < 0.05$) in response to incremental levels of the hydrocolloids. The pasting properties of pasta containing EW showed a linear decrease ($p < 0.05$) in response to incremental levels of EW. In contrast, the pasting properties of pasta containing GG and XG showed a linear increase ($p < 0.05$) in response to incremental levels of the hydrocolloids. Moreover, xanthan gum was the only hydrocolloid that significantly influenced ($p < 0.05$) the gel texture of the paste.

The findings of the present study demonstrated that hydrocolloids can enhance the quality and functional characteristics of banana flour-based pasta. However, the influence of hydrocolloids dependent on the type (source) and their inclusion levels. To optimize quality and functional characteristics texture of the banana flour pasta, inclusion levels of EW should be 19% while those of GG and XG should be 2 – 3%. The findings of study could be used to enhance the quality and functional characteristics of other gluten-free pasta products to improve food security and consumer acceptability.

Keywords: Pasta; Banana Flour; Egg White; Guar and Xanthan Gums; Cooking Behaviour; Texture, Colour; Pasting Properties; Gel Texture.

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DEDICATION

I dedicate this work to my mother, Mavis Dibakoane as well as Professor P. Q. Siyongwana, and Dr B. J. Ncabani.

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LIST OF ABBREVIATIONS/ACRONYMS

a*	Redness
ACCC	American Association of Cereal Chemists
DAFF	Department of Agriculture, Forestry and Fisheries
b	Brightness
c	Mean Saturation Index
DF	Dietary Fibre
EW	Egg whites
FAO	Food and Agricultural Organization
FD	Freeze- dried
FDA	Food and Drug Administration
GBF	Green Banana Flour
GF	Gluten- Free
GG	Guar gum
GI	Glycaemic index
h	Hue Angle
HI	Hydrolysis Index
IDF	Insoluble dietary fibre
L	Lightness
MC	Moisture Content
ODF	Oven Fried Flour
PPO	Polyphenol Oxidase
RS	Resistant Starch
RSM	Response Surface Methodology
SDF	Soluble dietary fibre
SDS	Soluble Digestible Starch
SEM	Standard Error of Mean
TDF	Total dietary fibre
TS	Total Starch
XG	Xanthan gum

1 CHAPTER ONE: GENERAL INTRODUCTION

1.1 Background

Bananas (*Musa spp.*) account for more than 50% of tropical fruits produced globally and 70% of all horticultural crops traded globally and have the highest per-consumption rate of 15 kg (FAO, 2020). The production of bananas increased from 67 million tonnes to 114 million tonnes from 2002 to 2019 (FAO, 2021). Bananas are primarily produced for consumption and local sales by smallholder farmers; as a result, only 15% of bananas produced globally are traded in global markets (FAO, 2021). Therefore, bananas are an essential livelihood, economic, and nutritional fruit in the developing world (Aurore *et al.*, 2009; DAFF, 2017; Dotto *et al.*, 2019; Mashau *et al.*, 2012; Padalino *et al.*, 2016). Bananas contribute 44% of the total gross value of horticultural crops and are the fourth most produced crop (531 400 tonnes) in South Africa between 2022 - 2023, behind citrus (3 674 001 tonnes) and apples (1 180 897 tonnes) (DAFF, 2017; DALRRD, 2023). However, one-third of bananas are discarded due to inadequate postharvest handling facilities and consumer preferences (Amini Khoozani *et al.*, 2019; Juarez-Garcia *et al.*, 2006; Mashau *et al.*, 2012). The conversion of bananas into flour has reduced their wastage, preserved their nutritional properties, and improved their market value (Li *et al.*, 2020). Due to its high nutritional value (dietary fiber and resistant starch), flour processed from bananas can be used to develop nutrient-dense foods such as pasta (Li *et al.*, 2020; Tangthanantorn *et al.*, 2021b; Yangilar, 2015).

Pasta is essential for human nutrition and the sustainability of food systems because it has a long shelf life, minimum cooking and transportation requirements, and is palatable (Amini Khoozani *et al.*, 2019; Camelo-Méndez *et al.*, 2018; Woomer & Adedeji, 2021). Pasta is rich in complex carbohydrates but lacks dietary fiber, resistant starch, and bioactive compounds

(Pablo M Palavecino *et al.*, 2019; Torres Vargas *et al.*, 2021). Given its high nutrient density (carbohydrates, vitamins, resistant starch, minerals, and bioactive compounds) (Dotto *et al.*, 2019; Tangthanantorn *et al.*, 2021b), bananas have been used to improve the quality and functionality of gluten-free (GF) pasta without significantly altering consumer preferences (Flores-Silva *et al.*, 2015; Ovando-Martinez *et al.*, 2009). Hence, this study evaluates the combined influence of hydrocolloids (egg protein, guar, and xanthan gums) on the quality and functional characteristics of banana flour-based pasta.

1.2 Problem Statement

Longer shelf life, minimum cooking and transportation requirements, and palatability have made pasta among the most consumed foods globally (Camelo-Méndez *et al.*, 2018; Woomer & Adedeji, 2021). However, incidents of gluten-related allergies (celiac disease, etc.) have negatively impacted the consumption of wheat-based pasta. These gluten-related allergies are caused by a protein called gluten found in wheat/semolina-based pasta (Woomer & Adedeji, 2021). Gluten allergies, namely celiac disease, causes lifelong intolerance to gluten and inflammation of the small intestines, resulting in low nutrient absorption (Larrosa *et al.*, 2013; Myhrstad *et al.*, 2021; Saturni *et al.*, 2010). Gluten-related allergies can be treated by strict adherence to a gluten-free (GF) diet (Saturni *et al.*, 2010). However, gluten-free products have poor sensory and technological qualities as non-gluten flours cannot withstand over-processing (Alessandra Marti & Pagani, 2013; Rachman *et al.*, 2020b). Hence, gluten-free pasta has poor sensory properties, high cooking losses, and poor textural qualities such as stickiness (Padalino *et al.*, 2016). Furthermore, GF pasta lacks protein, fiber, iron, calcium, magnesium, zinc, and vitamins (B12, D, folate, niacin, and riboflavin) (Saturni *et al.*, 2010).

Banana flour has been proposed to replace conventional flour in pasta due to its high nutrient density (Campuzano *et al.*, 2018). The production of banana flour has also been used to minimize the wastage of bananas globally especially in banana-producing regions (Li *et al.*, 2020). The challenge with banana flour is that it has less protein than wheat flour (Rachman *et al.*, 2020b; Thakaeng *et al.*, 2021). Consequently, banana flour-containing products have low cooking quality, high cooking losses, darker color, and poor textural quality (Padalino *et al.*, 2016; Rachman *et al.*, 2020b). Therefore, there is a need to identify and evaluate ingredients to improve the quality of banana flour-based pasta. Hydrocolloids such as gums, and egg white can improve the quality and functional characteristics of banana flour pasta.

1.3 Justification

Hydrocolloids are polymers formed by a long chain of proteins and polysaccharides. Castelo-Branco *et al.* (2017c) reported that tagliatelle pasta prepared with 15- 30% banana flour and blended with egg protein showed no dark color. Tangthanantorn *et al.* (2021b) demonstrated that the incorporation of 1.0 and 1.5% guar gum and xanthan significantly reduced the cooking losses and improved the texture of 30% dried banana noodles. Furthermore, Rachman *et al.* (2020b) reported that incorporating egg protein into banana pasta improved the protein levels of banana flour pasta. In addition, Zandonadi *et al.* (2012) found that banana pasta blended with egg protein and guar and xanthan gums recorded higher acceptability compared to semolina-based pasta amongst celiac patients. Hydrocolloids improve the quality properties of pasta, namely cooking quality and texture, by interacting with starch granules to form a compact and robust internal pasta structure to prevent excess loss of solids and reduce the rate at which water can penetrate the pasta structure (Padalino *et al.*, 2013; Zheng *et al.*, 2016).

Colour is a key determinant in consumer acceptance of all food products. Hydrocolloids can improve the colour of pasta by forming a more stable protein matrix which prevents excess solids by limiting water penetration into the pasta matrix (Raungrusmee *et al.*, 2020; Sosa *et al.*, 2018; Xie *et al.*, 2020; Zheng *et al.*, 2016). Egg whites improve the colour of pasta by interlinking protein aggregates and starch granules to reduce the pore size of the gel microstructure and increases the intensity of reflected light (Bai *et al.*, 2022; Lorenzo *et al.*, 2018). Gums improve the colour of pasta preventing excess loss of solids due to its high water absorption capacity (Gasparre & Rosell, 2019; Javaid *et al.*, 2021; Raungrusmee *et al.*, 2020).

Increasing quantities of guar gum and xanthan gum has been shown to improve the pasting properties of wheat-based noodles (Liu *et al.*, 2023; Xu *et al.*, 2022b). The improvements emanate from the fact that guar gum at higher inclusion levels can increase inter-molecular interaction or entanglement with the starch granules, thereby increasing the viscosity of the pasta (Chauhan *et al.*, 2017). An increase in the viscosity of the pasta containing xanthan gum is attributed to the surface of hydrogen bonds of starch and the interaction of the starch with the hydrocolloid (xanthan gum) (Xu *et al.*, 2022b). However, some studies have suggested that hydrocolloids reduce the pasting properties (peak and final viscosity) of pasta wheat-based pasta containing guar gum (Aravind *et al.*, 2012) and jasmine flour noodles containing egg white (Detchewa *et al.*, 2022b). Hydrocolloids reduce the viscosity of pasta by reducing the quantity of water and starch available for swelling of starch granules and viscosity (Aravind *et al.*, 2012; Detchewa *et al.*, 2022b). Other studies have also suggested that incorporating hydrocolloids into pasta greatly decreased the breakdown, trough, and setback viscosity of millet-pomace-based pasta (Gull *et al.*, 2018) and wheat flour noodles (Liu *et al.*, 2023). Gums reduce the breakdown viscosity of pasta by forming a protective layer on the surface of the starch granules, thereby restricting swelling of the starch granules (Shahzad *et al.*, 2019).

Moreover, hydrocolloids reduce the setback viscosities by interacting with amylose to prevent the reconfiguration of the amylose chains (Chauhan *et al.*, 2017).

Hydrocolloids have been suggested to improve the gel firmness of food paste. Ding *et al.* (2024) found that the firmness of the gels of the wheat highland noodles increased as the inclusion levels of EW increased. Ding *et al.* (2024) attributed the increase in the gel of the wheat highland barley noodles containing EW to ionic bonds, hydrogen bonding, hydrophobic interactions, and disulphide bonds. Other studies conducted by scholars such as Shahzad *et al.* (2019) found that gums increased the firmness of potato starch gels. The higher firmness of the gels was attributed to the high molecular mass of guar gum, which enables greater interaction with starch granules to form a more rigid internal structure and increase the hardness of the gels (Saha & Bhattacharya, 2010). The rigid and conformational structure of xanthan gum increases the firmness of the gels/starch pastes by forming rigid 3D networks through electrostatic complexes with some protein fractions present in the pasta (Pongpichaiudom & Songsermpong, 2018). This will improve the hardness of the pasta and reduced its stickiness, thereby improving consumer acceptability of banana-flour pasta. Currently, limited studies have assessed the influence of hydrocolloids on the functional characteristics (pasting properties and gel texture) of banana based pasta. Hence, this study is significant as it attempts to elucidate how hydrocolloids (egg white, guar, and xanthan gums) influence the pasting and gel texture properties of banana flour-based pasta. Furthermore, studies on the effect of banana flour prepared from South African cultivars on pasta products have not yet been conducted. Therefore, this study is novel because it will be the first to evaluate the combined effect of hydrocolloids on pasta prepared using banana flour from South African cultivars. Hence, this study assessed how the interaction of egg protein, guar, and xanthan gums affects the quality of banana flour-based gluten-free pasta.

1.4 Aims and Objectives

1.4.1 Aim

The study assessed the combined effect of hydrocolloids (egg protein, guar, and xanthan gums) on the quality and functional characteristics of banana flour-based gluten-free pasta.

1.4.2 Objectives

1. To assess the effect of varying inclusion levels of three types of hydrocolloids (egg protein, guar, and xanthan gums) on the cooking quality, texture, and colour of banana flour-based pasta
2. To assess the effect of varying inclusion levels of three types of hydrocolloids (egg protein, guar, and xanthan gums) on the pasting properties and gel texture of banana flour-based pasta.

1.5 Research Hypotheses

The research hypotheses are as follows:

1. Null hypothesis: The inclusion levels of hydrocolloids (egg protein, guar, and xanthan gums) will not influence the quality and functional characteristics of banana flour-based pasta.

Alternative Hypothesis: The inclusion levels of hydrocolloids (egg protein, guar, and xanthan gums) will affect the quality and functional characteristics of banana flour-based pasta.

2. Null hypothesis: Incorporation of hydrocolloids at optimized levels will not improve the quality and functional characteristics of banana flour-based pasta.

Alternative Hypothesis: Incorporation of hydrocolloids at optimized levels will improve the quality and functional characteristics of banana flour-based pasta.

2. CHAPTER TWO: LITERATURE REVIEW

2.1 Description of Banana

Banana has two classes: plantain (cooking) and dessert banana type (Table 2.1). Plantains are cooking bananas with high carbohydrate content and are described as larger, more angular fruits from hybrid triploid cultivars. Furthermore, plantains are less prone to browning and Maillard reactions compared to dessert banana cultivars. However, unripe mature plantains are not valued due to their firmness caused by high carbohydrate content. Dessert bananas are pulpy, firmer to finer fruits without seeds and have a distinct flavor (Arvanitoyannis & Mavromatis, 2009). Dessert bananas are easy to detach from trees without any implements and are mostly used for commercial purposes (Kongolo *et al.*, 2017). Bananas are rich in resistant starch, dietary fibre (DF) (Anyasi *et al.*, 2013), phenolic compounds, vitamins and minerals (Dotto *et al.*, 2019). Hence, bananas are suitable for treating and preventing diseases such as diabetes, colon cancer, and obesity (Choo & Aziz, 2010; Menezes *et al.*, 2011). It has been suggested that banana production accounts for 75% of the monthly income generated by smallholder farmers (Aurore *et al.*, 2009). Smallholder farmers rely on indigenous cultivars for revenue generation (Mashau *et al.*, 2012) and household consumption (Anyasi *et al.*, 2013). In contrast, commercial farmers rely on commercial cultivars, which are superior to indigenous cultivars in terms of consumer acceptability, length, size, and weight for trade and export (Anyasi *et al.*, 2018).

Table 2. 1 Subgroups and main cultivars of Banana (Aurore *et al.*, 2009; Bakry *et al.*, 1997; Nakasone & Paull, 1998; Rieger, 2006).

Genomic Group	Subgroup	Cultivar Type	Dessert/Plantain (Cooking) Type	Distribution (Geographical)
AA	Sucrier	Fraysinette	Sweet Dessert	All continent

	Figue sucre´e			
	Pisang Lilin		Dessert	Indonesia, Malaysia
	Pisang Berangan		Dessert	
	Lakatan		Dessert	
AAA	Gros Michel	Gros Michel	Dessert	All continent
	Cavendish	Lactan	Dessert	Export Countries
		Poyo		
		Williams		
		Grand Nain		
		Petite Naine		
	Figue rose	Figue rose	Dessert	
	Lujugira	Intintu	Cooking	East Africa Region
		Lujugira	Cooking	
	Champa			
AAAA	Nasik		Dessert	
AAAB	Goldfinger	Goldfinger	Dessert	America, Australia
AB	Ney Poovan	Safet Velchi	Dessert	India, East Africa
		Sukari	Dessert	
	Figue			
AAB	Pomme	Maca silk	Dessert	All continent
	Pome	Prata	Dessert	Brazil, India
	Mysore			India
	Plantain	French Horn	Cooking	Africa, Carribean
		Come	Cooking	
ABB	Bluggoe	Bluggoe	Cooking	Phillipipines, America
	Poteau		Cooking	
	Fisang Awak	Fougamou	Dessert	
ABBB		Klue terapod	Cooking	
BBB	Saba	Saba	Cooking	Indonesia, Malaysia

2.2 Composition of Bananas

Bananas are mainly composed of the peel and pulp (Amini Khoozani *et al.*, 2019). The peel constitutes 35% of the mature fruit and has a high concentration of flavonoids, DF, and polyunsaturated fatty acids (Rebello *et al.*, 2014). The high antioxidant capacity in the banana peel reduces the glycemic index (GI) of foods, reduces cholesterol, and improves the fermentation capacity of the intestines (Castelo-Branco *et al.*, 2017c). In terms of yield, the pulp of unripe plantain flour recorded a higher yield (17.8%) compared to peel of unripe

plantain flour (3.8%) (Castelo-Branco *et al.*, 2017c). However, some scholars have demonstrated that peel flour of unripe Kluai Namwa plantain cultivars had a significantly higher yield (12.9%) compared to pulp starch (6.17%) and peel starch (0.69%) (Nasrin *et al.*, 2015). These variations in yield might be influenced by processing conditions (Khoozani *et al.*, 2019); ripeness stage (Campuzano *et al.*, 2018) and variations in the composition of the various portions of the banana fruit.

Studies have shown that the nutritional value of the peel and pulp varies. For example, Ramli *et al.* (2009) found that peel flour of unripe Cavendish (*Musa acuminata* L., cv *cavendshii*) and Dream (*Musa acuminata* colla. AAA, cv 'Berangan') cultivars had less RS content and more fibre content compared to pulp flour. Likewise, Nasrin *et al.* (2015) found that pulp starch had higher RS (76.83%) compared to peel starch (63.78%) and peel flour (8.60%) of unripe Kluai Namwa plantain cultivars. Regarding the concentration insoluble fraction of dietary fibre (DF), it has been suggested that plantain peel of unripe *Musa paradisiaca* L. (plantain) flour contained higher cellulose levels than hemicellulose and lignin (Agama-Acevedo *et al.*, 2016). In addition, green peel flour of unripe *Musa paradisiaca* L. (plantain) recorded the highest phenolic content (40.3%) compared to 32.9% in green pulp flour (Agama-Acevedo *et al.*, 2016). Flavonoids in the peel cause peel flour to have high phenolic and antioxidant content (Rebello *et al.*, 2014).

Hence, peel flour had a high antioxidant capacity compared to extractable flavonoids (Agama-Acevedo *et al.*, 2016). This high antioxidant capacity in peel flour is due to the insoluble fibres such as lignin, hemicellulose, and cellulose in banana peels. Some studies have also shown that of unripe plantain peel flour has more ash, fat, and protein content compared to pulp flour (Castelo-Branco *et al.*, 2017c; Nasrin *et al.*, 2015). Polysaccharides and essential amino acids

found in the peel, coupled with adding non-starch ingredients/components, are responsible for the high ash, fat, and protein content of the peel flour of *Musa balbisiana*) and *Musa AAA* Cavendish cultivars (Castelo-Branco *et al.*, 2017c; Rebello *et al.*, 2014).

2.3 Properties of Unripe Banana Flour

2.3.1 Physicochemical Properties

Banana flour contains more ash and dietary fibre than cassava and semolina flour (Table 2.2) (Rachman *et al.*, 2021). However, banana flour has less protein content compared to semolina flour (Table 2.2), with some studies showing that the protein content of unripe banana flour (4.98%) is about four (4) times lower compared to wheat flour (14.82%) (Thakaeng *et al.*, 2021).

Table 2. 2 Physicochemical Properties of Wheat and Banana Flour (Rachman *et al.*, 2021) (Vernaza *et al.*, 2011).

Components	Wheat Flour (%)	Banana Flour (%)
Moisture	12.61 - 17.48	8.50 – 8.91
Protein	10.60 – 12.36	4.54 – 4.99
Fat	0.77 - 0.94	0.36 - 0.44
Carbohydrates	75.46	82.58
Dietary fibre	2.44	8.88
Insoluble dietary fibre (IDF)	5.42	12.91
Soluble dietary fibre (SDF)	1.65	3.35
Total dietary fibre (TDF)	7.07	16.49
Ash	0.07 - 0.49	3.16 - 3.51

Banana flour has less protein content compared to semolina flour because it does not have gluten and has high starch content. Campuzano *et al.* (2018) demonstrated that the protein, fat, total sugar, and ash content increased as the banana ripened (Table 2.3). The ripening of bananas involves the conversion of starches into sugars, driven by the action of enzymes whose activity is typically increased rather than decreased (Schmitz *et al.*, 2022; Thompson *et al.*, 2019). Protein enzymes are crucial for this conversion, but they are not converted into sugars themselves (Merino & Cherry, 2007; Thompson *et al.*, 2019). Instead, they facilitate the biochemical processes that lead to the sweeter taste and softer texture of a ripe banana (Merino & Cherry, 2007; Thompson *et al.*, 2019).

Stage 1 to 2 of ripening involves minor conversion of starch, primarily resistant starch into sugars (Campuzano *et al.*, 2018; Cheng *et al.*, 2024). However, as ripening progresses from stage 3 to 4, there is rapid conversion of starch into sugar, hence, the low resistant starch (Campuzano *et al.*, 2018; Cheng *et al.*, 2024). Hence, it has been reported that ripening reduced the apparent amylose and moisture content (MC) in banana flour (Campuzano *et al.*, 2018). The low amylose content and MC could be due to the conversion of starch into sugar, which reduces the indigestible starch portions of starch content. The MC values mentioned above are significantly lower compared to the one reported for the green banana flour-pork skin composite gel (48.28% ww.b.) (Alves *et al.*, 2016). The green banana flour-pork skin composite gel recorded higher MC values because it was not subjected to any drying process. The ripening of bananas affects the application of banana flour in both research and the food industries. For example, studies have suggested that flour processed from bananas at stage 1 and 2 of ripening can be used for the development of functional bakery and food products due to their their rheological and nutritional properties, such as high peak viscosity, high final viscosity and high

resistant starch content (Campuzano *et al.*, 2018). However, flour processed from stage 3 and 4 of ripening can be used for the creation of puree or baby foods due to its high bioactive compounds, as well as its sugar and fat content, and improved taste and palatability (Campuzano *et al.*, 2018; Cheng *et al.*, 2024).

Table 2. 3 Influence of maturation on physicochemical properties (%) of Banana flour (Campuzano *et al.*, 2018)

	Moisture	Fat	Protein	Ash	Carbohydrates
Maturity stage					
1	10.88	1.33	3.69	2.10	82.3
2	10.67	1.38	3.68	1.63	83.0
3	6.77	2.87	8.82	2.61	80.4
4	8.63	3.67	5.52	2.27	80.1

2.3.2 Total, Resistant and Digestible Starch.

The portion of starch that cannot be hydrolyzed by enzymes in the small intestines of a healthy individual is called resistant starch (RS) (de Barros Mesquita *et al.*, 2016). The four types of RS are type 1: plant cells, type II- native granular starch (banana, potatoes, etc.), type III- retrograded starch and type IV- chemically modified starch (de Barros Mesquita *et al.*, 2016; Khoozani *et al.*, 2019) and type V- amylose-lipid complexes. Flour processed from green bananas has more resistant starch content (30 – 40%) compared to wheat flour (2.8%) (Kongolo *et al.*, 2017). Some studies have shown that the RS content of banana flour ranges from 3.91% (Hoffmann Sardá *et al.*, 2016a) to 90 % (Chang *et al.*, 2022). Resistant starch can mitigate the incidence of diseases such as diabetes and cancer by producing short-chain fatty acids,

modulating GUT microbial composition, increasing satiety (Dibakoane *et al.*), and inhibiting colon carcinogenesis (Menezes *et al.*, 2011). The concentration of RS in banana flour foods does not influence its nutraceutical potential, as some studies have shown that foods with 2.3% RS content can protect against diabetes, obesity, and other non-communicable diseases (Dibakoane *et al.*).

The RS content of banana flour is influenced by its amylose content (building of RS2) and processing conditions (de Barros Mesquita *et al.*, 2016; Khoozani *et al.*, 2019). Khoozani *et al.* (2019) demonstrated that the RS value for freeze-dried (FD) samples (46.72%) was comparable to the flour samples dried at 50° C in a hot-air oven (44.58%). However, the RS content of the oven-dried flour samples decreased below 40% as the drying temperatures increased from 80° C to 110° C. The low RS content in the oven-dried banana flour samples could be due to the modification/disruption of their molecular and crystalline structure at high temperatures. The high RS content of FD banana flour could be due to its high amylose crystallinity (2 times more than that of wheat flour), as some studies have suggested that the amylose content is correlated with the RS content of a given flour (de Barros Mesquita *et al.*, 2016; Khoozani *et al.*, 2019). However, contrary findings were made concerning the correlation of amylose and RS content (de Barros Mesquita *et al.*, 2016). The highest amylose content (29.1%) was found in Maca, while Grand Nine recorded the highest RS content (82.67%). Hence, more research is warranted to unravel the effects of processing conditions on the amylose and the resistant starch nexus in banana flour.

Hoffmann Sardá *et al.* (2016a) found that banana flour samples recorded total starch (TS) of 60% and above. However, Kongolo *et al.* (2017) demonstrated that maize (90.4%) and wheat (75.8%) flour showed the highest values for total starch (TS) compared to banana flour (59.1 – 77.2%). Resistant starch content is the most abundant form of starch in green bananas [20],

hence, maize and wheat flour might have more TS content compared to unripe banana flour. Furthermore, food processing conditions influence the starch composition of banana flour. Hence, it has been reported that banana flour oven dried at 80 and 100 °C recorded higher digestible starch values compared to the freeze dried banana flour (Khoozani *et al.*, 2019). High digestible starch content in the banana flour oven dried at 80 and 100 °C is attributed to retrogradation and degradation of starch molecules (Bi *et al.*, 2017; Khoozani *et al.*, 2019).

2.4 Pasta and Celiac Diseases

Pasta originated in Italy and has existed since 2000 BC (Woomer & Adedeji, 2021). The most common forms of pasta on the supermarket shelves are: pasta screws, macaroni, fusilli, penne, tagliatelle, spaghetti, and lasagne plates ((Myhrstad *et al.*, 2021). Other forms of pasta include bigoli, fettuccine, bombardini, capunti and gigli (Woomer & Adedeji, 2021). The form of pasta products is influenced by shape, stuffing, length, and ingredients. Conventional pasta is derived from semolina found in wheat, which contains gluten. However, incidents of celiac disease and non-wheat allergy caused by gluten have prompted a shift towards GF pasta. A compromised gluten network causes GF pasta to have less desirable quality and sensory attributes (Alessandra Marti & Pagani, 2013) by causing granules to swell and excess amylose content, which produces pasta with high stickiness, low firmness, and high cooking losses (Almanza-Benitez *et al.*, 2015; Rachman *et al.*, 2020b). Hence, there is still ongoing research to assess the effects of novel grains, hydrocolloids, enzymes, and processing techniques on the quality and functionality of GF pasta (Woomer & Adedeji, 2021).

2.5 Description and Effects of gluten

Barley, oat, rye, and wheat contain gliadin and glutenin, two proteins that when mixed together in water form gluten, which is responsible for dough elasticity, baking quality characteristics, cohesivity, and water absorption (Do Nascimento *et al.*, 2014). Gliadins are responsible for the extensibility of gluten, while glutenins maintain the elasticity and strength of gluten (Balakireva & Zamyatnin, 2016). Gluten has been used as a stabilizing and functional ingredient due to its affordability (Myhrstad *et al.*, 2021). The popularity of gluten has decreased over the years due to intestinal disorders. Gluten causes inflammation, atrophy, and hyperplasia in celiac patients (Padalino *et al.*, 2016). Inflammation of the small intestines is caused by the accumulation of glutamine and proline, which are resistant to gastrointestinal digestion. Symptoms associated with gluten intolerance are diarrhea, nausea, skin rashes, macrocytic anaemia, and depression, which can be treated by adhering to a GF diet.

2.6 Challenges of Gluten Free Diets

Arguments about the proper definition of gluten-free products are ongoing because there is no international consensus on the most appropriate definition of gluten-free diets (Demirkesen & Ozkaya, 2020). The recommended concentration of gluten in gluten-free diets is 20 ppm/50 mg/day. Food products that do not contain prohibited grains (wheat, barley, rye, and crossbreds), gluten ingredients, and ≤ 20 ppm of gluten are considered to be gluten-free by the Food and Drug Administration (FDA) of the United States of America (Demirkesen & Ozkaya, 2020). Furthermore, food products with < 20 ppm (0.002%) and < 100 ppm (0.01%) should be labelled as products with no gluten or low levels of gluten (Verma *et al.*, 2017). New Zealand and Australia use the same definition provided by CODEX (Demirkesen & Ozkaya, 2020). However, these countries do not permit diets with oat or malt because current detection systems cannot detect these grains and their derivatives.

There is limited variety of gluten-free food products, they are insufficiently labelled, are pricey, and have quality defects caused by cross-contamination (Demirkesen & Ozkaya, 2020). Cornicelli *et al.* (2018) characterized and compared the nutritional properties of GF and regular food products in the Italian market. The study found that GF pasta recorded low fibre content, while higher protein content was found in conventional pasta. Hence, it is recommended for a celiac patient to read the labelling on food products, focus on whole daily dietary patterns, or consult a dietician (Cornicelli *et al.*, 2018; Demirkesen & Ozkaya, 2020). A study by Altamore *et al.* (2020) demonstrated that Italian consumers believe that pasta made from local grains is healthy. However, most consumers are ignorant about the origin and effects of local grains. In addition, A. R. Lee *et al.* (2007b) demonstrated that gluten-free diets cost twice as much as their wheat counterparts. Gluten-free products are found in grocery stores (36%), upscale markets (41%), food stores (94%) and internet (100%) (Anne R Lee *et al.*, 2007a). In addition, the strong presence of GF products on online shopping platforms has prompted the FDA to introduce new legislation regarding the online labelling of GF products. Banana flour can be used to develop and produce cost-effective gluten-free products due to its wide availability and underutilization (Cronjé *et al.*, 2018a; Cronjé *et al.*, 2018b; Mashau *et al.*, 2012; Ovando-Martinez *et al.*, 2009; Tangthanantorn *et al.*, 2021b). The underutilization of bananas in South Africa is more pronounced as some studies have reported that about 42 – 50% of bananas are wasted.

2.7 Application of Banana Flour in Gluten-Free Foods

Studies have shown that banana flour has anti-obesity, anti-colorectal cancer, and anti-diabetic properties (Amini Khoozani *et al.*, 2019; Juarez-Garcia *et al.*, 2006; Li *et al.*, 2020; Sidhu & Zafar, 2018; Singh *et al.*, 2016). These properties have resulted in the incorporation of banana flour into foods such as pasta (Castelo-Branco *et al.*, 2017c; Zandonadi *et al.*, 2012; Zheng *et*

et al., 2016), ice cream (Yangilar, 2015), bread (Juarez-Garcia *et al.*, 2006) and biscuits (Cahyana *et al.*, 2020). Banana flour has also been incorporated into beverages (de Oliveira Lomeu *et al.*, 2020; Hoffmann Sardá *et al.*, 2016b; Ribeiro Vieira *et al.*, 2017) and dietary intervention/supplementation (Agustin *et al.*, 2019; Almeida-Junior *et al.*, 2017; Alvarado-Jasso *et al.*, 2020). However, most banana flour-based foods exhibit poor technological and sensory properties (Rachman *et al.*, 2020a) due to their lack of gluten-like properties (hydrocolloidal properties) and low protein content (Rachman *et al.*, 2020b; Thakaeng *et al.*, 2021) which results in the formation of less extensive starch-protein network. Hydrocolloidal properties refers to the ability of a dough to be elastic, cohesive, have high water absorption and extensibility (Do Nascimento *et al.*, 2014). The less extensive starch-protein network in banana flour causes pasta products to have less extensible dough and poor textural properties (i.e., stickiness) (Zandonadi *et al.*, 2012). Hydrocolloids have been used to reduce the undesirable quality properties of banana flour-containing foods. Studies by Castelo-Branco *et al.* (2017c) and Zheng *et al.* (2016) demonstrated that banana flour pasta containing egg protein had an extensive starch-protein network and showed no dark color on its surface. Furthermore, Tangthanantorn *et al.* (2021b) and Zandonadi *et al.* (2012) found that increasing the inclusion levels of guar and xanthan gums reduced the cooking losses and improved the acceptability of banana flour pasta amongst celiac patients. It is suggested that the hydrocolloids improve the quality, sensory, and technological properties of foods such as pasta by improving the extensibility of banana flour dough and interacting with starch granules to form a more extensive starch-protein network, which prevents excess cooking losses and water absorption by the starch granules (Castelo-Branco *et al.*, 2017a; Zandonadi *et al.*, 2012; Zheng *et al.*, 2016).

2.8 Hydrocolloids in Pasta

Hydrocolloids are polymers formed by a long chain of proteins and polysaccharides (Woomer & Adedeji, 2021). When included in the dough formulation, they modify its rheology and improve food quality, stability, functionality, safety, and nutritional composition (Saha & Bhattacharya, 2010). The global hydrocolloid market is expected to rise by 50% within 5 - 10 years (Saha & Bhattacharya, 2010; Yemenicioğlu *et al.*, 2020). Hydrocolloids are extracted from plant, animal, seaweed, and microorganisms and are used as stabilizers, emulsifiers and thickening agents in products (Yemenicioğlu *et al.*, 2020). Hydrocolloids are used in both the pharmaceutical, packaging, personal skin care industries and food industries (Chaturvedi *et al.*, 2021). The applications of the various hydrocolloids and their applications are summarized in Table 2.4.

Table 2. 4 Type of Hydrocolloids (*Yemenicioğlu et al., 2020*)

Source	Type	Applications	References
Plant	Microcrystalline cellulose (MCC)	Bakery and confectionary toppings; Meat Products, Beverages, Dairy products, dressings, emulsions and edible films plus probiotics.	(Nsor-Atindana <i>et al.</i> , 2017)
	Pectin	Jams and Jellies, Beverages and Yoghurts	
	Guar Gum	Ice cream. Chapati, Bread, Cake and Fried Products	(Sharma <i>et al.</i> , 2018)
	Methylcellulose (MC) and Carboxymethyl cellulose (CMC)	Dairy deserts, fried foods, sauces,	(Sung-Wan Lee <i>et al.</i> , 2010)
Animal	Whey Protein	Beverages, bars and yoghurts	(Yemenicioğlu <i>et al.</i> , 2020)
	Gelatin	Dairy products; Meat products and low-calorie products	(Yemenicioğlu <i>et al.</i> , 2020)
		Bakery Products and Gels	(Razi <i>et al.</i> , 2023; Yemenicioğlu <i>et al.</i> , 2020)
	Egg- based hydrocolloids (Whole eggs, egg white)		

Seaweeds	β –glucan	Prebiotic sausages, dairy products, beverages, extrude snacks, bakery products and food formulations	(Zhu <i>et al.</i> , 2016)
Microorganisms			
Xanthomonas campestris	Xanthan	Bakery Products, Beverages, Dairy Products and Meat Products	(Chaturvedi <i>et al.</i> , 2021)
Pseudomonas elodea	Gellan	Gels, Food Films, Deserts and Jams	(Iurciuc <i>et al.</i> , 2016)
Kamagataeibacter xylinus	Cellulose	Packaging, microencapsulation, food stabilizers, functional foods and starch foods.	
Acetobacter xylinum			(Mu <i>et al.</i> , 2019)

Egg-based hydrocolloids are extensively used in the food industry due to their high nutritional value, pasting properties, emulsification, and coagulation properties (Xie *et al.*, 2020; Yemenicioğlu *et al.*, 2020). Rachman *et al.* (2020b) found that egg protein increased the protein digestibility of banana flour pasta. However, the egg protein decreased the digestibility of the banana flour pasta (Rachman *et al.*, 2020b). Hydrocolloids from seaweeds are used for their bioactive polysaccharides, such as laminarin and a β –glucan (Saha & Bhattacharya, 2010; Yemenicioğlu *et al.*, 2020). Hydrocolloids from microorganisms improve water absorption, textural properties, and mouthfeel of bakery, dairy, and meat products (Yemenicioğlu *et al.*, 2020).

Tangthanantorn *et al.* (2021b) found that incorporating 1 – 1.5% of xanthan gum significantly improved the glycaemic index (GI) and quality of 30% banana-dried noodles. Likewise, Padalino *et al.* (2013) demonstrated that incorporation of carboxyl methylcellulose and chitosan improved the structure of maize and oat bran pasta by forming a stable network. Hydrocolloids reduced the bulkiness and adhesiveness of spaghetti as they formed a stable protein matrix, which restricted the rupturing of granules and leaching of amylose. They also have a higher affinity for water (hydrophilic nature) and can modify the gelatinization temperature of the gluten-free products such as pasta (Padalino *et al.*, 2016). Hence, maize and oat pasta enriched with hydrocolloids show a modified gelatinization temperature (Padalino *et al.*, 2013).

2.9 Influence of Hydrocolloids on the Quality and Functional Properties of Banana Flour Pasta

2.9.1 Color Properties

Thakaeng *et al.* (2021) reported that flour processed from bananas has a darker color compared to flour processed from wheat. Hence, according to Amini Khoozani *et al.* (2019), unripe banana flour pasta tends to be darker than wheat-based pasta. The darker colour of unripe

banana flour pasta is caused by polyphenol oxidase (PPO) and Maillard reactions, and excess loss of solids caused by a compromised starch-protein matrix. It has been suggested that the activity of PPO leads to enzymatic browning of banana flour, which results in the formation of foods with unpleasant and undesirable colour properties, such as a darker colour on banana flour pasta (Anyasi *et al.*, 2015; Anyasi *et al.*, 2017). However, Castelo-Branco *et al.* (2017c) reported that unripe banana flour pasta made with egg protein did not have a darker color. This corroborates the findings of Zheng *et al.* (2016) who found that egg white produced a more pronounced protein structure in unripe banana flour pasta samples, which has been suggested to prevent excess loss of solids. The absence of darker colour on banana flour pasta containing egg protein (hydrocolloids) is due to the interaction of starch granules and hydrocolloids, which induces the strengthening of the physical structure/starch-protein network (Zheng *et al.*, 2016). A strong starch-protein network reduces water absorption capacity and loss of solids from the structure of the pasta during the cooking process; hence, GF pasta, such as banana flour pasta containing hydrocolloids, did not exhibit any darker colour (Castelo-Branco *et al.*, 2017a; Zandonadi *et al.*, 2012; Zheng *et al.*, 2016).

2.9.1.1 Lightness

It has been suggested in the literature that consumers prefer pasta with a brighter and yellowish colour; hence, pasta with a dull and less yellowish colour is deemed to be of low quality (Lorenzo *et al.*, 2018). The lightness of uncooked and cooked pasta increased in response to the incremental levels of hydrocolloids (Table 2.5). Bai *et al.* (2022) found that the lightness of cold steamed noodles increased from 64.1 – 68.68 as the inclusion levels of the egg white increased from 1 – 3%. Similarly, Javaid *et al.* (2021) and Xu *et al.* (2022b) found that the lightness of the non-fried potato noodles and wheat highland barley noodles increased from 53.34 – 57.85 and 70.41 – 75.15 as the inclusion levels of xanthan gum increased from 0.3 – 0.7% and 0.5 – 1.5% respectively. However, Kraithong and Rawdkuen (2020) found that the

lightness of red jasmine rice noodles decreased from 23.10 – 21.80 as the inclusion levels of guar gum increased from 0.2 – 0.4%, which suggested that an antagonistic interaction exists between the guar gum and rice flour components. The increase in the lightness of the pasta is attributed to the interaction of starch granules and the protein in egg whites, as well as the high water absorption capacity of the gums (Ertaş *et al.*, 2021; Gasparre & Rosell, 2019; Javaid *et al.*, 2021).

Evidence from literature suggests that cooked pasta has lower lightness compared to uncooked pasta (Table 2.5), albeit with some variations. Uncooked corn starch noodles had higher L* (85.20) compared to cooked proso-millet pasta (76.87 – 78.51) (Table 2.5) (Ertaş *et al.*, 2021; Motta Romero *et al.*, 2017). Likewise, Motta Romero *et al.* (2017) found that the lightness of the cooked proso-millet pasta (76.87 – 78.51) was lower than the uncooked pasta (82.23 – 83.84). This may be due to the lack of a synergized interaction between the gums and leached amylose (Shahzad *et al.*, 2019). On the other hand, cooked cassava starch and proso-milled pasta had higher L* values (69 – 78.51) compared to uncooked jasmine flour noodles (22.30 – 23.4), soya-channa flour pasta (29.63), wheat highland barley noodles (70.41 – 75.15) and non-fried potato noodles (53.34 – 57.85) (Table 2.5) (Javaid *et al.*, 2021; Kraithong & Rawdkuen, 2020; Milde *et al.*, 2020; Motta Romero *et al.*, 2017; Susanna & Prabhasankar, 2013; Xu *et al.*, 2022b).

The inclusion levels of the hydrocolloids influence the L* of the cooked pasta. Milde *et al.* (2020) found that the lightness of the cooked cassava starch pasta increased from 69 – 72 as the inclusion levels of xanthan gum increased from 0.4 – 0.6. Similar trends were reported by Motta Romero *et al.* (2017) for cooked proso-millet pasta. The high L* cooked pasta is attributed to the high water-absorption capacity of the gums (Gasparre & Rosell, 2019; Yalcin & Basman, 2008). The increase in the lightness of the cooked pasta may also be associated with the increasing inclusion levels of the hydrocolloids, which form a compact

structure and prevent excess leaching solids from the pasta structure, thereby preserving the lightness of the pasta (Detchewa *et al.*, 2022b; Gasparre & Rosell, 2019; Rachman *et al.*, 2020b; Zheng *et al.*, 2016). Xanthan gum prevents discoloration of pasta by interacting with amylopectin to increase the water-absorption capacity and viscosity of the pasta to prevent excess loss of solids (Raungrusmee *et al.*, 2020). The increased lightness of the cooked pasta is attributed to starch gelatinization (Sanguinetti *et al.*, 2015). Research has shown that starch gelatinization increases the lightness of pasta (Sanguinetti *et al.*, 2015).

2.9.1.2 Redness

The redness (a^*) of the uncooked pasta was greater than that of the cooked pasta with some variations (Table 2.5). The effects of the varying inclusion levels of hydrocolloids varied between studies (Table 2.5). Bai *et al.* (2022) demonstrated that the a^* of uncooked corn starch noodles decreased as the inclusion levels of egg white increased from 1 – 3%. Ertaş *et al.* (2021) found that pasta containing egg white had higher a^* values (-0.32) compared to those containing whey protein, transglutaminase, and hydroxypropyl methylcellulose (- 0.45 to - 0.60). The increase in the redness of the uncooked pasta is attributed pasta containing EW is attributed to its high protein content, and pale colour (Ertaş *et al.*, 2021).

Furthermore, Javaid *et al.* (2021) found that the a^* of non-fried potato noodles decreased from 5.66 to 3.71 as xanthan gum increased from 0.3 – 0.7%. Similar trends were reported for pasta containing 0.2 – 0.4% guar gum (Kraithong & Rawdkuen, 2020). Xu *et al.* (2022b) also found that the a^* of wheat highland barley noodles increased from 2.90 to 3.15 as xanthan gum increased from 0.5 – 1.5%. The increase in the a^* values of the pasta containing guar and xanthan gums is attributed to the interaction of the gums and pigments in any given flour/ingredient (Javaid *et al.*, 2021; Kraithong & Rawdkuen, 2020; Milde *et al.*, 2020). This interaction promotes equal distribution of the pigments across the pasta structure increases redness of the pasta (Javaid *et al.*, 2021).

Detchewa *et al.* (2022b) found that the a^* of cooked jasmine rice noodles containing 5% egg white was 0.13. This was lower than the values reported by Pablo Martín Palavecino *et al.* (2017) for sorghum flour pasta (2.93 – 10.2) containing 4 – 9% egg white. The variations between the studies could be attributed to the inherent color properties of the flour used. Pablo Martín Palavecino *et al.* (2017) found that black sorghum flour pasta (10.24) was greater than white sorghum flour pasta. Motta Romero *et al.* (2017) found that the brightness of the cooked proso-millet pasta decreased from – 1.54 to – 1.94 as the inclusion levels of guar and xanthan gums increased from 1 – 2%. The a^* value of the cooked pasta decreased due to the thermal degradation of the carotenoids present in the egg white and the ingredients (i.e., flour) used to manufacture pasta (Motta Romero *et al.*, 2017). However, Milde *et al.* (2020) found that a^* values of cooked cassava pasta increased from 0.5 to 1 as xanthan gum increased from 0.4 to 0.6%. These trends could be due to the lighter colour of the cassava, as some studies have suggested that the colour of the ingredients (i.e., flour) has more effect on the colour of pasta than the hydrocolloids (Kraithong & Rawdkuen, 2020).

Table 2. 5 Effects of Hydrocolloids and Cooking on the Colour Parameters of Pasta

Type of Pasta	State	Type of Hydrocolloid	Inclusion levels (%)	L	a	b	c	h	References
Corn starch noodles	Uncooked	Egg white	10	85.20	- 0.45	27.55	27.55	90.96	(Ertaş <i>et al.</i> , 2021)
Red jasmine flour noodles	Uncooked	Guar gum	0.2 – 0.4	23.10 – 21.80	6.30 – 5.50	5.55 – 6.30	8.39 – 8.37	41.39 – 48.89	
Red jasmine flour noodles	Uncooked	Xanthan gum	0.2 – 0.4	22.30 – 23.40	5.89 – 5.71	5.40 – 5.75	8.00 – 8.12	42.40 – 44.99	
Steamed cold noodles	Uncooked	Egg white	1 - 3	64.1 – 68.68	- 1.70 – (-2.05)	-1.24 – (-0.39)			(Bai <i>et al.</i> , 2022)
Non-fried potato noodles	Uncooked	Xanthan gum	30 – 70	53.34 – 57.85	5.66 – 3.71	19.33 – 20.10			(Javaid <i>et al.</i> , 2021)
Wheat-highland barley noodles	Uncooked	Xanthan gum	0.5 – 1.5	70.41 - 75.15	2.90 – 3.15	12.16 – 15.73			(Xu <i>et al.</i> , 2022b)
Soya-channa flour pasta	Uncooked	Guar gum	0.5	29.63	5.83	10.54			(Susanna & Prabhasankar, 2013)
Jasmine rice flour noodles	Cooked	Egg white	5	67.87	0.13	14.02			(Detchewa <i>et al.</i> , 2022b)
Sorghum flour pasta	Cooked	Egg white	4 – 9	47.27 - 65.57	2.93 – 10.24	12.38 – 17.33			(Pablo Martín Palavecino <i>et al.</i> , 2017)
Soya-channa flour pasta	Cooked	Guar gum	0.5	31.16	4.77	10.64			(Susanna & Prabhasankar, 2013)

Proso-millet pasta	Cooked	Guar gum	1 – 2	76.87 – 77.27	- 1.54 - (-1.60)	16.04 – 15.84	(Motta Romero <i>et al.</i> , 2017)
Proso-millet pasta	Cooked	Xanthan gum	1 - 2	78.23 – 78.51	–1.94	14.92 – 14.80	
Cassava starch pasta	Cooked	Xanthan gum	0.4 – 0.6	69 – 72	0.5 – 1	22 – 28	(Milde <i>et al.</i> , 2020)

*L = lightness; a = redness/greenness, b = yellowness/blueness, c = mean saturation index and h = hue angle

2.9.1.3 Brightness

The brightness of pasta containing hydrocolloids increased for the uncooked pasta and decreased for the cooked pasta, even at high hydrocolloidal inclusion levels (Table 2.5). The brightness of the uncooked pasta containing egg white had the highest brightness value compared to those containing xanthan gum and guar gum (Table 2.5) (Ertaş *et al.*, 2021). Furthermore, Bai *et al.* (2022) also found that the brightness of the steamed cold noodles increased from -1.46 to -0.39 as the inclusion levels of egg white increased from 1 – 3%. The increase in the b^* values of pasta containing EW is attributed to the pale color and carotenoid pigments in the egg white and the interlinking of protein aggregates and starch granules, which reduces the pore size of the gel microstructure and increases the intensity of reflected light (Bai *et al.*, 2022; Lorenzo *et al.*, 2018). Xu *et al.* (2022b) and Javaid *et al.* (2021) found that the brightness of the non-fried potato noodles and wheat flour increased from 19.33 – 20.10 and 12.16 – 15.73 as the inclusion levels of xanthan gum increased from 0.15 – 1.5% and 30 – 70% respectively. Kraithong and Rawdkuen (2020) found that the brightness of uncooked red jasmine flour noodles increased from 5.55 – 6.30 as the inclusion levels of GG increased from 0.2 to 0.4%. The gums' high-water absorption capacity increases the pasta's brightness (Gasparre & Rosell, 2019; Javaid *et al.*, 2021; Raungrusmee *et al.*, 2020) by preventing excess leaching of solids from the pasta structure. The high-water absorption capacity of gums such as XG is attributed to its double helical structure, multiple spiral polymer form, and ability to interact with amylopectin (Raungrusmee *et al.*, 2020).

The findings from the literature suggest that uncooked banana pasta tend to have higher brightness compared to cooked pasta, albeit with variations (Table 2.5). Motta Romero *et al.* (2017) found that the brightness of the cooked proso-millet pasta containing XG and GG was less than that of the uncooked pasta. Similarly, the brightness of the cooked sorghum flour pasta containing egg white (12.38 – 17.3) is less than that reported for corn-starch noodles

(27.5) (Bai *et al.*, 2022; Pablo Martín Palavecino *et al.*, 2017). The reduction in the brightness of the cooked pasta could be due to the destruction of pigments present in the ingredients as the pasta undergoes thermal processing (i.e., cooking) (Motta Romero *et al.*, 2017). The low b^* values of pasta containing EW are due to the destruction of carotenoids, which results in less reflected light and less compact protein structure (Bai *et al.*, 2022; Lorenzo *et al.*, 2018).

2.9.1.4 Mean Saturation Index and Hue Angle

The mean saturation index (C^*) and hue angle (h^*) of the uncooked pasta increased with incremental levels of hydrocolloids (Table 2.5). This may be due to the increased brightness of the pasta (Table 2.5). The hue angle (h^*) angle of uncooked pasta in response to the incremental levels of the hydrocolloids (Table 2.5). This implies that more light is reflected from the pasta's surface, which causes the sample's color to be skewed towards the red spectrum. The C^* and h^* values of the corn-starch pasta containing egg white were significantly greater than rice flour noodles containing guar and xanthan gums (Table 2.5). Carotenoids in the egg white is more effective in accentuating the brightness of pasta compared to other types of hydrocolloids (Table 2.5). Although no current studies have reported on the effect of hydrocolloids on the C^* and h^* values of cooked pasta, an inference may be made based on the brightness trends of the cooked pasta. The C^* and h^* values of cooked pasta will show a decreasing pattern even with increasing inclusion levels of hydrocolloids (Table 2.5). This could probably be due to the degradation of the brightness of pasta, which has been influencing the C^* and h^* values of pasta.

2.9.2 Textural Properties

Gluten-free pasta products tend to have undesirable textural properties because gluten-free flours cannot withstand overcooking and have higher water absorption rates, resulting in sticky pasta products forming (Plate 2.1; Table 2.6). Hence, Zandonadi *et al.* (2012) found that the

standard pasta was more firm and less sticky compared to green banana pasta. Flores-Silva *et al.* (2015) found that control pasta had more firmness and elasticity than chickpea-banana flour composite pasta. Likewise, Patiño-Rodríguez *et al.* (2019) found that control pasta samples had higher hardness, chewiness, cohesiveness, and elasticity values compared to unripe plantain flour products. This suggests that gluten-free flours tend to have poor textural qualities due to their limited elasticity caused by their lack of gluten. However, hydrocolloids such as guar gum can improve the elasticity of gluten-free flours (Padalino *et al.*, 2013). Hence, Milde *et al.* (2020) found that cassava starch-corn flour composite pasta containing hydrocolloids had higher firmness, hardness, and chewiness values compared to the pasta not containing hydrocolloids.

Hardness is the magnitude of force required to compress the food between the tongue and palate (Park *et al.*, 2020). Food products with high hardness (firmness) are deemed high quality due to their enhanced quality properties (Park *et al.*, 2020). It has been suggested that incorporating hydrocolloids improves the hardness of pasta by interacting with the starch granules/flour components to form a robust and compact internal pasta structure. Larrosa *et al.* (2016) found that the hardness of corn-starch pasta increased 621.00 – 2395.31 g as the inclusion levels of egg white increased from 1 – 3%. Similarly, Xie *et al.* (2020) and Guo *et al.* (2020) found that the hardness of rigatoni pasta and oat noodles increased from 134.56 – 234.53 g and 210.42 – 258.04 g as the inclusion levels of egg white increased from 3 – 5% and 10 – 30% respectively. Egg white (EW) increases the firmness of pasta by interacting with starch granules to form an extensive protein network and compact structure in the pasta (Bai *et al.*, 2022; Rachman *et al.*, 2020b; Rachman *et al.*, 2019; Zheng *et al.*, 2016).

The hardness of red jasmine flour noodles increased from 1074.21 – 1143.96 g as the inclusion levels of the xanthan gum increased from 0.2 – 0.4% (Table 2.6). The increase in hardness of the pasta containing xanthan gum is attributed to the presence of ionic charges, which enables

xanthan gum to interact and bind soluble starch granules, thereby enhancing the structural compactness of the pasta (Milde *et al.*, 2020; Widelska *et al.*, 2019). However, Motta Romero *et al.* (2017) found that the hardness of cooked proso-millet pasta decreased from 5753,24 – 4340.93 g as the inclusion levels of xanthan gum increased from 1 – 2%. This observation could be attributed to the high-water holding capacity of xanthan gum, which has been shown in certain instances to reduce the hardness of the pasta. However, Motta Romero *et al.* (2017) found that the hardness of proso-millet pasta increased from 4365,41 – 4568.33 g as the inclusion levels of guar gum increased from 1 – 2%. The increase in the hardness values of the pasta containing guar gum is attributed to its ability to interact with the starch granules to form a stable matrix inside the pasta (Gasparre & Rosell, 2019). This is in contrast with the findings of Kraithong and Rawdkuen (2020) who found that the firmness of the red jasmine noodles decreased in response to incremental levels of guar gum.

An increase in the hardness reduces the adhesiveness of the pasta (Guo *et al.*, 2020). Adhesiveness is defined as the adherence of leached solids on the surface of pasta (Guo *et al.*, 2020). It is also the force required to remove food that is adhered to the mouth (Park *et al.*, 2020). High adhesiveness is not desirable as it implies that the pasta has a sticky texture (an undesirable property to consumers); hence, it has been suggested that hydrocolloids reduce the adhesiveness of gluten-free pasta (Padalino *et al.*, 2013). The adhesiveness of pasta containing egg white, guar, and xanthan gums decreased in response to incremental levels of the hydrocolloids (Table 2.6). Larrosa *et al.* (2016) and Guo *et al.* (2020) found that the adhesiveness of corn-starch pasta and oat noodles decreased as the inclusion levels of egg white increased. Likewise, Kraithong and Rawdkuen (2020) also found that the adhesiveness of the red jasmine noodles decreased as the inclusion levels of guar and xanthan gums increased. The decrease in adhesiveness is attributed to the formation of a stable protein matrix in the pasta structure, which prevents excess leaching of solids during cooking, resulting in less sticky pasta

(Widelska *et al.*, 2019). The findings in the literature suggest that hardness is negatively correlated with adhesiveness, and hence increasing the hardness of the pasta greatly improves the textural properties of pasta, such as extensibility, as demonstrated by Kraithong and Rawdkuen (2020) and Tangthanantorn *et al.* (2021b).

Table 2. 6 Effects of Hydrocolloids on the Textural Properties of Pasta

Type of Pasta	Type of Hydrocolloid	Inclusion levels (%)	Hardness (g)	Adhesiveness (g.sec)	References
Corn starch-flour pasta	Egg white	1 – 3	621 – 2395.31 (6.09 – 23.49 N)	1.82 – 0.66	(Larrosa <i>et al.</i> , 2016)
Wheat flour (rigatoni pasta)	Egg white	3 – 5	134.56 – 234.53 (1.3 – 2.3 N)		(Xie <i>et al.</i> , 2020)
Oat noodles	Egg white	10 – 30	210.42 - 258.04	1.37 - 0.82	(Guo <i>et al.</i> , 2020)
Tigernut flour noodles	Xanthan gum	20	10349 - 10711	70 – 114	(Gasparre & Rosell, 2019)
Red jasmine flour noodles	Guar gum	20	10986 – 12765	39 – 79	(Kraithong & Rawdkuen, 2020)
	Guar gum	0.2 – 0.4	1798 – 1766	-40.70 to -41.27	
	Xanthan gum	0.2 – 0.4	1074.21 – 1143.96	-42.06 to -42.16	
Proso-millet flour pasta	Guar gum	1 - 2	4365,41 – 4568.33 (42.81 - 44.80 N)		(Motta Romero <i>et al.</i> , 2017)
	Xanthan gum	1 – 2	5753,24 – 4340.93 (56.42 - 42.57 N)		

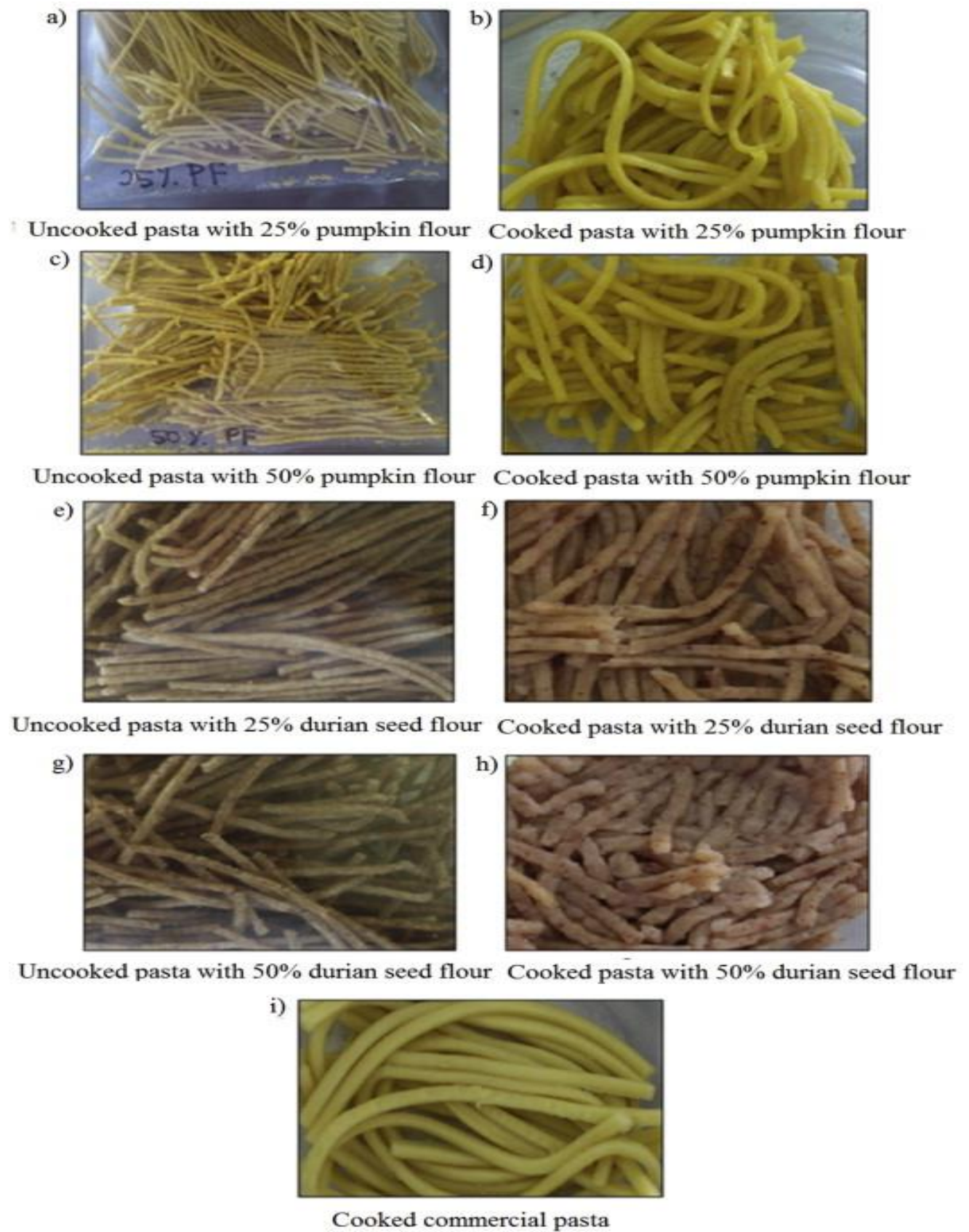


Plate 2. 1 Textural Properties of Gluten-Free Pasta (Mirhosseini *et al.*, 2015)

2.9.3 Cooking Quality

Cooking time is the time required for the pasta to lose its white core and form a flat paper-like position (AACC, 2000). Several studies have demonstrated that banana flour pasta has longer cooking times compared to its wheat counterparts. Zandonadi *et al.* (2012) found that standard pasta and green banana pasta containing hydrocolloids (egg white, guar, and xanthan gum) had longer cooking times compared to the standard pasta. Pasta made with gluten-free and starch-rich ingredients (banana flour) tends to have longer cooking times because more time and energy are required to gelatinize resistant starch (Zandonadi *et al.*, 2012). Furthermore, it has been demonstrated that increasing the quantities of hydrocolloids increases the cooking time of pasta (Table 2.7). Xie *et al.* (2020) found that the cooking time of wheat flour pasta increased from 9 to 15 minutes as the quantity of egg white increased from 3 to 5%. These cooking times were similar to those reported for banana flour pasta (8 min) and jasmine rice noodles (15.08 min) containing 5% and 31.5% EW, respectively.

Similarly, the cooking time of amaranth flour pasta increased from 3 to 4 minutes as the quantity of guar gum increased from 0.5 – 1% (Motta Romero *et al.*, 2017). Likewise, the cooking time of cassava starch noodles increased from 5 to 7 minutes as the quantity of xanthan gum increased from 0.4 – 0.8% (Milde *et al.*, 2020). The longer cooking time of pasta containing high quantities of egg white may be due to the formation of a compact structure that retards the penetration of water into the pasta core (Sosa *et al.*, 2018; Xie *et al.*, 2020). This implies that more time and higher temperatures will be required to gelatinize the starch granules. The longer cooking time associated with increasing guar gum quantities could be due to the formation of a denser and more crystalline structure which results in a less porous structure, thereby retarding the entrance of water into the pasta core. An increase in the cooking time of pasta may also be attributed to the formation of a more compact structure which results

from combining two or more types of hydrocolloids in a given food product (i.e., pasta) as demonstrated by Detchewa *et al.* (2022a) and Zheng *et al.* (2016) (Table 2.7).

Gluten-free pasta incurs higher cooking losses due to the lack of protein matrix that can reduce the excess diffusion of solids(amylose) from the pasta structure (Padalino *et al.*, 2016; Padalino *et al.*, 2013). Cooking loss refers to the amount of amylose or solids that diffuses from the pasta during the cooking (Sosa *et al.*, 2018; Zandonadi *et al.*, 2012). The recommended/acceptable cooking loss values for pasta ranges between 8 and 10%. Zandonadi *et al.* (2012) found that the cooking loss of green banana pasta was greater than that of commercial semolina pasta. High cooking losses in banana flour pasta are caused by the disruption of the starch-protein matrix by dietary fibre (resistant starch), leading to a loose protein structure (Baah *et al.*, 2022). A loose protein structure causes excess leaching of solids from the pasta during cooking (Baah *et al.*, 2022). Hence, research has shown that incorporating hydrocolloids incrementally can reduce the cooking losses of banana flour pasta (Tangthanantorn *et al.*, 2021b). Xie *et al.* (2020) found that cooking losses of rigatoni pasta decreased from 3.4 to 2.6% as the inclusion levels of egg whites increased from 3 – to 5%. Similar findings were reported for amaranth flour pasta (11.4 – 8.03 min) and cassava starch noodles (8.4 – 5.4 min), which were containing 0.5 – 1.0% GG and 0.4 – 0.8% XG (Chauhan *et al.*, 2017; Milde *et al.*, 2020). The reduction in the cooking loss of pasta containing egg white is attributed to the formation of an extension protein that restricts the leaching of solids from the pasta structure. Gums reduce the cooking loss of pasta by interacting with the starch granules through hydrogen and hydrophilic interactions to encapsulate the starch granules and prevent amylose diffusion during cooking (Tangthanantorn *et al.*, 2021b).

Hydrocolloids also reduce the cooking losses of GF pasta by hydrocolloids by increasing the extensibility of the doughs and forming a more defined protein matrix structure, which reduces the penetration of water into the pasta structure and excess loss of solids during the cooking

process (Detchewa *et al.*, 2022b; Kraithong & Rawdkuen, 2020; Zheng *et al.*, 2016). In addition, the incorporation of hydrocolloids into pasta has been able to maintain cooking loss within the acceptable range of 8 to 10 %, except for rice noodles containing d egg white; red jasmynes and banana flour pasta containing a combination of hydrocolloids (Table 2.7). This may suggest that some hydrocolloids may have an antagonistic interaction. Hence, more research may be warranted to find which combination of hydrocolloids enhances the cooking quality properties of gluten-free pasta.

Table 2. 7 Effects of Hydrocolloids on the Cooking Quality of Pasta

Type of Pasta	Type of Hydrocolloid	Inclusion levels (%)	Cooking Time (minutes)	Cooking Loss (%)	Reference
Jasmine rice flour noodles	Egg white	5	15.08	32.40	(Detchewa <i>et al.</i> , 2022b)
Banana flour pasta	Egg white composited with GG and XG	31.5	8	12.75	(Zandonadi <i>et al.</i> , 2012)
Wheat flour (rigatoni) pasta	Egg white	3 – 5	9 – 15	3.4 – 2.6	(Xie <i>et al.</i> , 2020)
Jasmine rice noodles	Guar gum composited with EW and XG	1	19.22 – 19.27	22.05 – 22.25	(Detchewa <i>et al.</i> , 2022b)
Extruded red jasmine noodles	Guar gum	0.2 – 0.4	9.10 – 9.03	5.07 – 5.15	(Kraithong & Rawdkuen, 2020)
Amaranth flour pasta	Guar gum	0.5 – 1	3.30 – 4	11.4 – 8.03	(Chauhan <i>et al.</i> , 2017)
Cassava starch noodles	Xanthan gum	0.4 – 0.8	5 – 7	8.4 – 5.4	(Milde <i>et al.</i> , 2020)
Extruded red jasmine noodles	Xanthan gum	0.2 – 0.4	8.27	7.25 – 7.97	(Kraithong & Rawdkuen, 2020)
Jasmine rice flour noodles	Xanthan gum composited with EW and SP	1	20.25 – 22.04	27.25 – 22.50	(Detchewa <i>et al.</i> , 2022b)

EW = Egg white; GG = Guar gum; SP = Soy Protein and XG = Xanthan gum.

2.9.4 Pasting Properties

The effects of various types of hydrocolloids on the pasting properties of pasta are summarized in Table 2.8. Pasting properties are related to the behavior when subjected to heat and cooling cycles (during cooking (Fan *et al.*, 2018; Stute, 1992; Zhou *et al.*, 2023). It can also be used to evaluate the quality of foods, as starch has been suggested to influence the quality of food products (Yahia *et al.*, 2019). The pasting properties of starch are usually influenced by amylopectin side chain length, amylose content, grain size, lipid content, source, and crystalline structure of starch (Miao *et al.*, 2009). The most common pasting properties are peak viscosity, trough viscosity, breakdown viscosity, final viscosity, setback viscosity, and pasting temperature.

Peak viscosity is the extent to which starch granules can swell freely before physically breaking down (Gull *et al.*, 2018). It is suggested that higher peak viscosity is associated with a higher proportion of un-gelatinized starch in food products, while low peak viscosity is associated with starch degradation in food products (Aasima Rafiq *et al.*, 2017). Hence, it has been reported that incorporating carboxyl cellulose into pasta made with millet-pomace restricted the swelling of starch granules by increasing the peak viscosity (Gull *et al.*, 2018). Liu *et al.* (2023) found that the viscosity of wheat flour noodles increased from 1656.67 – 2015.33 mPa.s and 1627.67 – 1978 mPa.s as the inclusion levels of guar and xanthan gums increased from 0.1 – 0.5%. Similarly, Xu *et al.* (2022b) found that the peak viscosity of wheat-highland barley noodles increased from 2249.30 – 2903.50 mPa.s as the inclusion levels of xanthan gum increased from 0.5 – 1.0%. Increasing the inclusion levels of guar gum in pasta increases inter-molecular interaction or entanglement with the starch granules, increasing the viscosity of the pasta (Chauhan *et al.*, 2017). The surface of the starch's hydrogen bonds and the starch's interaction with the hydrocolloids are responsible for the increase in the peak viscosity of pasta containing xanthan gum (Xu *et al.*, 2022b).

However, some scholars have argued that incorporating hydrocolloids, such as whey protein, reduces the peak viscosity by reducing water intake by starch granules (Alessandra Marti *et al.*, 2014b). Aravind *et al.* (2012) found that the peak viscosity decreased from 1183 to 1080 mPa.s as the inclusion levels of guar gum increased from 2.5 to 15%. Guar gums compete with starch to inhibit the peak viscosity of pasta by competing with the starch granules for available water to inhibit starch pasting and retrogradation (Aravind *et al.*, 2012; Detchewa *et al.*, 2022b). Similarly, Detchewa *et al.* (2022b) found that rice flour pasta containing egg white and xanthan gum had lower peak viscosity values compared to the control (rice flour pasta not containing hydrocolloids). The lower peak viscosity values of pasta containing hydrocolloids are attributed to lower starch content and high protein content in the pasta sample due to the addition of egg white and the hygroscopic nature of hydrocolloids, which reduces the amount of water available for starch swelling (Detchewa *et al.*, 2022b). In addition, disulphide bonds found in casein and whey proteins reduce the peak viscosity of pasta by restricting swelling and maintaining the structural integrity of the starch granules through the formation of a protein network barrier (Manoj Kumar *et al.*, 2019).

Trough viscosity is related to the disruption of starch granules after gelatinization and tends to have a lower value compared to peak viscosity (Kongolo *et al.*, 2017). Aravind *et al.* (2012) found that the trough viscosity of the pasta decreased from 1190 – 1080 mPa.s as the inclusion levels of guar gum increased from 2.5 – 15%. However, Xu *et al.* (2022b) found that the trough viscosity of wheat-highland barley noodles increased from 2249.50 to 2903.50 mPa.s as the inclusion levels of xanthan gum increased from 0.5 to 1.5%.

Furthermore, breakdown viscosity measures the extent of change in the viscosity of the starch granules after they have been gelatinized. It also has to do with the behavior of starch granules when subjected to the disruptive action of mechanical shear (cooking) (Kongolo *et al.*, 2017). Foods with higher breakdown viscosity values will incur higher losses during processing (i.e.,

cooking) (Manoj Kumar *et al.*, 2019). Manoj Kumar *et al.* (2019) found that incorporation of casein and whey protein reduced millet pomace-based pasta's trough and breakdown viscosity values. Similarly, Hong *et al.* (2021) and Aravind *et al.* (2012) found that the breakdown viscosity of the wheat-flour noodles decreased from 756 – 618.67 mPa.s and 526 – 401 mPa.s as the inclusion levels of sodium alginate and guar gum increased from 0.1 – 0.5 and 2.5 – 15% respectively. The decrease in the breakdown viscosity of the fortified pasta is attributed to the ability of gums to provide a protective layer on the surface of the starch granules, which restricts the swelling of the starch granules (Shahzad *et al.*, 2019). However, Liu *et al.* (2023) and Xu *et al.* (2022b) found that the breakdown viscosity of wheat-based noodles increased from 191 – 230 mPa.s and 911.00 – 1118.00 mPa.s as the inclusion levels of guar gum and xanthan gum increased from 0.5 – 1.5%. An increase in the breakdown viscosity of pasta is associated with increased water absorption of guar gum and the inability of the XG to transfer into the interior of the starch to prevent amylose leaching or diffusion (Xu *et al.*, 2022b).

Final and setback viscosity is related to the reordering of starch molecules, following gelatinization, and escape of amylose from broken starch granules (Kongolo *et al.*, 2017). The final viscosity of pasta-fortified wheat-based noodles and pasta increased as the inclusion levels of hydrocolloids increased (Table 2.8), except for durum wheat spaghetti, whose final viscosity values decreased with an increase in the inclusion levels of guar gum (Aravind *et al.*, 2012). This trend may be due to the interaction of gum and starch, which restricts the rapturing of starch granules, distinct molecular structures, lack of interaction with leached amylose, and flexibility of gum chains (Shahzad *et al.*, 2019). Gluten-free composite pasta and millet pomace-based pasta containing carboxyl cellulose casein and whey protein had lower setback viscosity values than the pasta not containing hydrocolloids (Table 2.8) (Gull *et al.*, 2018). Similar findings have been reported by Aravind *et al.* (2012), Hong *et al.* (2021), Liu *et al.* (2023), and Xu *et al.* (2022b) who demonstrated that increases in the inclusion levels of

hydrocolloids greatly reduced the setback viscosity values of pasta. The interaction of hydrocolloids and leached amylose reduces the setback viscosity of foods such as pasta by prohibiting the reassociation of amylose chains; hence, increasing inclusion levels of hydrocolloids reduces the setback viscosity of pasta (Chauhan *et al.*, 2017). This demonstrates that hydrocolloids can improve the quality of gluten-free products through the formation of a stable starch-protein matrix (similar effects as gluten).

Table 2. 8 Effects of Hydrocolloids on the Pasting Properties of Pasta

Type of Pasta	Type of Hydrocolloid	Inclusion Levels (%)	Peak Viscosity (mPa.s)	Trough Viscosity (mPa.s)	Breakdown viscosity (mPa.s)	Final Viscosity (mPa.s)	Setback Viscosity (mPa.s)	Pasting Temperature (°C)	References
Rice flour noodles	Egg white	5	3600 mPas				1750 mPas	86	(Detchewa <i>et al.</i> , 2022b)
Durum wheat spaghetti	Guar gum	2.5 – 15	1709 – 1482 cP	1183 – 1080	526 – 401	2411-1836	1228 – 756	-	(Aravind <i>et al.</i> , 2012)
Wheat flour noodles	Guar gum	0.1 – 0.5	1656.67 – 2015.33		191.00 – 211.33	2379.00 - 2696.00	913.33 - 892.00	91.57 - 91.82	(Liu <i>et al.</i> , 2023)
	Xanthan Gum	0.1 – 0.5	1672.67 - 1978		209.00 – 230.50	2380.33 – 2640.50	916.67 – 867.00	91.78 – 91.20	
Wheat-highland flour barley noodles	Xanthan Gum	0.5 – 1.5%	2249.50 - 2903.50	1338.50 – 1785.50	911.00 – 1118.00	2877.50 – 3175.50	1539.00 - 1390.00	63.20 - 60.13	(Xu <i>et al.</i> , 2022a)
High land barley flour fortified. wheat noodles	Sodium Alginate	0.1 – 0.5	2044.00 – 2197.50		756.00 – 681.67		869.00 – 808.67	92.32 – 91.90	(Hong <i>et al.</i> , 2021)

N.B The pasting properties were done on pasta that was ground to flour or powder.

2.9.5 In-vitro hypoglycemic properties of banana flour pasta products

The glycemic index (GI) measures how fast starchy foods are converted to glucose upon consumption (Eli-Cophie *et al.*, 2017), while the hydrolysis index (HI) is used to study the amount of glucose that can be derived from starchy foods (G. Deepa *et al.*, 2010). Foods with a GI value of less than 55% are called low GI foods, while those GI values of 56% and 70% are labelled as medium and high GI foods (Eli-Cophie *et al.*, 2017). Tangthanantorn *et al.* (2021a) found that banana flour noodles had higher RS (9.54 – 23.54%) and lower GI (62.61 – 72.73%) and HI (41.72 – 60.15%) value of banana flour noodles was greater than that of wheat flour noodles (5.56; 76.98 and 67.89%). Ovando-Martinez *et al.* (2009) found that noodles made with banana flour (15 – 45%) had higher RS (2.84 – 12.42%) and lower HI (45 – 55%) values compared to the control pasta (1.11; 60%). Similarly, Almanza-Benitez *et al.* (2015) found that RS (12.72 – 19.09 g/100g) and HI (25 – 35%) values of spaghetti made with acid-treated and non-modified plantain flour were lower than control samples (0.82 g/100g and 54.5%). Choo and Aziz (2010) found that the noodles made with 30% banana flour and oat β -glucan had higher RS (12.3 – 14.4%) and lower GI (31.0 – 39.7%) compared to control samples (3.68 – 4.83; 35.7%). Hydrocolloids such as oat β -glucan enhance the hypoglycaemic properties of banana flour-based pasta by forming viscous solutions that limit the activity of gastrointestinal enzymes (Choo & Aziz, 2010). Furthermore, hydrocolloids complex with starch granules to form a physical barrier and viscous solutions around the surface of granules to reduce the activity of gastrointestinal enzymes, their nutrient absorption, and attachment to the food substrate (Choo & Aziz, 2010; Faisant *et al.*, 1995; Tester *et al.*, 2006; Zheng *et al.*, 2016).

Other studies have demonstrated that spaghetti made with banana flour (15 – 100%) had higher RS (2.93 – 6.95 g/100 g) and lower GI (70 – 77.7%) and HI (38 – 42%) compared to semolina flour noodles (3.15 – 3.46 g/100 g; 45 – 55 and 71.4 – 85.3%) (Bello-Perez *et al.*, 2015). The

findings from the literature demonstrate that unripe banana flour-based products such as pasta are suitable for treating type 2 diabetes mellitus, obesity, and other non-communicable diseases compared to wheat flour products due to their higher RS content and lower GI and HI values. Low GI foods are critical for the prevention of non-communicable diseases such as diabetes because they induce prolonged absorption of glucose, suppress free fatty acids, and counter-regulatory responses induce abnormal swings in blood glucose levels (Esfahani *et al.*, 2009). Suppression of free fatty acids causes glucose to be withdrawn from circulation at faster rates, causing blood glucose levels to remain at baseline levels (Esfahani *et al.*, 2009). This significantly reduces peak postprandial glucose rise while maintaining above baseline (Hatekar & GHodKE, 2009). Hence, unripe banana flour products can be recommended for insulin-resistant individuals (type-1 diabetes, obesity).

Table 2. 9 *In vitro* hypoglycaemic properties of banana flour pasta products.

% Banana flour	Products	Resistant Starch (%)	Hydrolysis Index (%)	Glycaemic Index (%)	Reference
10 – 50	Noodles	9.54 - 23.31	41.72 - 60.15	62.61 - 72.73	(Tangthanantorn <i>et al.</i> , 2021a)
15 – 45	Spaghetti	2.84 - 12.42	32 - 55	-	(Ovando-Martinez <i>et al.</i> , 2009)
30 and β - glucans 15- 100	Noodles	4.83 - 12.3	55-60	31 - 39.7	(Choo & Aziz, 2010)
	Spaghetti	3.15 – 6.95 g/100 g	40 - 50	70.00 – 76.9	(Bello-Perez <i>et al.</i> , 2015)
	Spaghetti	12.27- 19.09	23 - 35		(Almanza-Benitez <i>et al.</i> , 2015)

2.9.6 Consumer Acceptability of Unripe Banana Flour Pasta

Gluten-free products have lower consumer acceptability and preference compared to its wheat counterparts due to poor technological and sensory properties. Hence, Zandonadi *et al.* (2012) found that standard pasta recorded higher appearance values compared to green banana pasta. However, the authors reported that green banana pasta, amongst celiac patients, recorded higher flavor, texture, and overall quality values compared to standard pasta. This could be probably due to the healthy promoting properties of unripe banana flour induced by its high resistant starch content (Dibakoane *et al.*). Similarly, Castelo-Branco *et al.* (2017c) found that green banana pasta containing egg protein recorded higher flavor and texture values compared to wheat flour pasta. In addition, Tangthanantorn *et al.* (2021b) found that 30% dried banana flour pasta containing 1.5% carboxyl cellulose, guar gum, and xanthan gum recorded higher sensory values compared to wheat flour pasta. These observations could probably be due to improved texture, stable protein matrix, and increased elasticity of the dough, which implies that unripe banana flour pasta has similar sensory properties as its wheat counterparts.

The overall acceptability and quality of banana flour pasta containing B-glucan was greater than that of unripe banana flour pasta (Choo & Aziz, 2010). Similarly, the overall acceptability and quality of unripe banana, corn, and chickpea flour composite pasta containing 0.5% carboxymethyl cellulose was like that of commercial pasta but significantly higher than durian seed flour pasta (Flores-Silva *et al.*, 2015). Likewise, pumpkin flour pasta has similar sensory attributes to commercial pasta but significantly higher than durian seed flour pasta (Mirhosseini *et al.*, 2015). It has been suggested that hydrocolloids improve the of pasta by increasing the extensibility of the pasta and reducing the water absorption rate of the pasta structure, resulting in less sticky pasta. Hence, Padalino *et al.* (2013) found no significant differences in the sensory attribute values of maize-oat flour pasta containing hydrocolloids, maize-oat flour pasta, and the control (wheat) pasta.

2.10 Summary

A gluten-free diet is the only treatment for consumers who are allergic to gluten-containing foods. Unripe banana flour has been proposed as a replacement for conventional flour due to its wide availability and high nutrient density. Some studies have demonstrated that banana flour can be incorporated into pasta without significantly altering its sensory properties and overall acceptability. Furthermore, banana flour enhances the low glycaemic index, antioxidant capacity and nutritional properties of gluten-free pasta. These health benefits emanate from the high dietary and resistant starch content in unripe banana flour. However, banana flour compromises the protein content, sensory properties, colour, texture, and cooking quality of pasta. Thus, some scholars have incorporated guar gum, xanthan gums, and egg whites to improve the quality and functional characteristics of banana flour-based pasta. Hydrocolloids enhance the utility and application of banana flour in food products through improved quality parameters. Hydrocolloids interact with the starch granules in banana flour to form a more compact internal pasta structure, prevent excessive leaching of solids, and reduce the rate water enters the internal pasta structure. These mechanisms improve quality (cooking time and loss; colour and texture) and functional characteristics (pasting properties and gel texture) of banana flour-based food products such as pasta. Despite this, there is currently limited knowledge on the influence of hydrocolloids on the quality and functional characteristics of banana flour-based pasta. Hence, more research on the influence of hydrocolloids on the colour, texture, pasting, and gel texture properties of banana flour-based pasta is warranted. These studies will enable food processors and scientists alike to understand the influence of hydrocolloids on the behavior of the starch granules of banana flour-based pasta and its associated quality and functional characteristics.

3. CHAPTER 3: EFFECT OF HYDROCOLLOIDS ON THE QUALITY CHARACTERISTICS OF GLUTEN-FREE UNRIPE BANANA FLOUR PASTA

Abstract

Banana flour is a promising ingredient for developing functional foods such as pasta. However, many consumers do not desire banana flour pasta products due to their high cooking loss, darker colour, and stickiness caused by the low protein in banana flour. To address the challenges, the present study assessed the combined effects of three types of hydrocolloid, namely egg white (EW), guar gum (GG), and xanthan gum (XG), on the cooking parameters (time and loss), colour, and texture of banana flour pasta. The pasta samples were prepared using distilled water (36.1 – 40.1%), wheat flour (60.6%), banana flour (36.0%) with varying levels of egg white (18 – 22); guar gum (0.5 – 4.5%) and xanthan gum (0.5 – 4.5%), dried overnight and stored in sealed and airtight plastics pending analysis of cooking quality, colour, and texture of pasta according to standard procedures. The influence of the hydrocolloids on selected quality (cooking time and loss, texture, and colour) parameters were analyzed using ANOVA. The response surface regression analysis was used to determine the relationships/interactions between the inclusion levels of the hydrocolloids and the quality parameters of the pasta. Cooking time and pasta hardness showed linear increases ($p < 0.05$), while the cooking loss showed a linear decrease ($p < 0.05$) as the inclusion levels of the hydrocolloids (EW, GG, and XG) increased. The adhesiveness of the pasta showed a linear decrease ($p < 0.05$) in response to GG increment levels but showed a linear increase ($p < 0.05$) with increasing EW and XG levels. The redness and brightness of the uncooked pasta containing EW showed quadratic responses, while those containing GG and XG showed linear increases as levels of hydrocolloids increased. The brightness and mean saturation index of uncooked pasta showed a linear increase ($p < 0.05$) in response to the incremental levels of

EW, GG, and XG. The Hue angle of pasta showed quadratic responses to increasing GG and XG levels but a linear response as the inclusion levels of EW increased. Xanthan gum showed positive quadratic effects on the lightness of cooked pasta, while this parameter had positive linear effects as the EW and GG inclusion levels increased. The redness of cooked pasta showed a linear decrease as the inclusion levels of all hydrocolloids increased. The brightness and mean saturation index of the cooked pasta containing EW showed quadratic decreases, while those containing GG and XG showed linear declines. The hue angle of cooked pasta containing EW quadratically increases, while in pasta containing GG and XG, it showed linear increases in response incremental levels of the hydrocolloids. Based on quadratic responses, it was determined that to enhance the quality (cooking time, colour, and texture) of banana flour pasta, the optimal inclusion levels of EW should be 19%, while those of GG and XG should be 2 – 3%.

Keywords: Gluten-free; Pasta; Banana Flour; Egg white; Guar gum; Xanthan gum; Cooking Time; Cooking Loss; Colour; Texture.

3.1 Introduction

Pasta is among the most consumed foods across the globe due to its food systems because it has a long shelf life, minimum cooking and transportation requirements, and is palatable (Amini Khoozani *et al.*, 2019; Camelo-Méndez *et al.*, 2018; Woomer & Adedeji, 2021). Pasta is rich in complex carbohydrates but lacks dietary fibre, resistant starch, and bioactive compounds (Pablo M Palavecino *et al.*, 2019; Torres Vargas *et al.*, 2021). However, the advent of gluten-related disorders such as celiac disease has negatively impacted the health of consumers who are allergic to gluten. The only treatment for gluten-related disorders is a gluten-free diet. Hence, there is a need to develop GF products with acceptable sensory

properties. Banana flour is a suitable ingredient for the production and manufacturing of GF pasta because it is rich in carbohydrates, vitamins, resistant starch, minerals, and bioactive compounds (Dotto *et al.*, 2019; Tangthanantorn *et al.*, 2021b), with some studies suggesting that incorporating banana flour can enhance the quality of gluten-free (GF) pasta, without significantly altering consumer preferences (Flores-Silva *et al.*, 2015; Ovando-Martinez *et al.*, 2009). However, banana flour-based pasta products exhibit compromised quality properties due to their relatively low protein content and lack of gluten (Rachman *et al.*, 2020b; Thakaeng *et al.*, 2021). Hence, banana flour pasta has longer cooking times, high cooking losses, darker color, and poor textural quality, such as stickiness (Padalino *et al.*, 2016; Rachman *et al.*, 2020b). Therefore, there is a need to incorporate ingredients such as hydrocolloids into banana flour pasta for enhanced quality.

Hydrocolloids, polymers formed by long chains of polysaccharides and proteins, have enhanced the quality of foods such as pasta. Castelo-Branco *et al.* (2017c) reported that tagliatelle pasta prepared with 15- 30% banana flour and blended with egg protein showed no dark color. Tangthanantorn *et al.* (2021b) demonstrated that incorporating 1.0 and 1.5% guar gum and xanthan significantly reduced the cooking losses of 30% dried banana noodles. Rachman *et al.* (2020b) reported that incorporating egg protein into banana pasta improved banana flour-pasta protein levels. In addition, Zandonadi *et al.* (2012) found that green banana pasta made with egg protein, guar, and xanthan gums recorded higher acceptability compared to wheat-flour pasta in terms of overall acceptability, texture, aroma, and flavor by both celiac and non- celiac patients. Furthermore, some studies have also shown that incorporating egg white, guar, and xanthan gums reduced the stickiness and adhesiveness of pasta samples by increasing the hardness of the pasta (AACC, 2000; Chauhan *et al.*, 2017; Motta Romero *et al.*, 2017). These improvements emanate from the fact that hydrocolloids can interact with the starch granules present in banana flour to form a more stable protein matrix in the pasta, which

retards the penetration of water and minimizes the loss of solids from the pasta structure during cooking. Most studies, except that of Zandonadi *et al.* (2012), have only focused on the influence of one type of hydrocolloid on the quality of pasta. Hence, knowledge of the combined influence on the quality of banana flour pasta is limited. Thus, this assesses the combined influence of three types of hydrocolloids (egg white, guar, and xanthan gums) on the cooking quality, color, and texture of pasta made from banana flour.

3.2 Materials and Methods

3.2.1 Materials

Dried green banana flour was purchased from a local retail supermarket in Mbombela, South Africa. The composition of banana flour was 4.9% protein, 71% carbohydrates, 0.6% fat, and 12.8% dietary fibre. White bread wheat flour was also purchased from a local supermarket in Mbombela. It contained 11.4% protein, 69% carbohydrates, 2.3% fat, and 41% dietary fibre. Protein albumen egg white powder was purchased from Mopani Pharmacy (Mbombela), and it contained 84% protein, 4.5% carbohydrates, <0.1% fat, 0% dietary fibre, and 4.5% ash. Guar Gum (Essentially Natural and a local retail supermarket, Mbombela) had a composition of 4% protein, 0% carbohydrates, 0.2% fat, and 83% dietary fibre was purchased from the Dis-Chem Group, Mbombela. Xanthan Gum (Dis-Chem Group, Mbombela) comprised 6% protein, 0% carbohydrates and fat, and 76% dietary fibre. Salt (Meat World Retail Butchery, Mbombela) comprised 99% sodium chloride and 39% sodium.

3.2.2 Pasta Preparation and Formulation

The formulation of the pasta samples is summarized in Table 3.1. Each pasta sample was replicated three (3) times. The control samples were formulated according to Balmurugan *et al.* (2022) with slight modifications. Banana flour pasta samples were formulated according to

Zandonadi *et al.* (2012) with slight modifications. Ingredients were mixed manually (hand) for 10 minutes and with a Kitchen Aid Heavy Duty Bowl-Lift 4.8L Stand Mixer for 5 minutes to achieve homogenization. The dough was allowed to rest for 15 minutes in an air-tight container. The dough was strained and cut into fettuccine strips using a cylindrical machine (Progressive PL8 Professional Pasta Machine) and dried overnight at 45° C in a hot-air oven. The dried pasta samples were stored in airtight plastic packs at room temperature till further analysis.

Table 3. 1 Formulation (%) of Pasta Containing Egg White

Pasta Code	Salt	EW	Banana Flour	Water	Wheat Flour	GG	XG	Total
XG1	0.9	18	36	40.1	0	0.5	2.5	100
XG2	0.9	19	36	39.1	0	1.5	2.5	100
XG3	0.9	20	36	38.1	0	2.5	2.5	100
XG4	0.9	21	36	37.1	0	3.5	2.5	100
XG5	0.9	22	36	36.1	0	4.5	2.5	100

EW = Egg Whites; GG = Guar Gum; XG = Xanthan Gum

Table 3. 2 Formulation (%) of Pasta Containing Guar Gum

Pasta Code	Salt	EW	Banana Flour	Water	Wheat Flour	GG	XG	Total
XG1	0.9	20	36	40.1	0	0.5	2.5	100
XG2	0.9	20	36	39.1	0	1.5	2.5	100
XG3	0.9	20	36	38.1	0	2.5	2.5	100
XG4	0.9	20	36	37.1	0	3.5	2.5	100

XG5	0.9	20	36	40.1	0	4.5	2.5	100
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EW = Egg Whites; GG = Guar Gum; XG = Xanthan Gum

Table 3. 3 Formulation (%) of Pasta Containing Xanthan Gum

Pasta Code	Salt	EW	Banana Flour	Water	Wheat Flour	GG	XG	Total
XG1	0.9	20	36	40.1	0	2.5	0.5	100
XG2	0.9	20	36	39.1	0	2.5	1.5	100
XG3	0.9	20	36	38.1	0	2.5	2.5	100
XG4	0.9	20	36	37.1	0	2.5	3.5	100
XG5	0.9	20	36	36.1	0	2.5	4.5	100

EW = Egg Whites; GG = Guar Gum; XG = Xanthan Gum

3.2.3 Cooking Quality

The AACC method 66-50 (AACC, 2000) was used to analyze the cooking time and loss of the pasta. For analysis of cooking time, 25 g of banana flour pasta was weighed and cut into 5 cm long pieces. Thereafter, the pasta was transferred into boiling water and stirred to ensure that the pasta pieces separated. The pasta samples were taken from the boiling water and squeezed between two glasses to check whether the core of the pasta had disappeared. The time taken for the white core to disappear was recorded as cooking time. To determine cooking loss, the water used to cook the pasta was transferred into a pre-weighed 500 ml beaker. The water was in a hot-air convection oven for 20 hours at 110°C. The weight of remaining residue (cooking loss) was recorded and expressed as a percentage of the weight of the original pasta sample before cooking as follows:

$$\text{Cooking Loss (\%)} = \frac{\text{Remaining Solid Content After Drying (g)}}{\text{Weight of Fresh Pasta (g)}} \times 100$$

3.2.4 Colour

Colour analyses were done for both uncooked and cooked pasta. Samples were cooked according to methods prescribed by the AACC (2000). The samples were rinsed in 100 ml distilled water and rested for 10 minutes in plastic containers. The colour of the pasta was analyzed using a handheld colorimeter (Lovibond Chroma Meter). The colour parameters that were analyzed were lightness (L^*), redness/greenness (a^*), yellowness/blueness (b^*), chromaticity (C^*), and the hue angle (H^*). Each sample was measured ten times.

3.2.5 Texture

Texture analysis of the cooked pasta samples was done according to methods described by El-Sohaimy *et al.* (2020) with minor modifications. Ten grams of pasta was cooked in 1 litre of distilled water containing 2.5 ml of NaCl using cooking times determined in the cooking test. The cooked pasta was rinsed with 100 ml of distilled water and allowed to rest for 10 minutes at room temperature before they were analyzed for texture. The texture analyzer (TA/TX-plus; StableMicro system, Surrey, UK) was equipped with a 5 kg load cell, and the Exponent 32.6.0.2.0 software was used for recording data. The texture analyzer was also equipped with a P36 cylindrical probe and the default settings (2 mm/s pre-test speed, test speed, post-test speed, 75% strain, trigger type, 10 g - auto, and 200 pps (points per second) data acquisition). Each sample was analyzed seven times, and the TPA parameters of interest were hardness (g) and adhesiveness (g.sec).

3.3 Statistical Analysis

The SAS software V8 (SAS Institute, Inc., Cary, NC, USA) was used to analyze the data. The influence of the hydrocolloids on the quality of the pasta was analyzed using the One-way ANOVA. The means between the samples (95% confidence interval) were separated using Duncan's Multiple Range correlation test. The response surface regression analysis was carried

out to analyze the relationships between the inclusion levels of the hydrocolloids and the quality parameters of the pasta. The model that was used to assess the relationship between the inclusion levels and the response parameters was:

$$y = ax^2 + bx + c$$

where y is the response parameter; a and b are the model coefficients; c is the intercept; x is the inclusion level of the hydrocolloids; and $-b/2a$ is the x value that maximizes or minimizes (optimizes) a response parameter.

3.4 Results and Discussion

3.4.1 Cooking Time of Banana Flour Pasta

The effects of hydrocolloids on the cooking parameters of unripe banana flour pasta are presented (Table 3.4). Cooking time refers to the time it takes for the pasta to lose its white core and form a flat, paper-like position (AACC, 2000). The cooking time of pasta showed a linear response to incremental levels of the hydrocolloids (EW, GG, and XG) (Tables 3.4 and 3.5). Similar trends have been reported by Milde *et al.* (2020), Rachman *et al.* (2019), and Xie *et al.* (2020). Pasta made from banana flour has longer cooking times because higher temperature/more energy is needed to gelatinize resistant starch (Zandonadi *et al.*, 2012). Hydrocolloids interact with starch granules to form a compact protein network which retards water absorption and increases the time required to cook the pasta (Detchewa *et al.*, 2022a; Sosa *et al.*, 2018; Xie *et al.*, 2020).

The cooking time of the pasta containing EW showed a linear increase ($R^2 = 0.854$; $p < 0.0001$) as the inclusion levels of the hydrocolloid increased (Tables 3.4 and 3.5). Pasta containing 21 and 22% EW had a significantly longer ($p < 0.05$) cooking time compared to pasta containing 18 – 20% EW (Table 3.4). The cooking time of pasta containing EW was longer than that

reported by Detchewa *et al.* (2022a), Sosa *et al.* (2018) and Xie *et al.* (2020) for jasmine rice noodles (15.08 min), quinoa-zein noodles (12 – 15 min), and semolina noodles (9 – 15 min). The longer cooking time of pasta containing high inclusion levels of EW could be due to the formation of a compact structure, which retards the penetration of water into the pasta core (Sosa *et al.*, 2018; Xie *et al.*, 2020), thus requiring more time and higher temperatures to gelatinize the starch granules.

Furthermore, the cooking time of the pasta containing GG showed a linear increase ($R^2 = 0.91$; $p < 0.001$) in response to the incremental levels of GG (Tables 3.4 and 3.5). The cooking time of pasta containing 2.5% GG was significantly higher ($p < 0.05$) than that of pasta containing 0.5 – 1.5% GG but lower ($p < 0.05$) than those containing 3.5 – 4.5% GG (Table 3.4). The cooking times of pasta containing 0.5 – 2.5% GG are like those reported by Detchewa *et al.* (2022a) for jasmine flour rice noodles (19.22 – 19.27 mins) made with a combination of guar gum and/or with soy protein and egg white but higher than those reported by Kraithong and Rawdkuen (2020) for Jasmine rice noodles (8.43 – 8.53 min). The longer cooking time associated with increasing GG inclusion levels could be due to the formation of a denser (less porous) and more crystalline structure, thereby retarding the entrance of water into the pasta core and slow water intake by the fibres (Padalino *et al.*, 2013).

Moreover, the cooking time of the containing XG showed a linear increase ($R^2 = 0.83$; $p < 0.001$) in response to incremental levels of XG (Tables 3.4 and 3.5). Pasta containing 2.5% – 4.5% XG had significantly higher ($p < 0.05$) cooking time compared to pasta containing 0.5 – 1.5% XG (Table 3.4). Pasta containing GG and XG had similar cooking time values (Table 3.4). The cooking time of pasta samples containing 0.5 – 2.5% XG was similar to those reported by Detchewa *et al.* (2022a) of 22.40 – 25.20 min for jasmine rice flour noodles but significantly higher than those reported by Kraithong and Rawdkuen (2020), Martín-Esparza *et al.* (2018) and Milde *et al.* (2020) of 2 – 8.2 min. The higher cooking time reported in the present study

may be due to the formation of a more compact structure, which results from combining two or more types of hydrocolloids in a given food product (i.e., pasta) as demonstrated by Detchewa *et al.* (2022a) and Zheng *et al.* (2016).

The cooking times of the pasta containing hydrocolloids were significantly higher than those reported in previous studies. This may be due to variations in the chemical composition and number of hydrocolloids between studies. Banana flour pasta has higher cooking times compared to other flours because it contains resistant starch which require longer cooking times because higher temperature/more energy for it to gelatinize. This results in delayed gelatinization and increase onset temperature of gelatinization. This was evidence as the pasting temperature of the pasta containing increased in response to incremental levels of EW (Table 4.1). Furthermore, pasta from previous studies contain a maximum of two type of hydrocolloids, whilst those in the present study contain three. Increasing the number and concentrations of hydrocolloids in pasta significantly increasing the cooking times by creating a more robust and compact structure, which retards penetration of water into the pasta structure. Hence, the pasta in the present study has a higher cooking time compared to those in literature.

3.4.2 Cooking Loss of Banana Flour Pasta

Cooking loss refers to the number of solids that leach out of the pasta structure during cooking (Sosa *et al.*, 2018; Zandonadi *et al.*, 2012). The recommended/acceptable cooking loss values for pasta samples range between 8% and 10%. The cooking loss of the pasta decreased in response to the incremental levels of the hydrocolloids (Table 3.4). Similar trends have been reported by (Milde *et al.*, 2020), (Rachman *et al.*, 2019), and (Tangthanantorn *et al.*, 2021b). Hydrocolloids cannot form the appropriate protein network at lower concentrations; hence, pasta with lower hydrocolloid inclusion levels (EW, GG, and XG) had higher cooking losses.

Lower inclusion levels cannot facilitate the effective interaction of hydrocolloids and starch granules (Zheng *et al.*, 2016).

Table 3. 4 Effects of Hydrocolloids on the Cooking Time and Cooking Loss of Pasta

Parameters	Inclusion levels of Hydrocolloids (%)					Significance	
						P-Linear	P-Quadratic
	Egg White						
	18	19	20	21	22		
Cooking Time (Mins)	18.67 (0.67) ^a	19.67 (0.88) ^a	22 (1.73) ^a	28.67 (0.88) ^b	31 (0.58) ^b	<0.001	0.1292
Cooking Loss (%)	7.1 (0.033) ^d	5.93 (0.24) ^a	6.1 (0.1) ^a	5.43 (0.08) ^{ab}	4.6 (0.15) ^b	<0.001	0.9029
	Guar Gum						
	0.5	1.5	2.5	3.5	4.5		
Cooking Time (Mins)	17.33 (0.67) ^a	19.67 (1.76) ^a	23.33 (0.33) ^d	30 (0.58) ^b	32 (1.15) ^b	<0.0001	0.5934
Cooking Loss (%)	7.07 (0.08) ^b	6.87 (0.18) ^{ab}	6.40 (0.1) ^{ab}	6.26 (0.36) ^{ab}	5.73 (0.59) ^a	0.052	0.8029
	Xanthan Gum						
	0.5	1.5	2.5	3.5	4.5		
Cooking Time (Mins)	19 (1.0) ^a	19.67 (0.88) ^a	25.33 (1.76) ^c	30.67 (0.88) ^b	30.33 (0.67) ^b	<0.0001	0.6645
Cooking Loss (%)	7.9 (0.35) ^b	7.07 (0.27) ^{ab}	6.70 (0.06) ^a	6.33 (0.15) ^a	6.0 (0.30) ^a	<0.0001	0.2721

Values in brackets are standard errors of means; ^{a,b,c}Means with a different letter superscript in each row are significantly (p<0.05) different

The cooking loss of pasta containing EW showed a linear decrease ($R^2 = 0.85$; $p < 0.001$) in response to the incremental levels of EW (Tables 3.4 and 3.5). The cooking loss of pasta samples containing 18% EW was significantly higher ($p < 0.05$) compared to pasta containing 19–22% EW (Table 3.4). Furthermore, the cooking loss of pasta samples containing 22% EW significantly differed ($p < 0.05$) from those containing 18–21% EW, while those containing 19 and 20% EW did not differ ($p > 0.05$). Cooking losses of pasta containing EW were within ranges reported by A. Marti *et al.* (2013) and Rachman *et al.* (2019) for banana flour and rice pasta (4.71 – 9.71%). The low cooking loss of the pasta containing EW could be formation of a more stable and extensive structure (Zheng *et al.*, 2016). Indeed, it has also been reported that egg albumen was more effective in reducing the cooking loss of rice flour pasta compared to whey proteins (A. Marti *et al.*, 2013).

Furthermore, a linear decrease ($R^2 = 0.44$; $p = 0.052$) was observed on the banana flour-based pasta as the inclusion levels of GG increased (Tables 3.4 and 3.5). Pasta containing 0.5% guar gum (GG) recorded significantly higher ($p < 0.05$) cooking losses compared to pasta containing 1.5% – 4.5% GG (Table 3.4). The cooking loss reported in the present study for GG-fortified pasta samples is higher than those reported by Kraithong and Rawdkuen (2020) and (Tangthanantorn *et al.*, 2021b) for extruded jasmine rice noodles (5.27 – 5.32) and dried banana flour samples (3.71 – 3 – 4.02%). Guar gum (GG) reduced the cooking losses of banana pasta samples by interacting with the starch granules through hydrogen and hydrophilic interactions to encapsulate the starch granules and prevent amylose diffusion during cooking (Tangthanantorn *et al.*, 2021b).

Moreover, the cooking loss of pasta containing XG showed a linear decrease ($R^2 = 0.74$; $p < 0.001$) in response to incremental levels of XG (Tables 3.4 and 3.5). Pasta containing 0.5% XG had significantly higher ($p < 0.05$) cooking losses compared to pasta containing 1.5 – 4.5% XG (Table 3.4). A similar trend was observed on the pasta containing GG (Table 3.4). The

findings reported in the present study are similar to those reported by (Milde *et al.*, 2020) and (Kraithong & Rawdkuen, 2020) for cassava-starch-corn flour pasta samples (5.4 – 8.4%) and extruded jasmine flour noodles (7.25 – 7.97%). The cooking loss of XG samples is higher than that of GG and EW samples. It has been suggested that the highly branched nature of XG increased the cooking loss of extruded rice noodles (Kraithong & Rawdkuen, 2020). A highly branched molecule is characterized by high rehydration, which may soften and weaken the pasta structure and trigger diffusion of solids when cooked (Kraithong & Rawdkuen, 2020; Tangthanantorn *et al.*, 2021b).

3.4.3 Interactions of Hydrocolloids and Cooking Parameters

The cooking time of the pasta showed a linear increase as the inclusion levels of hydrocolloids increased with R^2 values ranging from 0.82 – 0.91 (Table 3.5 and Figures 3.1 and 3.2). This is similar to the findings of Detchewa *et al.* (2022a) who demonstrated that combining EW and soy protein with XG and GG in a single product increased the cooking time of jasmine rice noodles. Cooking loss showed a linear decrease ($R^2 = 0.44 – 0.85$; $p < 0.05$) in response to the incremental levels of the hydrocolloids (Table 3.10). The cooking losses reported in the present study were lower than those reported for jasmine noodles (22.1 – 32.4%) (Milde *et al.*, 2020). The variations in the cooking losses reported in the present study and those of jasmine flour, were influenced by interaction of the food matrices and inclusion levels. Hence, optimizing the inclusion levels for flour-based products is warranted because various ingredients have unique interactions with the hydrocolloids (alone or in composite form). To optimize the cooking quality, the literature recommends that optimum inclusion levels for egg whites are 3 – 47% (Castelo-Branco *et al.*, 2017c; A. Marti *et al.*, 2013; Rachman *et al.*, 2019; Sosa *et al.*, 2018; Xie *et al.*, 2020; Zandonadi *et al.*, 2012; Zheng *et al.*, 2016). It further recommends that the optimum inclusion levels of GG and XG are 0.4 – 2.5% (Martín-Esparza *et al.*, 2018; Milde *et al.*, 2020; Tangthanantorn *et al.*, 2021b).

Table 3. 5 Relationship between Incremental Levels of Hydrocolloids and Cooking Parameters of Banana Flour Pasta

Parameters	Hydrocolloids	Equation	Significance			
			R ²	P-Linear	R ²	P-
			Linear		Quadr atic	Quadratic
Cooking time (mins)	Egg White (EW)	y = 30.42 – 2.22x	0.854	<0.001	0.0264	0.1292
	Guar Gum (GG)	y = 15.24 + 3.13x	0.9082	<0.0001	0.0022	0.5934
	Xanthan Gum (XG)	y = 15.87 + 4.20x	0.8253	<0.0001	0.028	0.6645
Cooking loss (%)	EW	y = 10.06 – 0.19x	0.8485	<0.001	0.0002	0.9029
	GG	y = 7.19 – 0.22x	0.44	0.052	0.028	0.8029
	XG	y = 8.23 – 0.081x	0.74	<0.0001	0.026	0.2721

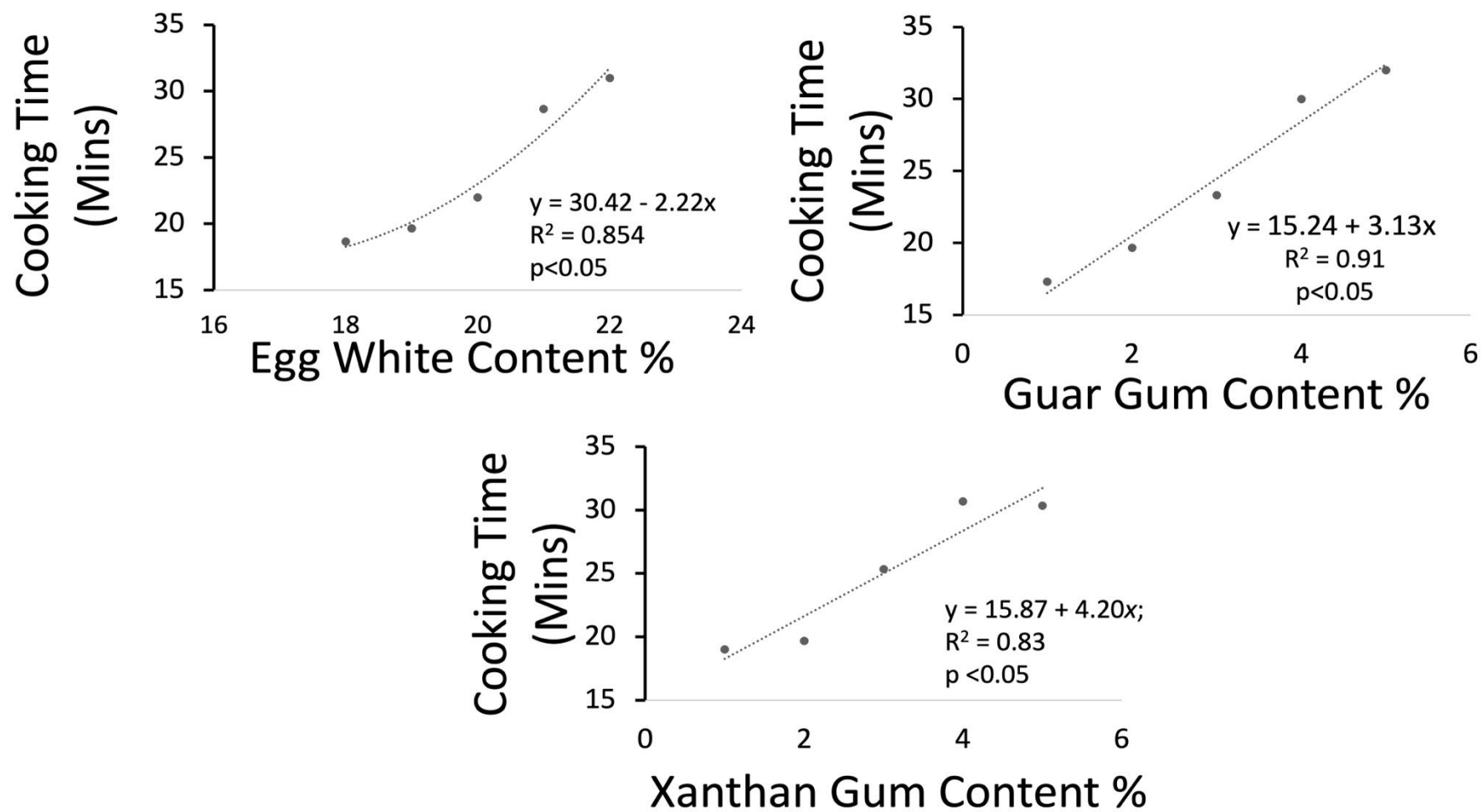


Figure 3. 1 Relationships between inclusion levels of hydrocolloids and cooking time of banana flour-based pasta

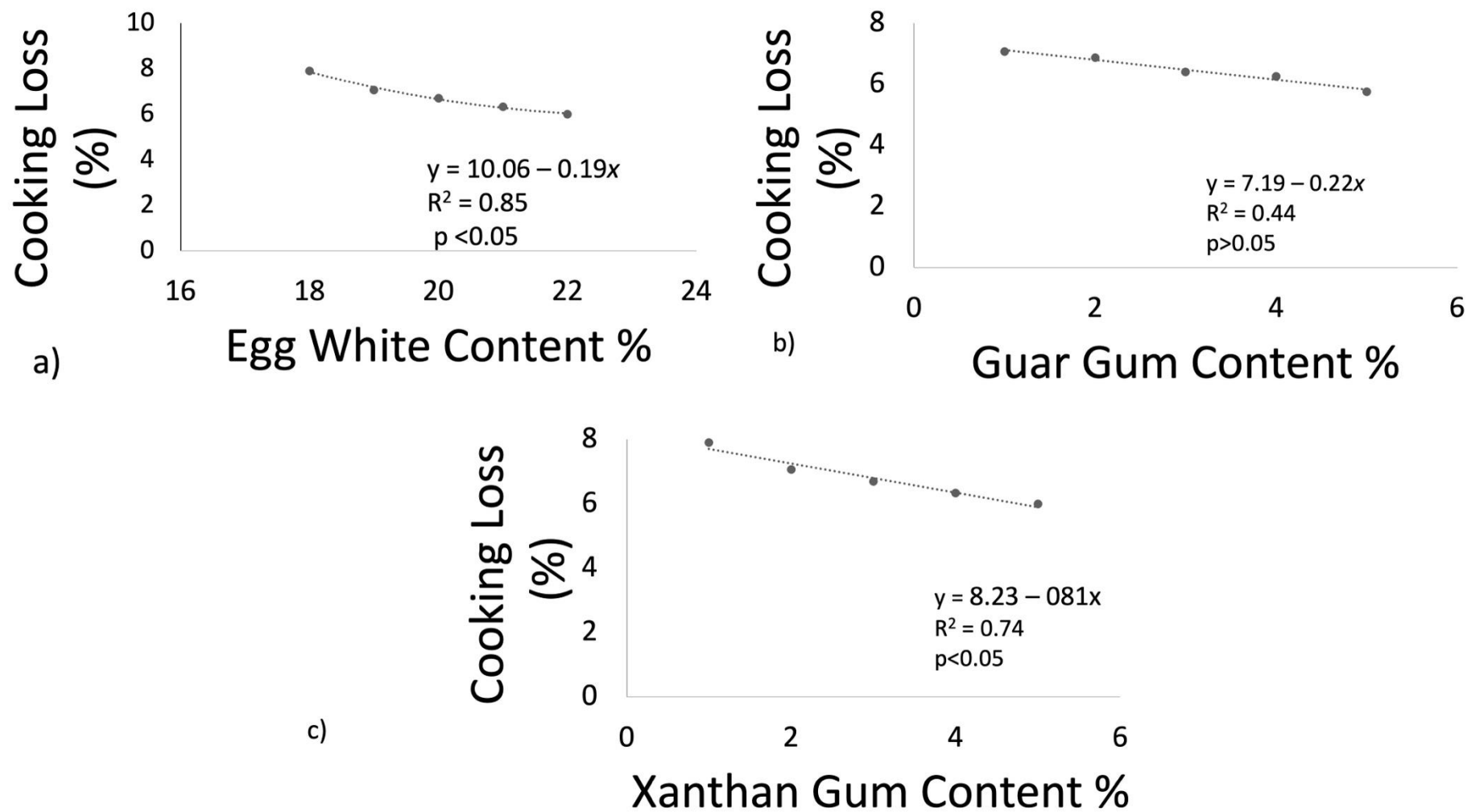


Figure 3. 2 Relationships between inclusion levels of hydrocolloids and cooking loss of banana flour-based pasta

3.4.4 Texture of Banana Flour Pasta

Gluten-free foods such as pasta are sticky and undesirable due to the lack of a stable protein matrix and the inability of GF flour to withstand overcooking or high temperatures (Padalino *et al.*, 2013; Rachman *et al.*, 2020b; Rachman *et al.*, 2019). Hydrocolloids can improve the textural properties (high firmness, low adhesiveness, stiffness, and stickiness) of pasta by interacting with ingredients to form a stable protein matrix to reduce the loss of solids from the pasta structure (Guo *et al.*, 2020; Tangthanantorn *et al.*, 2021b; Widelska *et al.*, 2019; Xie *et al.*, 2020; Zheng *et al.*, 2016). Hydrocolloids are also able to reduce the leaching of solids from the pasta structure due to their hydrophilic nature, which increases the water absorption capacity of the pasta by forming a protective layer around starch granules to improve their resilience during the cooking process (Gasparre & Rosell, 2019; Thuy *et al.*, 2023). Hence, in the present study, the hardness, positive area, and area-to-peak of the pasta containing hydrocolloids increased with an increase in the concentration of the hydrocolloids (EW, XG, and GG) (Table 3.6). The adhesiveness (except for pasta containing EW and XG), negative area, and gradient modulus (stiffness) decreased in response to the incremental levels of the hydrocolloids (EW, XG, and GG). Similar trends and findings were made for corn-based pasta (Larrosa *et al.*, 2016); rigatoni pasta (Xie *et al.*, 2020); banana flour pasta (Tangthanantorn *et al.*, 2021b) and horse chestnut flour noodles (Syed Insha Rafiq *et al.*, 2016).

3.4.4.1 Hardness

Hardness measures the force required to compress food between the tongue and palate of any penetration (Park *et al.*, 2020). Food products with high hardness (firmness) are deemed high quality due to enhanced textural properties (Park *et al.*, 2020). The hardness showed a linear increase ($R^2 = 0.71$; $p < 0.001$) in response to incremental levels of EW (Table 3.6). In the present study, the hardness of the pasta containing 22% EW was significantly higher than those containing 18 – 21% EW (Table 3.6). This trend has been reported by Bai *et al.* (2022) and

Guo *et al.* (2020) who reported that the hardness of the pasta increased in response to incremental levels of EW. The hardness values reported in the present study are higher than those reported for corn flour-starch pasta (612.85 - 3485.39 g) (Larrosa *et al.*, 2016) and rigatoni pasta (132.56 – 244.73 g) (Xie *et al.*, 2020). These variations could be due to the use of relatively low inclusion levels of EW compared to those used in the present study, given that the hardness of pasta depends on the inclusion levels of the hydrocolloids (Witek *et al.*, 2020).

The hardness of pasta containing 1.5 – 4.5% GG is significantly higher ($p < 0.05$) than those containing 0.5% GG (Table 3.6). The hardness of the pasta containing GG showed a linear increase ($R^2 = 0.56$; $p < 0.0001$) in response to incremental levels of GG (Table 3.7). The hardness of pasta containing GG was lower than that of tiger nut flour pasta (10986 – 12765g) (Gasparre & Rosell, 2019). This could be due to differences the composition of the flour and their unique interaction and hydrocolloids. However, the hardness of the pasta containing GG was higher than those of extruded rice flour pasta (1766.10 – 1798.58g) (Kraithong & Rawdkuen, 2020) and proso-millet pasta (4364.39 – 4568.33 g) (Motta Romero *et al.*, 2017). The increase in the hardness values of the pasta is due to the ability of GG to interact with the starch granules to form a stable matrix inside the pasta (Gasparre & Rosell, 2019).

The hardness of the pasta containing 4.5% XG was higher than those containing 0.5 – 3.5% XG (Table 3.6). No significant variations ($p > 0.05$) in the hardness of the pasta containing XG. The hardness of the pasta containing XG showed a linear increase ($R^2 = 0.18$; $p = 0.13$) in response to the incremental levels of XG (Table 3.7). The hardness values of pasta containing XG are higher than those of non-fried potato noodles (20.9 – 3690.12 g) (Javaid *et al.*, 2021), rice flour pasta (807.61 g) (Sanguinetti *et al.*, 2015) and proso-millet flour pasta (4364.39 – 4568.33 g) (Motta Romero *et al.*, 2017) but significantly lower than that of tiger nut flour pasta (10349 – 10711 g) (Gasparre & Rosell, 2019). The presence of ionic charges enables XG to increase the hardness of the pasta by interacting and binding soluble starch granules to enhance

the structural compactness of the pasta (Milde *et al.*, 2020; Widelska *et al.*, 2019). The hardness of the pasta in the present study compared to those in the literature could be attributed to the high concentration of junction zones in banana flour compared to other conventional flours such as corn flour. Junction zones create a more compact three-dimensional amylopectin chain to increase the rigidity of the pasta (Saha & Bhattacharya, 2010).

Table 3. 6 Effect of Hydrocolloids on the Texture Profile of Banana Flour-Based Pasta

Inclusion Levels of Hydrocolloids (%)						Significance		
						P-Linear	P-Quadratic	X _{min/max} (%)
Parameters	Egg White							
	18	19	20	21	22			
Hardness (g)	4373.99(284.17) ^a	4832.82(105.04) ^{ab}	4885.48(401.35) ^{ab}	5232.32(115.84) ^{ac}	5394.13(228.76) ^c	0.001	0.5792	
Adhesiveness (g.sec)	- 6.82 (2.08) ^b	-4.79 (1.80) ^{ab}	-3.99 (0.66) ^a	-3.69 (0.44) ^a	-3.31 (2.17) ^a	0.0012	0.2574	
Gradient Modulus (g.sec)	6397.97 (316.34) ^a	7156.83 (352.39) ^b	6792.33 (251.84) ^{ab}	6713.73 (243.57) ^{ab}	6525.82 (260.06) ^a	0.8356	0.0370	19.39
	Guar Gum							
	0.5	1.5	2.5	3.5	4.5			
Hardness (g)	4207.72 (263.87) ^b	5012.32 (362.42) ^a	5229.17 (106.37) ^a	5380.85 (153.60) ^a	5274.54 (208.55) ^a	<0.0001	0.0012	
Adhesiveness (g.sec)	-1.26 (0.92) ^b	-3.18 (1.94) ^{ab}	-4.22 (0.88) ^a	-4.19 (0.39) ^a	-4.37 (1.22) ^a	0.0034	0.0796	
Gradient Modulus (g.sec)	6894.79 (412.71) ^{ab}	7608.86 (492.76) ^c	7281.15 (272.36) ^{bc}	6919.91 (179.14) ^{ab}	6470.28 (55.03) ^a	0.0096	0.0065	2.01

	Xanthan Gum						
	0.5	1.5	2.5	3.5	4.5		
Hardness (g)	4785.50 (347.14) ^a	5042.44 (177.06) ^a	5206.16 (370.89) ^a	4893.72 (445.90) ^a	5318.58 (229.32) ^a	0.1317	0.9416
Adhesiveness (g.sec)	1.98 (1.08) ^a	-2.85 (1.82) ^a	-1.45 (0.61) ^a	-1.37 (1.44) ^a	-1.71 (0.78) ^a	0.4412	0.8534
Gradient Modulus (g.sec)	7506,71(696.81) ^a	7631.23(226.87) ^a	7229.49(375.41) ^a	6358.76 (435.64) ^b	6003.86(139.26) ^b	0.0002	0.1677

*Values in brackets are standard deviation

*Means with a different letter in each column are significantly (p<0.05) different

[‡]X_{min/max} = the value of x that maximizes or minimizes the response parameter

3.4.4.2 Adhesiveness

An increase in the hardness of the pasta has been shown to reduce the adhesiveness of the pasta (Guo *et al.*, 2020). Adhesiveness is the adherence of leached/diffused starch granules on the surface of pasta (Guo *et al.*, 2020). It is also the force required to remove food that is adhered to the mouth (Park *et al.*, 2020). High adhesiveness is not desirable as it implies that the pasta has a sticky texture (an undesirable property to consumers); hence, it has been suggested that hydrocolloids reduce the adhesiveness of gluten-free foods such as pasta (Padalino *et al.*, 2013). The adhesiveness of pasta containing GG showed a linear decrease ($R^2 = 0.44$; $p = 0.0034$) in response to the incremental levels of GG (Tables 3.6 and 3.7). Similar trends have been reported for extruded rice flour pasta (Kraithong & Rawdkuen, 2020) and whole amaranth flour pasta (Chauhan *et al.*, 2017). The adhesiveness values of the pasta containing GG are higher than those of buckwheat noodles (-24.31 to 84.60 g.mm) (Jang *et al.*, 2015); whole amaranth flour pasta (-16.52g to - 36.31g.sec) (Chauhan *et al.*, 2017) but lower than that of rice-flour pasta (305.91 – 414g.sec) (Sanguinetti *et al.*, 2015). The decrease in the adhesiveness to the ability of GG to form a stable protein matrix prevents excess leaching of solids from the pasta during cooking, resulting in less sticky pasta (Gasparre & Rosell, 2019; Tangthanantorn *et al.*, 2021b).

However, the adhesiveness of pasta containing EW and XG increased in response to incremental levels of EW and XG (Table 3.6). The adhesiveness of the pasta showed a linear increase ($R^2 = 0.4007$; $p = 0.0112$) in response to incremental levels of EW (Table 3.7). The findings of the present study are like those reported for corn-based pasta made with 0.25% and 0.42% EW, whose adhesiveness values increased from 1.41 – 1.82% and 1.12 – 1.22% as the moisture content in the pasta formulation increased 36.15% to 37.5% (Larrosa *et al.*, 2016). It is suggested that high moisture content and less protein content increase the adhesiveness of the pasta due to the lack of a compact structure (Larrosa *et al.*, 2016). However, the present

study contradicts previous research by Guo *et al.* (2020) which demonstrated that increasing egg white levels in the pasta formulation reduced the adhesiveness of oat noodles. It also contradicted the hypothesis that aggregation of proteins enables pasta to withstand cooking and have less stickiness (Bai *et al.*, 2022; Guo *et al.*, 2020). The increase in adhesiveness of the pasta containing EW may be attributed to prolonged cooking times, which may have caused solids to escape the pasta matrix, as suggested by Xie *et al.* (2020). The adhesiveness of the pasta containing EW is lower than reported for corn-based pasta (67.30 – 158.89 g.sec) (Larrosa *et al.*, 2016) and oat noodles (82.60 – 138.88 g.mm) (Guo *et al.*, 2020).

The high water absorption capacity of the XG causes the pasta to have more stickiness (Gasparre & Rosell, 2019; Thuy *et al.*, 2023). Xanthan gum cannot form a more robust protein matrix like GG and EW; hence, some studies concluded that pasta containing GG had more firmness compared to XG (Gasparre & Rosell, 2019; Sanguinetti *et al.*, 2015). The adhesiveness of pasta containing XG showed a linear increase ($R^2 = 0.0500$; $p = 0.412$) in responses to incremental levels of EW (Table 3,6). These findings are consistent with those reported horse chestnut flour noodles (Syed Insha Rafiq *et al.*, 2016). This contradicts the findings made on non-fried potato noodles (Javaid *et al.*, 2021), maize-field bean pasta (Widelska *et al.*, 2019) and rice flour pasta (Sanguinetti *et al.*, 2015). The adhesiveness values of the XG fortified pasta are lower than those of horse chestnut flour noodles (30.59 – 50.99 g/mm) (Syed Insha Rafiq *et al.*, 2016); tiger nut flour noodles (70 – 1144 g.sec) (Gasparre & Rosell, 2019) and cassava starch noodles (20.39 g.sec) (Milde *et al.*, 2020); but significantly higher than reported for spinach noodles (-30 – 90 g.sec) (Shere *et al.*, 2020); extruded flour noodles (-40.70 – 41.27 g.sec)) (Kraithong & Rawdkuen, 2020).

It has been suggested that gums increased the adhesiveness of potato pasta delaying swelling of starch granules and restricted amylose leaching Kaur *et al.* (2015). The pasting properties of the pasta containing decreased in response to incremental levels of E (Table 4.1). Therefore,

the high adhesiveness values of the pasta containing EW could be attributed decrease in the pasting properties, caused by competition of EW other biopolymers for available water, reducing water uptake/intake of the starch granules and the amount of starch available for gelatinization (Alessandra Marti *et al.*, 2014a; Saleh *et al.*, 2017). Interestingly, the adhesiveness of the pasta containing XG had higher adhesiveness values, despite increasing pasting properties value. This suggests that processing (cooking) and the inherent properties may have a significant role compared to hydrocolloid-starch interactions.

3.4.4.3 Area

The positive area and area to peak correlate with the pasta's hardness, hence, the positive area and area to peak of the pasta containing the hydrocolloids increased in response to incremental levels of the hydrocolloids (Figures 3.3 and 3.4). The increase in the pasta's positive area and area to peak can be attributed to a stable and compact protein network inside the pasta. Furthermore, the negative area of pasta and its adhesiveness are positively correlated (Figure 3.5). The negative values of the pasta containing EW increased in response to incremental levels of EW (Figure 3.5), which is consistent with the observations made for the adhesiveness of the pasta. However, the negative area values decreased as the inclusion of GG and XG increased (Figure 3.5), signifying that the influence of any given hydrocolloid on the texture of the pasta may be influenced by its inherent properties and starch interactions. It has been suggested that the negative area values can be used to infer the stickiness of the pasta (Jang *et al.*, 2015). Therefore, it can be suggested that at higher concentration, hydrocolloids reduce stickiness of the pasta by preventing excess cooking losses.

3.4.4.4 Gradient Modulus

The gradient modulus is used in materials physics to measure a given material's elasticity or rigidness/response to elastic or springy deformation (Askadskii *et al.*, 2017; Jones & Ashby, 2019). Materials with a high gradient modulus stretch very little when pulled, while those with

low modulus materials stretch a lot (Jones & Ashby, 2019). It has been suggested that incorporating hydrocolloids improves the elasticity of pasta (Tangthanantorn *et al.*, 2021b; Xie *et al.*, 2020). In the present study, the gradient modulus of the pasta decreased in response to incremental levels of the hydrocolloids (EW, GG, and XG) (Table 3.6). The gradient modulus of the pasta containing EW (0.3135 ; $p = 0.0370$) and GG ($R^2 = 0.328$; $p = 0.0065$) showed quadratic decreases as the inclusion levels of the hydrocolloids increased (Table 3.14). The gradient modulus of the pasta containing XG showed linear responses ($R^2 = 0.6748$; $p = 0.0002$) as the inclusion of XG increased (Table 3.7). These findings are similar to those of previous studies that demonstrated that incorporating EW, XG, and GG increased the elasticity of rigatoni pasta (Xie *et al.*, 2020) and extruded rice flour noodles (Kraithong & Rawdkuen, 2020). This demonstrated that the hydrocolloids can interact with the ingredients (i.e., starch granules in banana flour) to enhance the elasticity of the pasta dough and overall texture of the pasta.

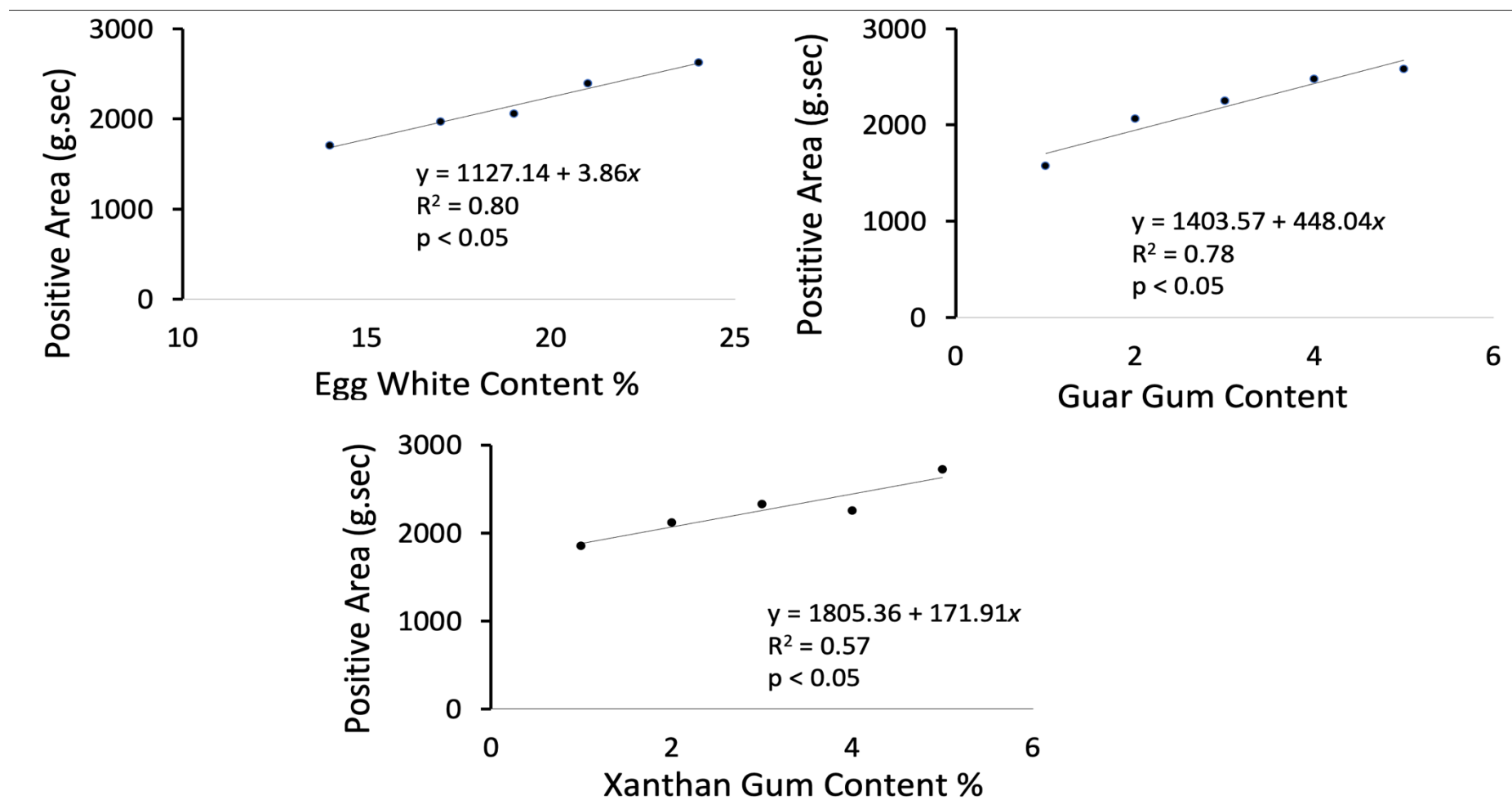


Figure 3. 3 Effect of Incremental Levels of Hydrocolloids on the Positive Area Values of Banana Flour-Based Pasta

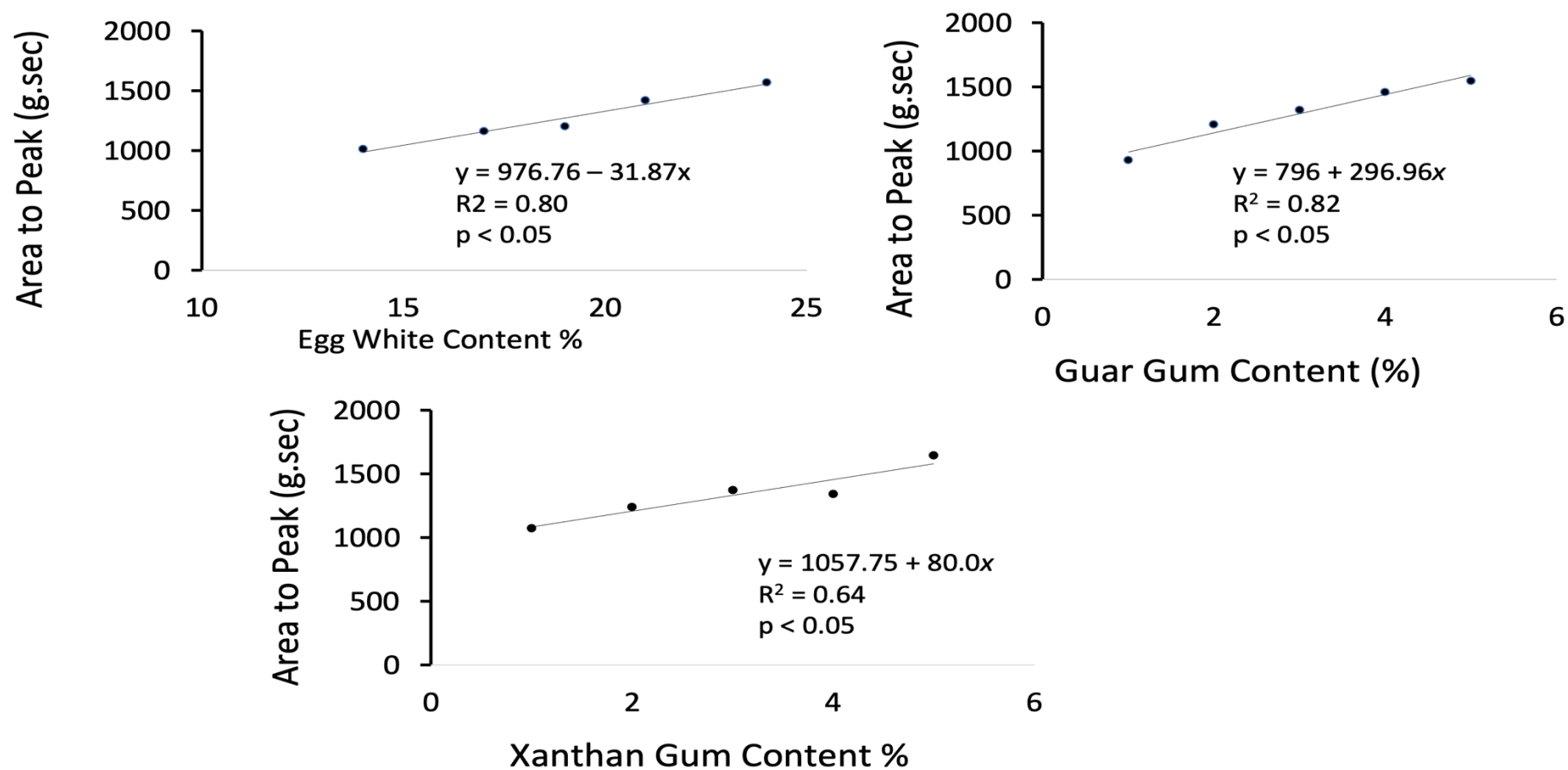


Figure 3. 4 Effect of Incremental Levels of Hydrocolloids on the Area to Peak of Banana Flour-Based Pasta

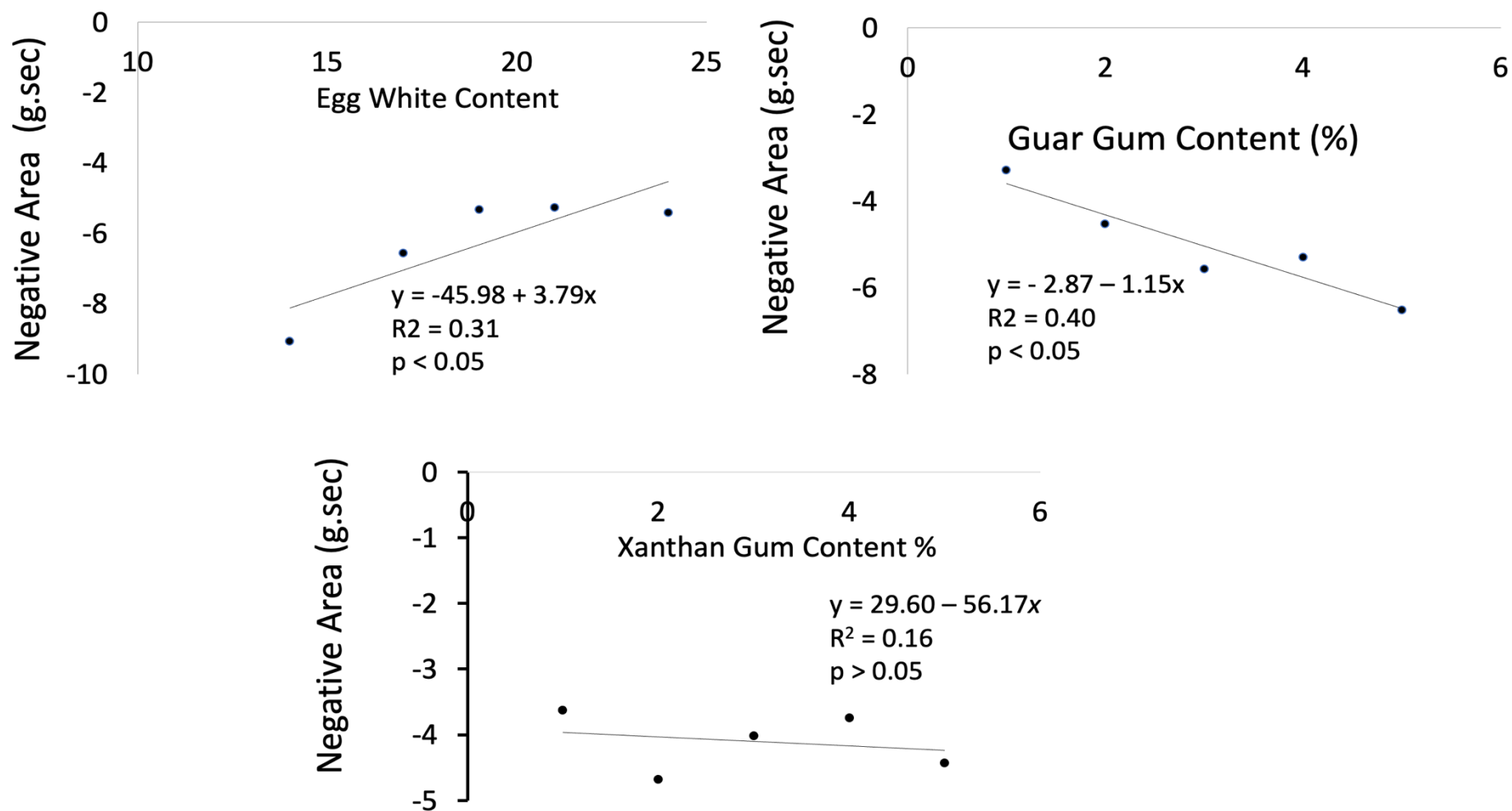


Figure 3. 5 Effect of Graded Levels of Hydrocolloids on the Negative Area of Banana Flour-Based Pasta

Table 3. 7 Effect of Graded Levels of the Hydrocolloids on Texture of the Banana Flour Pasta

Parameters	Hydrocolloids*	Equation	Significance				$X_{\min/\max}$ (%)
			R^2 Linear	P-Linear	R^2 Quadratic	P-Quadratic	
Hardness (g)	Egg White (EW)	$y = 1375 + 264x$	0.7096	0.001	0.0077	0.5792	
	Guar Gum (GG)	$y = 3817.7 + 930.66x$	0.5660	<0.0001	0.2465	0.0012	
	Xanthan Gum (XG)	$y = 4790.44 + 119.89x$	0.1789	0.1317	0.0004	0.9416	
Adhesiveness (g.sec)	EW	$y = -30.44 + 2.36x$	0.4007	0.0112	0.0632	0.2574	
	GG	$y = -0.30 - 2.29x$	0.4354	0.0034	0.1229	0.0796	
	XG	$y = 2.48 + 0.35x$	0.0500	0.4412	0.0028	0.8534	
Gradient Modulus (g.sec)	EW	$y = -1513.67 + 873.12x - 22.52x^2$	0.026	0.8356	0.3135	0.0370	19.39
	GG	$Y = 6735.60 + 644x - 159.96x^2$	0.2812	0.0096	0.328	0.0065	2.01
	XG	$y = 7594.78 + 60.88x$	0.6748	0.0002	0.0495	0.1677	

* $X_{\min/\max}$ = the value of x that maximizes or minimizes the response parameter.

3.4.5 Colour of Banana Flour Pasta

The influence of hydrocolloids on the colour of the banana flour-based pasta is presented in Tables 3.8 and 3.10. Colour is the first parameter influencing a consumer's acceptance or rejection of a food product. It has been suggested that consumers prefer foods with a brighter and yellowish colour; hence, pasta with a dull and less yellowish colour is deemed low quality. Hydrocolloids improve the colour of pasta by forming a more stable protein matrix which prevents excess solids by limiting water penetration into the pasta matrix (Raungrusmee *et al.*, 2020; Sosa *et al.*, 2018; Xie *et al.*, 2020; Zheng *et al.*, 2016).

The influence of hydrocolloids on the colour of pasta depends on the inherent properties of a given flour and the state of the pasta (uncooked/cooked) (Motta Romero *et al.*, 2017; Sanguinetti *et al.*, 2015; UK *et al.*, 2022). In the present study, all the colour parameters of uncooked pasta increased in response to the incremental levels of hydrocolloids (EW, GG, and XG) (Table 3.6). This improvement in colour properties of the uncooked is due to the interaction of the hydrocolloids and starch granules and pigments present in banana flour. However, the colour values of cooked pasta, except for lightness (L^*) and hue angle (h^*) values, decreased as the inclusion levels of hydrocolloids increased (Figure 3.12 – 3.16). Similar trends have been reported for rice-corn-starch-milk protein pasta (Sanguinetti *et al.*, 2015), proso-millet flour pasta (Motta Romero *et al.*, 2017) black-gram-carrot-drumstick-powder pasta (UK *et al.*, 2022) and soya-channa flour pasta (Susanna & Prabhasankar, 2013). The deterioration of the colour of the pasta may be due to the degradation of pigments present in the ingredients used to develop a given pasta product caused thermal processing (Motta Romero *et al.*, 2017).

3.2.5.1 Uncooked Pasta

3.4.5.1.1 Lightness

The lightness of samples containing 20 – 22% egg white (EW) was significantly greater ($p < 0.05$) than that of pasta containing 18 – 19% EW (Table 3.8). The L^* of the pasta containing EW showed a quadratic increase ($R^2 = 0.0098$; $p = 0.230$) as the inclusion levels of EW increased (Table 3.9). The L^* values of the pasta containing EW were significantly lower than reported for corn-starch-lentil pasta (84.03) (Ertas *et al.*, 2021) and wheat flour (64.14 – 68.68) (Bai *et al.*, 2022). The increase in the L^* values of pasta containing EW may be due to the increase in the brightness of the pasta, given that an increase in the brightness increases the lightness of the pasta (Milde *et al.*, 2020).

Furthermore, pasta containing 2.5% guar gum (GG) had significantly lower ($p < 0.05$) lightness compared to pasta containing 0.5 – 1.5% XG and 3.5 – 4.5% GG (Table 3.8). The L^* of pasta containing GG showed a quadratic increase ($R^2 = 0.0292$; $p = 0.036$) in response to incremental levels of GG (Table 3.9). The L^* values of pasta containing GG are lower than those reported by black-gram-carrot-drum powder pasta (52.7 – 76.64) (UK *et al.*, 2022) but significantly higher than those reported for soya-channa flour pasta (20.63) (Susanna & Prabhasankar, 2013) and extruded jasmine rice flour noodles (21.80 – 23.30) (Susanna & Prabhasankar, 2013). Moreover, pasta containing 2.5 % xanthan gum (XG) had a significantly lower ($p < 0.05$) lightness compared to pasta containing 0.5 – 1.5% XG and 3.5 – 4.5% XG (Table 3.8). The L^* of the pasta containing XG showed a quadratic increase ($R^2 = 0.0458$; $p = 0.087$) in response to incremental levels of XG (Table 3.9). The L^* values of the pasta containing XG are lower than reported for hard wheat flour noodles (70.41 – 75.15) (Xu *et al.*, 2022b), rice noodles (88) (Yalcin & Basman, 2008) and non-fried potato noodles (53.34 – 57.85) Javaid *et al.* (2021) Gums (GG and XG) can increase the L^* values of pasta due to their high water absorption capacity (Gasparre & Rosell, 2019; Yalcin & Basman, 2008).

The higher L* values reported in the literature compared to those in the present study could be due to using ingredients with a lighter colour. Banana flour has a darker colour compared to most flours (i.e. rice and wheat flour), hence it has lower lightness values compared to those reported in the literature. Hence, it may suggest that to maximize benefits of hydrocolloids on the colour of pasta, it should be composited with flours with a lighter colour.

3.4.5.1.2 Redness

The redness (a*) values of pasta made with 19% and 22% EW were significantly greater ($p < 0.05$) than that of pasta containing 18, 20, and 21% EW (Table 3.8). The redness of pasta containing EW showed a quadratic increase ($R^2 = 0.0272$; $p = 0.0427$) in response to incremental levels of EW (Table 3.9). Pasta containing EW had a* values that were higher than those reported rice-starch-lentil pasta (-0.32) and wheat flour pasta (-1.70 – (-2.70)) (Bai *et al.*, 2022; Ertaş *et al.*, 2021). This variation could probably be due to the use of relatively low inclusion levels of EW (<5% EW) compared to the ones used in the present study (14.21 – 24.11%) and the lack of pigments in wheat and rice flour. The increase in the a* values in the pasta containing EW is attributed to its high protein content, and pale colour (Ertaş *et al.*, 2021).

Table 3. 8 Effect of Hydrocolloids on the Colour Profile of Uncooked Pasta

Inclusion of Levels of Hydrocolloids (%)						Significance		
						P-Linear	P-Quadratic	X _{min/max} (%)
Parameters	Egg White							
	18	19	20	21	22			
Lightness	35.4 (0.64) ^a	36.2 (0.60) ^a	39.2 (0.79) ^b	40.5 (0.53) ^{bc}	41.1 (0.59) ^c	0.9221	0.230	19.61
Redness	4.59 (0.121) ^a	4.78 (0.152) ^a	4.48 (0.234) ^b	4.48 (0.131) ^a	5.13 (0.121) ^b	0.1179	0.0427	15.25
Brightness	6.90 (0.146) ^a	7.10 (0.125) ^a	7.62 (0.143) ^b	8.45 (0.101) ^c	10.2 (0.146) ^d	<0.0001	<0.0001	
Mean Saturation Index	8.28 (0.142) ^a	8.60 (0.134) ^a	8.90 (0.216) ^a	12.1 (2.482) ^b	11.1 (0.365) ^{ab}	0.0121	0.9655	
Hue Angle	56.4 (0.88) ^a	56.3 (0.92) ^a	60.1 (1.08) ^b	62.2 (0.62) ^{bc}	63.1 (0.70) ^c	<0.0001	0.8869	
	Guar Gum							
	0.5	1.5	2.5	3.5	4.5			
Lightness	39.6 (0.66) ^a	39.7 (0.78) ^a	36.7 (0.55) ^b	38.3 (0.53) ^{ab}	38.7 (0.65) ^a	0.1507	0.0358	2.87
Redness	3.93 (0.152) ^b	4.48 (0.160) ^a	4.83 (0.101) ^a	5.36 (0.134) ^c	6.15 (0.127) ^d	<0.0001	0.1816	
Brightness	6.91 (0.193) ^a	6.91 (0.193) ^a	7.94 (0.127) ^c	9.32 (0.122) ^d	10.47 (0.112) ^e	<0.0001	<0.0001	
Mean Saturation Index	8.00 (0.180) ^a	8.62 (0.117) ^b	9.29 (0.122) ^c	10.7 (0.126) ^d	12.1 (0.133) ^e	<0.0001	<0.0001	
Hue Angle	60.2 (1.26) ^a	58.7 (1.01) ^a	58.5 (0.66) ^a	60.6 (0.69) ^a	59.6 (0.50) ^a	0.7662	0.2912	2.3
	Xanthan Gum							

	0.5	1.5	2.5	3.5	4.5			
Lightness	41.4 (0.74) ^a	41.7 (0.70) ^a	38.8 (0.46) ^b	41.6 (0.55) ^a	42.1 (0.52) ^a	0.5060	0.087	2.35
Redness	4.28(0.180) ^{ac}	3.96 (0.175) ^c	4.58 (0.123) ^{bc}	4.58 (0.156) ^{bc}	4.74 (0.163) ^b	0.0034	0.5730	
Brightness	7.80 (0.085) ^a	7.70 (0.140) ^a	8.01 (0.151) ^{ab}	8.41 (0.183) ^b	9.24 (0.162) ^c	<0.0001	0.0006	
Mean Saturation Index	8.84 (0.146) ^a	8.60 (0.156) ^a	9.28 (0.141) ^b	9.63 (0.173) ^b	10.4 (0.171) ^c	<0.0001	0.0060	
Hue Angle	61.7 (0.99) ^{ab}	62.7 (1.05) ^{ab}	60.4 (0.61) ^a	61.3 (1.08) ^{ab}	63.1 (0.83) ^b	0.6845	0.1758	2.32

*Values in brackets are standard errors of means

*Means with a different letter in each row are significantly (p<0.05) different

[¥]X_{min/max} = the value of x that maximizes or minimizes the response parameter

The redness of pasta containing 3.5 – 4.5% GG was significantly greater ($p < 0.05$) than that of pasta containing 0.5 – 2.5% GG (Table 3.8). The a^* values of pasta containing GG falls within the range reported by UK *et al.* (2022) for black-gram-carrot-drum stick powder (1.2 – 9.5) (UK *et al.*, 2022); comparable to those reported for whole amaranth flour pasta (5.22 – 5.75) (Chauhan *et al.*, 2017) but significantly higher than those reported for rice-flour-corn-starch-milk-protein pasta (-1.41 – (-1.43) (Sanguinetti *et al.*, 2015). The redness of the pasta containing GG showed a linear increase ($R^2 = 0.4901$; $p < 0.0001$) in response to incremental levels of GG (Table 3.9).

Furthermore, the redness (a^*) of pasta containing 0.5 - 1.5% XG was significantly lower ($p < 0.05$) than those containing 2.5% - 4.5% XG (Table 3.8). The a^* values of the pasta containing XG are similar to those of non-fried potato noodles (3.71 – 5.40) (Javaid *et al.*, 2021) and jasmine rice flour noodles (5.71 – 5.89) (Kraithong & Rawdkuen, 2020) but significantly higher than reported for proso-millet pasta (-1.17 – (-0.9) (Motta Romero *et al.*, 2017) and hard wheat flour pasta (2.90 – 3.25) (Xu *et al.*, 2022b). The pasta containing XG showed a linear increase ($R^2 = 0.0568$; $p = 0.0034$) as the inclusion levels of XG increased (Table 3.9). The increase in the a^* values of the pasta containing GG and XG is caused by the interaction of the gums and pigments in the flour (i.e., banana flour) (Javaid *et al.*, 2021; Kraithong & Rawdkuen, 2020; Milde *et al.*, 2020). This interaction promotes equal distribution of the pigments across the pasta structure, thereby increasing the pasta's a^* and b^* (Javaid *et al.*, 2021).

3.4.5.1.3 Brightness

Pasta containing 21 – 22% EW had significantly higher ($p < 0.05$) brightness compared to pasta containing 18 – 20% EW (Table 3.8). This is significantly higher than the values reported by Bai *et al.* (2022) for wheat flour pasta (-0.124 – (-0.39)) (Bai *et al.*, 2022) but significantly lower than those reported by (Ertaş *et al.*, 2021) for rice-starch-lentil pasta (28.79). The lower

b* of the wheat flour pasta could be due to its low concentrations of pigments compared to banana flour. The increase in the b* values of pasta containing EW is attributed to the pale color and carotenoid pigments in the egg white and the interlinking of protein aggregates and starch granules, which reduces the pore size of the gel microstructure and increases the intensity of reflected light (Bai *et al.*, 2022; Lorenzo *et al.*, 2018). The b* of the pasta containing EW showed a linear increase ($R^2 = 0.643$; $p < 0.0001$) in response to the incremental levels of EW (Table 3.9).

The brightness of the pasta samples containing 2.5 – 4.5% GG was significantly greater ($p < 0.05$) than that of pasta containing 0.5 – 1.5% GG (Table 3.8). The b* values of pasta containing GG are comparable to those of soya-channa flour pasta (10.54) (Susanna & Prabhasankar, 2013) and rice-flour-corn-starch-milk-protein pasta (9.77 – 10.23) (UK *et al.*, 2022) but significantly lower than those reported for whole-amaranth flour pasta (19.21 – 22.61) (Chauhan *et al.*, 2017). The b* of pasta containing GG showed a linear increase ($R^2 = 0.7264$; $p < 0.0001$) in response to incremental levels of GG (Table 3.15). Furthermore, the brightness of pasta containing 2.5 – 4.5% XG was significantly greater ($p < 0.05$) than that of pasta containing 0.5 – 1.5% XG (Figure 3.9). The b* values of pasta containing XG are similar to hard-wheat flour pasta (12.61 – 15.76), comparable to those reported for rice noodles (7.86 – 8.41) (Yalcin & Basman, 2008); rice-corn-starch-milk protein pasta (10.13 – 10.44) (Sanguinetti *et al.*, 2015) and lower than those reported for proso-millet flour pasta (22.76 – 23.31) (Motta Romero *et al.*, 2017). The b* of the pasta containing XG showed a linear increase ($R^2 = 0.2717$; $p < 0.0001$) as the inclusion levels of XG increased (Table 3.9).

Gums can increase the brightness of the pasta. The high-water absorption of gums (GG and XG) preserves the brightness of pasta by preventing excess loss of solids (Gasparre & Rosell, 2019; Javaid *et al.*, 2021; Raungrusmee *et al.*, 2020). Gums have a higher water absorption

capacity because they are multiple spiral polymers with a double helical structure and can interact with amylopectin (Raungrusmee *et al.*, 2020).

3.4.5.1.4 Mean Saturation Index

The c^* of the pasta containing EW showed a linear increase ($R^2 = 0.0420$; $p = 0.0121$) in response to incremental levels of EW (Table 3.9). The mean saturation index (C^*) of pasta containing 21% EW was significantly greater ($p < 0.05$) than those containing 18 – 20% and 22% EW (Table 3.8). The C^* values of pasta containing EW are lower than reported for rice starch-lentil pasta (28.79) (Ertaş *et al.*, 2021). The C^* value of pasta containing 3.5 – 4.5% GG was significantly higher ($p < 0.05$) than those containing 0.5 – 2.5% GG (Table 3.8). The c^* of pasta containing GG showed a linear increase ($R^2 = 0.760$; $p < 0.0001$) in response to incremental levels of GG (Table 3.9). Furthermore, the C^* values of pasta containing 0.5 – 1.5% XG were significantly lower ($p < 0.05$) than those containing 2.5 – 4.5% XG (Table 3.8). The c^* of the pasta containing GG and XG showed a linear increase ($R^2 = 0.3048$; $p < 0.0001$) in response to incremental levels of XG (Table 3.9). The C^* values of pasta containing XG and GG are comparable to those reported by Kraithong and Rawdkuen (2020) for jasmine rice flour noodles (8.00 – 8.39). The increase in the mean saturation index (c^*) of the uncooked pasta with incremental levels of the hydrocolloids could be due to the increase in the pasta's brightness caused by the water absorption capacity of the gums (XG and GG) (Gasparre & Rosell, 2019; Javaid *et al.*, 2021; Raungrusmee *et al.*, 2020). It could also be due to the pale colour and carotenoid pigments of EW and the interlinking of protein and starch granules which increases the intensity of the reflected light (Bai *et al.*, 2022; Lorenzo *et al.*, 2018).

3.4.5.1.5 Hue Angle

The hue angle (h^*) of pasta containing 22% EW was significantly higher ($p < 0.05$) than that of pasta containing 18 – 21% EW (Table 3.8). The h^* of pasta containing EW is lower than that of rice-starch-lentil pasta (90.63) (Ertaş *et al.*, 2021). The h^* of the pasta containing EW

showed a linear increase ($R^2 = 0.258$; $p < 0.0001$) in response to incremental levels of EW (Table 3.9). No significant differences ($p > 0.05$) in the h^* of the pasta containing GG (Table 3.8). The h^* of pasta containing GG showed quadratic interactions ($R^2 = 0.0076$; $p = 0.2912$) in response to incremental levels of GG (Table 3.9). Furthermore, the h^* of pasta samples containing 2.5% XG was significantly lower ($p < 0.05$) was lower than those containing 0.5 – 1.5% XG and 3.5 – 4.5% XG (Table 3.8). The h^* of pasta containing XG showed quadratic responses ($R^2 = 0.0124$; $p = 0.1758$) in response to incremental levels of XG (Table 3.9). The h^* values of pasta containing GG and XG are higher than those reported on jasmine rice noodles (41.39 – 48.36) (Kraithong & Rawdkuen, 2020). The increase in the C^* and h^* values with increasing inclusion levels of the EW and XG could be due to the increase in the brightness of the pasta. This implies that more light is reflected from the surface of the pasta (Bai *et al.*, 2022; Lorenzo *et al.*, 2018), which causes the pasta's color to be skewed towards the red spectrum.

Table 3. 9 Effect of Graded Levels of Hydrocolloids on the Colour of Uncooked Banana Flour Pasta

Parameters	Hydrocolloids*	Equation	R ² Linear	P-Linear	R ² Quadratic	Significance P-Quadratic	X _{min/max} (%)
Lightness	Egg White (EW)	$y = -1087.85 + 120.42x - 3.07x^2$	0.0001	0.9221	0.0098	0.230	19.61
	Guar Gum (GG)	$y = 40.92 - 2.13x + 0.37x^2$	0.0136	0.1507	0.0292	0.0358	2.87
	Xanthan Gum (XG)	$y = 42.68 - 2.07x + 0.44x^2$	0.0029	0.5060	0.0458	0.087	2.35
Redness	EW	$Y = 10.12 - 0.061x + 0.02x^2$	0.0161	0.1179	0.0272	0.0427	15.25
	GG	$y = 3.85 + 0.27x$	0.4901	<0.0001	0.0062	0.1816	
	XG	$y = 4.15 + 0.30x$	0.0568	0.0034	0.0020	0.5730	
Brightness	EW	$y = 18.01 - 1.41x$	0.643	<0.0001	0.0825	<0.0001	
	GG	$y = 6.78 + 0.14x$	0.7264	<0.0001	0.0292	<0.0001	
	XG	$y = 7.92 - 0.34x$	0.2717	<0.0001	0.0569	0.0006	
Mean Saturation Index	EW	$y = 2.98 + 0.30x$	0.0420	0.0121	0.0000	0.9655	
	GG	$y = 7.86 + 0.23x$	0.7690	<0.0001	0.0262	<0.0001	
	XG	$y = 8.82 - 0.18x$	0.3048	<0.0001	0.0349	0.0060	
Hue Angle	EW	$y = 45.43 + 0.60x$	0.2558	<0.0001	0.0001	0.8869	
	GG	$y = 60.39 - 1.15x + 0.25x^2$	0.0006	0.7662	0.0076	0.2912	2.3
	XG	$y = 62.97 - 1.58x + 0.34x^2$	0.0011	0.6845	0.0124	0.1758	2.32

*X_{min/max} = the value of x that maximizes or minimizes the response parameter

3.4.5.2 Cooked Pasta

The colour parameters (a^* , b , and c^*) of the cooked pasta, except for lightness (L^*), decreased in response to incremental levels of hydrocolloids (EW, GG, and XG) (Table 3.10). Similarly, Motta Romero *et al.* (2017) reported that the b^* and c^* values of the cooked proso-millet pasta showed a slight decrease in response to incremental levels of GG and XG. It has been suggested that cooking causes the colour of pasta to degrade, probably due to the degradation of pigments in the flour (Baek & Lee, 2014; Kraithong & Rawdkuen, 2020; Motta Romero *et al.*, 2017). Hence, the decrease in the a^* , b^* , and C^* of the cooked pasta may be due to the degradation of pigments present in the banana flour. The increase in the lightness of the cooked pasta is attributed to the compact structure formed by the hydrocolloids which prevent excess leaching solids from the pasta structure and preserves the lightness of the pasta (Detchewa *et al.*, 2022b; Gasparre & Rosell, 2019; Rachman *et al.*, 2020b; Zheng *et al.*, 2016).

3.4.5.1.1 Lightness

The lightness of pasta containing 21% EW was greater than those containing 18 – 20% EW and 22% (Table 3.10). The L^* of the pasta showed linear responses ($R^2 = 0.1790$; $p < 0.001$) in response to incremental levels of EW (Table 3.11). The L^* values reported for pasta containing EW are significantly lower than reported for extruded jasmine flour noodles (67.87 – 69.90) (Detchewa *et al.*, 2022b) and white-black sorghum flour pasta (47.27 – 65.17) (Pablo Martín Palavecino *et al.*, 2017). Furthermore, the lightness (L^*) of pasta containing 4.5% GG was significantly greater ($p < 0.05$) than that of pasta containing 0.5 – 3.5% GG (Table 3.10). The L^* of the pasta containing GG showed linear responses ($R^2 = 0.1047$; $p < 0.0001$) in response to incremental levels of GG (Table 3.11). The L^* values of pasta containing GG are higher than those reported for soy-channa flour pasta (31.16) but significantly lower than reported for rice-starch-milk pasta (71.17 – 72.49) (Sanguinetti *et al.*, 2015) and extruded jasmine rice flour

noodles (67.21 – 66.90) (Detchewa *et al.*, 2022b). These variations could be due to differences in the lightness of the ingredients used between the studies.

Furthermore, the lightness of pasta containing 3.5% XG was significantly greater ($p < 0.05$) than that of pasta containing 0.5 – 2.5% XG and 4.5% XG (Table 3.10). The L^* of the pasta containing XG showed linear responses ($R^2 = 0.86$; $p < 0.001$) as the inclusion levels of XG increased (Table 3.11). The L^* values reported for pasta containing XG are lower than reported proso-millet pasta (76.87 – 77.27) (Motta Romero *et al.*, 2017); black sorghum flour pasta (47.27 – 57.17) (Pablo Martín Palavecino *et al.*, 2017); and rice pasta with autoclaved starch (45.3 – 54.48) (Raungrusmee *et al.*, 2020). The L^* of the pasta containing XG showed linear responses ($R^2 = 0.86$; $p < 0.001$) as the inclusion levels of XG increased (Table 3.11).

The lower L^* values reported in the present study compared to those in the literature could be due to the darker colour of the banana flour used in the present study compared to light coloured flour used in previous studies. Nevertheless, the L^* values of the pasta increased in response to incremental quantities of the hydrocolloids. This increase was attributed to the formation of a protective layer around starch granules, which prevents excess leaching and preserves the lightness of the pasta (Shahzad *et al.*, 2019). Egg white (EW) preserves and increases the lightness of pasta by enhancing the tighter bonding of starch granules and proteins to form a stable protein matrix that prevents excess solids from the pasta structure (Detchewa *et al.*, 2022b; Saha & Bhattacharya, 2010; Sosa *et al.*, 2018; Xie *et al.*, 2020; Zheng *et al.*, 2016). The high water absorption capacity of the gums (GG and XG) increases the preventing excess loss of solids (Raungrusmee *et al.*, 2020). Gums also prevent the discoloration of pasta by interacting with amylopectin to increase the viscosity and excess loss of solids (Raungrusmee *et al.*, 2020). The increase in the lightness of the cooked pasta could be due to the fact that starch gelatinization causes the lightness of pasta to increase (Sanguinetti *et al.*, 2015).

Table 3. 10 Effect of Hydrocolloids on the Colour Profile of Cooked Banana Flour Pasta

Inclusion of Levels of Hydrocolloids (%)						Significance		
						P-Linear	P-Quadratic	X _{min/max} (%)
Parameters	Egg White							
	18	19	20	21	22			
Lightness	36.3 (0.40) ^a	36.3 (0.21) ^a	37.1 (0.15) ^b	37.1 (0.15) ^b	37.9 (0.20) ^c	<0.001	0.845	
Redness	7.17 (0.122) ^a	7.26 (0.086) ^a	7.19 (0.059) ^a	6.88 (0.098) ^b	6.90 (0.080) ^b	0.0016	0.2705	
Brightness	11.5 (0.21) ^a	12.5 (0.15) ^a	11.9 (0.12) ^a	11.6 (0.16) ^a	10.5 (0.17) ^b	<0.0001	<0.0001	19.00
Mean Saturation Index	13.6 (0.23) ^a	14.4 (0.16) ^c	13.9 (0.13) ^{bc}	13.4 (0.17) ^a	12.6 (0.17) ^d	<0.0001	<0.0001	18.55
Hue Angle	58.0 (0.32) ^b	59.6 (0.28) ^a	58.7 (0.30) ^{ab}	59.2 (0.26) ^a	56.7 (0.35) ^c	0.0045	<0.0001	19.11
	Guar Gum							
	0.5	1.5	2.5	3.5	4.5			
Lightness	37.0 (0.29) ^a	37.6 (0.39) ^{ab}	37.5 (0.29) ^{ab}	38.1 (0.21) ^{bc}	38.6 (0.16) ^c	<0.0001	0.6404	
Redness	7.38 (0.123) ^a	7.07 (0.115) ^{ab}	7.27 (0.142) ^a	7.09 (0.085) ^{ab}	6.90 (0.101) ^b	0.0104	0.7294	
Brightness	12.8 (0.15) ^a	12.4 (0.13) ^a	12.4 (0.18) ^a	11.9 (0.18) ^c	11.2 (0.15) ^b	<0.0001	0.0474	
Mean Saturation Index	14.9 (0.18) ^b	14.3 (0.14) ^a	14.4 (0.19) ^{ab}	13.8 (0.18) ^d	13.1 (0.17) ^c	<0.0001	.1521	
Hue Angle	60.1 (0.32) ^a	60.1 (0.50) ^a	59.8 (0.49) ^a	59.0 (0.30) ^{ab}	58.3 (0.28) ^b	0.0002	0.1605	
	Xanthan Gum							
	0.5	1.5	2.5	3.5	4.5			
Lightness	33.2 (0.20) ^d	36.0 (0.32) ^a	37.5 (0.33) ^{ab}	40.2 (0.14) ^c	38.9 (1.21) ^{bc}	<0.0001	<0.0001	
Redness	7.72 (0.068) ^b	7.68 (0.112) ^b	7.22 (0.078) ^c	6.83 (0.075) ^a	6.65 (0.102) ^a	<0.0001	0.5319	

Brightness	12.5 (0.16) ^b	12.9 (0.17) ^b	12.4 (0.15) ^b	11.6 (0.16) ^a	11.4 (0.12) ^a	<0.0001	0.0088
Mean Saturation							
Index	14.6 (0.16) ^{bc}	15.1 (0.19) ^c	14.3 (0.16) ^b	13.5 (0.16) ^a	13.3 (0.16) ^a	<0.0001	0.0399
Hue Angle	58.2 (0.29) ^b	59.3 (0.27) ^a	59.7 (0.25) ^a	59.3 (0.42) ^a	59.9 (0.26) ^a	0.0006	0.1153

*Values in brackets are standard error of means

*Means with a different in each row are significantly ($p < 0.05$) different

[‡] $X_{\min/\max}$ = the value of x that maximizes or minimizes the response parameter

3.4.5.2.2 Redness

The redness (a^*) of pasta samples containing 18 – 20% EW was significantly greater ($p < 0.05$) than those containing 21 – 22% (Table 3.10). The a^* values of pasta containing EW are higher than reported for the jasmine rice flour noodles (0.15 – 0.17) (Detchewa *et al.*, 2022b) but significantly lower than those reported for black sorghum flour pasta (7.87 – 10.87) (Pablo Martín Palavecino *et al.*, 2017). The decrease in redness of the pasta is probably due to thermal degradation of the carotenoids present in the egg white due to their heat-labile nature (Motta Romero *et al.*, 2017). The a^* of pasta containing EW showed linear responses ($R^2 = 0.0652$; $p = 0.0016$) in response to incremental levels of EW (Table 3.11).

Pasta containing 4.5% GG was significantly lower ($p < 0.05$) a^* than that of pasta containing 0.5 – 3.5% GG (Table 3.10). The redness values reported in this study are higher than those of soya-channa flour pasta (4.77) (Susanna & Prabhasankar, 2013), jasmine rice noodles (0.17 – 0.21) (Detchewa *et al.*, 2022b) and rice-flour-corn-starch pasta (-1.89 to - 2.03) (Sanguinetti *et al.*, 2015). The a^* of the pasta containing GG showed linear responses ($R^2 = 0.0438$; $p = 0.0104$) in response to incremental levels of GG (Table 3.11). Furthermore, pasta containing 3.5 and 4.5% XG was significantly lower ($p < 0.05$) a^* compared to pasta containing 0.5 – 2.5% XG (Table 3.10). The redness (a^*) of the pasta containing XG is higher than reported by Milde *et al.* (2020) for cassava starch noodles (1 – 2); black sorghum flour pasta (7.48 – 10.87) (Pablo Martín Palavecino *et al.*, 2017) and rice-flour pasta (-1.89 to - 3.59) (Sanguinetti *et al.*, 2015). The a^* of the pasta containing XG showed linear responses ($R^2 = 0.4306$; $p < 0.0001$) as the inclusion levels of XG increased (Table 3.11).

The higher redness (a^*) values obtained in this study compared to those in the literature could be due to the use of relatively lighter ingredients in those studies that do not have high concentrations of pigments, such as banana flour and interaction of the gums and carotenoids in banana flour (Javaid *et al.*, 2021; Kraithong & Rawdkuen, 2020). It has been suggested that

pigments that influence the redness of pasta are heat-labile and degrade when subjected to high temperatures (Aravind *et al.*, 2012; Motta Romero *et al.*, 2017). Hence, the decreasing a^* values of the cooked pasta is responsible to increasing quantities of the hydrocolloids could be due to the longer cooking time, which exposes the pigments to higher temperatures for prolonged periods, thereby increasing their degradation.

3.4.5.2.3 Brightness

The brightness (b^*) of the cooked decreased in response to the incremental levels of the hydrocolloids (Table 3.10). The brightness of pasta containing 22% EW was significantly lower ($p < 0.05$) than that of pasta containing 18 – 21% EW (Table 3.10). The b^* values of pasta containing EW are comparable to those reported for extruded jasmine rice flour noodles (Detchewa *et al.*, 2022b) but lower than reported for white sorghum flour pasta (17.33) (Pablo Martín Palavecino *et al.*, 2017). The b^* of pasta containing EW showed quadratic responses ($R^2 = 0.1753$; $p < 0.0001$) in response to the incremental levels of EW (Table 3.11).

Pasta containing 0.5 – 2.5% GG had significantly higher ($p < 0.05$) compared to pasta containing 3.5 – 4.5% GG (Table 3.10). The b^* of pasta containing GG showed a linear decrease ($R^2 = 0.2782$; $p < 0.0001$) in response to incremental levels of GG (Table 3.11). The b^* of pasta containing GG are comparable to those of soya-channa flour pasta (10.64) [1] and sorghum flour pasta (12.38 – 17.33) [2] but are lower than the reported for cassava starch pasta (22 – 28) [3]. Furthermore, pasta containing 0.5 – 2.5% XG had significantly higher ($p < 0.05$) brightness compared to pasta containing 3.5 – 4.5% XG (Table 3.10). The b^* values of pasta containing XG are higher than reported for rice-starch-milk protein pasta (8.66 – 8.55) (Sanguinetti *et al.*, 2015); comparable to those reported for rice-autoclaved-starch pasta (14.22 – 16.35) (Raungrusmee *et al.*, 2020) and proso-millet flour pasta (15.84 – 16.04) (Motta Romero *et al.*, 2017). The b^* of pasta containing XG showed linear responses ($R^2 = 0.2323$; $p < 0.0001$) as the inclusion levels of XG increased (Table 3.11).

The low b^* values of pasta containing EW could be due to the destruction of carotenoids, which results in less reflected light (Bai *et al.*, 2022; Lorenzo *et al.*, 2018). Furthermore, the low b^* of the pasta containing GG and XG is due to the destruction of pigments in the ingredients as the pasta undergoes thermal processing (i.e., cooking) (Motta Romero *et al.*, 2017). Aravind *et al.* (2012) reported that the brightness of cooked pasta decreased substantially at 10 – 20% GG. This suggests that hydrocolloids may negatively affect the pasta's structural integrity at higher inclusion levels, hence, optimal inclusion levels of the various hydrocolloids are required to improve the brightness of pasta. The low b^* values may deter consumer acceptability of the cooked banana pasta because consumer prefer pasta with higher yellowness (brightness).

3.4.5.2.4 Mean Saturation Index

Pasta containing 19% EW had a significantly higher ($p < 0.05$) mean saturation index (c^*) compared to pasta containing 18% and 20 – 22% EW (Table 3.10). The c^* of pasta containing EW showed quadratic/linear responses ($R^2 = 0.1325$; $p < 0.0001$) in response to incremental levels of EW (Table 3.11). Furthermore, the C^* value of pasta containing 0.5% GG was significantly higher than those containing 1.5 – 4.5% GG. The c^* of pasta containing GG showed linear responses ($R^2 = 0.2627$; $p < 0.0001$) in response to incremental levels of GG (Table 3.11). Moreover, the C^* values of pasta containing 1.5% XG were significantly greater ($p < 0.05$) than those reported for pasta containing 0.5% XG and 2.5 – 4.5% XG (Table 3.10). The c^* of pasta containing XG showed linear responses ($R^2 = 0.3014$; $p < 0.0001$) in response to incremental levels of XG (Table 3.11).

The mean saturation index (C^*) is associated with the brightness of pasta (Javaid *et al.*, 2021). The decreasing C^* values of the cooked pasta in response to incremental levels of the hydrocolloids (Table 3.10), was consistent with trends observed in the b^* values of the cooked pasta (Table 3.10). The decrease in the C^* of the pasta was correlated with decrease in the

brightness of the pasta. In addition, The decreasing c^* values of pasta with increasing inclusion levels of the hydrocolloids could be due to the thermal degradation of carotenoids in EW and pigments of banana flour. Hence, optimal inclusion levels are warranted to prevent deterioration of C^* and b^* of the pasta caused by longer cooking time and high inclusion levels.

3.4.5.2.5 Hue Angle

No significant differences were apparent in the h^* values of both cooked and uncooked pasta, thereby signalling the hydrocolloids have a minimal effect ($p > 0.05$) on the hue * values of the pasta. This suggests that the inherent properties of the ingredients have the greatest influence on the h^* values. However, the h^* values of pasta containing 0.5% XG were significantly lower ($p < 0.05$) than that of pasta containing 1.5 – 4.5% XG, with those containing 4.5% XG having the highest value (59.88) (Table 3.10). The h^* of pasta containing XG showed a linear response ($R^2 = 0.0752$; $p = 0.0006$) in response to incremental levels of XG (Table 3.11). Xanthan gum (XG) increased the h^* of the pasta by preventing excess loss of solids, which preserves the colour of the pasta and causes more reflection of light. Furthermore, pasta containing 18% and 22% EW had significantly lower ($p < 0.05$) compared to pasta containing 19 – 21% EW (Table 3.10). The h^* of pasta containing EW showed quadratic responses ($R^2 = 0.0441$; $p = 0.0045$) in response to incremental levels of EW (Table 3.11). Moreover, pasta containing 4.5% GG had a significantly lower ($p < 0.05$) compared to pasta containing 0.5 – 3.5% GG (Table 3.10). The h^* of pasta containing GG showed linear responses ($R^2 = 0.0903$; $p = 0.0002$) in response to incremental levels of GG (Table 3.11). The low h^* value of the pasta containing EW and GG at high inclusion levels could be due to the thermal degradation of pigments present in the banana flour (Motta Romero *et al.*, 2017).

Table 3. 11 Effect of graded levels of the hydrocolloids on the colour of Cooked Banana Flour Pasta

Parameters	Hydrocolloids	Equation	R ² Linear	P-Linear	R ² Quadratic	Significance P-Quadratic	X _{min/max} (%)
Lightness	Egg White (EW)	$Y = 32.37 + 0.29x$	0.1790	<0.001	0.0002	0.845	
	Guar Gum (GG)	$Y = 36.96 + 0.192x$	0.1047	<0.0001	0.0013	0.6404	
	Xanthan Gum (XG)	$y = 31.08 + 4.08x$	0.86117	<0.0001	0.813067	<0.0001	
Redness	EW	$y = 5.97 + 0.16x$	0.0652	0.0016	0.0077	0.2705	
	GG	$y = 7.33 - 0.04x$	0.0438	0.0104	0.0008	0.7294	
	XG	$y = 7.91 - 0.22x$	0.4306	<0.0001	0.0015	0.5319	
Brightness	EW	$y = -5.20 + 1.90x - 0.05x^2$	0.1330	<0.0001	0.1753	<0.0001	19.00
	GG	$y = 12.75 + 0.04x$	0.2782	<0.0001	0.0191	0.0474	
	XG	$y = 12.54 + 0.22x$	0.2323	<0.0001	0.0351	0.0088	
Mean Saturation Index	EW	$y = -0.97 + 1.67x - 0.045x^2$	0.1325	<0.0001	0.1325	<0.0001	18.55
	GG	$y = 14.90 - 0.07x$	0.2627	<0.0001	0.0102	0.1521	
	XG	$y = 14.84 + 0.04x$	0.3014	<0.0001	0.0198	0.0399	
Hue Angle	EW	$y = 27.02 + 3.44x - 0.09x^2$	0.0441	0.0045	0.1782	<0.0001	19.11
	GG	$y = 60.03 + 0.26x$	0.0903	0.0002	0.0121	0.1605	

	XG	$y = 57.88 + 0.99x$	0.0752	0.0006	0.0155	0.1153
$x_{\min/\max}$	= the value of x that maximizes or minimizes the response parameter					

Kraithong and Rawdkuen (2020) and Sanguinetti *et al.* (2015) suggested that the inherent properties of the ingredients used to manufacture the pasta have more influence on the pasta's color than hydrocolloids. Hence, Pablo Martín Palavecino *et al.* (2017) found that the lightness of white sorghum pasta was significantly greater than black sorghum flour pasta, even though both pasta types were containing egg white and egg protein. Hence, it can be recommended that the positive effects of hydrocolloids on the colour of pasta products can be enhanced by compositing them with higher-lightness ingredients.

3.4.6 Implications for Consumer Acceptability

Consumers prefer pasta with cooking losses that are below the thresholds of 8 - 10%, hence, banana flour pasta fortified with hydrocolloids may be more consumers because its cooking losses were below the recommended thresholds (8 - 10%). However, the challenge is that the cooking time of the banana flour pasta may not be suitable for majority of urban dwellers, who prefer foods with a shorting cooking time given their schedules. Consumers prefer pasta with less stickiness (low adhesiveness), hence, based on the findings of the present study, pasta containing GG may be accepted by more consumer compared to those fortified with EW and XG. The high adhesiveness at high quantities of EW and XG are attributed to longer cooking times and high-water absorption capacity of the XG. Moreover, recent studies suggest that consumer prefer pasta with a brighter and vivid yellow colour. The colour parameters of the uncooked pasta increased in response to incremental quantities of the hydrocolloids. However, the colour parameters of the cooked pasta, except lightness, decreased in response to incremental quantities of the hydrocolloids. This demonstrates that longer cooking times may reduce the consumer acceptability of banana flour-based pasta as it reduces its brightness and

increasing its adhesiveness. Hence, studies on the optimal inclusion levels of the hydrocolloids are warranted to increase consumer acceptability of the banana flour pasta.

For food processors, incorporation of hydrocolloids into banana flour pasta makes the production more efficient and enables them to produce pasta with high quality due to its extensibility (decreasing gradient modulus). This means that the pasta will have no cracks and extensive cooking losses, and thereby will generate high revenues due to high consumer acceptability. However, the challenges for most food processors will be to find optimal inclusion levels for the hydrocolloids given that high quantities of hydrocolloids deteriorate the quality of pasta. In addition, sourcing bananas and processing them to flour, may be a challenge because it is a laborious undertaking.

3.5 Conclusion

This study demonstrated that hydrocolloids could enhance the quality of banana flour pasta through reduced cooking losses and increased lightness and hardness. However, the colour parameters of the cooked pasta, except for lightness, decreased as the inclusion levels of the hydrocolloids increased. Hydrocolloids interact with starch granules in the banana flour to form a more stable and compact protein matrix to reduce water penetration into and loss of solids from the pasta structure. This demonstrates that hydrocolloids can be applied to improve the quality properties of gluten-free foods such as bread, cookies and other gluten-free pasta. This will reduce incidences of gluten-related disorders and improve food and nutrition security for gluten-intolerant consumers. This present study did not assess consumer acceptability of the banana flour-pasta fortified with hydrocolloids, hence research in this regard may be warranted. Furthermore, more research on the optimal inclusion levels of hydrocolloids in pasta samples is needed as higher inclusion levels in pasta samples have been shown to increase the cooking time, which is not desirable in urban settings. To optimize the quality (cooking time, colour, and

texture) of banana flour pasta, the recommended inclusion levels of EW should be 19 – 20%, while those of GG and XG should be 2 – 3%.

4. CHAPTER FOUR: EFFECTS OF HYDROCOLLOIDS ON THE FUNCTIONAL CHARACTERISTICS OF BANANA FLOUR PASTA.

Abstract

Pasting properties are said to give valuable information about the potential behavior of starch granules during the cooking process. However, there is currently limited knowledge on how hydrocolloids influence the functional characteristics of banana flour-based pasta. Hence, the present study evaluates the combined effect of three types of hydrocolloids, namely egg white, guar, and xanthan gums, on the pasting properties and gel texture of banana flour-based pasta. Pasta samples were prepared using distilled water, wheat flour, banana flour with varying levels of egg white (18 – 22%), guar gum, and xanthan gum (0.5 – 4.5%), dried overnight and stored in sealed and airtight plastics till further analysis. Milled pasta samples were transferred to an aluminum container filled with 25g of distilled water for RVA analysis. The resultant paste was then kept overnight at room temperature and analyzed for gel texture. The pasting properties of the pasta containing egg white decreased while those containing xanthan gum and guar gum increased. Xanthan gum and guar gum had a significant effect ($p < 0.05$) on all the pasting properties of the pasta except for peak time and final viscosity. In addition, egg white had a significant effect ($p < 0.05$) on the pasting properties, except for peak time and setback viscosity. The firmness of the pasta gels increased as the inclusion levels of the hydrocolloids increased. Xanthan gum is the only hydrocolloid that significantly influenced ($p < 0.05$) the gel texture of the paste. These variations could be attributed to the unique way each hydrocolloid interacts with the starch granules present in the flour. Hence, more research is warranted to understand how the inclusion levels and type of hydrocolloids influence the pasting properties and gel texture of banana flour-based pasta products. The inclusion levels for optimal gel

texture properties (increased firmness/stiffness and reduced adhesiveness) are 20.7% egg white and 2 – 3% for guar and xanthan gums.

Keyword(s): Banana flour; Pasta;, Xanthan Gum; Guar Gum; Egg White; Pasting Properties, Gel Texture.

4.1 Introduction

Climate change, decreasing wheat production levels, and incidences of gluten intolerance have significantly reduced the demand for wheat-based pasta products and increased the demand for healthier pasta products such as banana flour (Woomer & Adedeji, 2021). Banana flour pasta is desirable to consumers due to its high nutraceutical value and resistant starch content (Dotto *et al.*, 2019; Tangthanantorn *et al.*, 2021b). However, banana flour pasta has compromised quality properties such as high cooking losses, darker color, and high stickiness (Padalino *et al.*, 2016; Rachman *et al.*, 2020b). Incorporating hydrocolloids such as egg white, guar, and xanthan gums can improve the quality and sensory attributes of banana flour pasta by reducing its cooking loss and stickiness and increasing its lightness (Castelo-Branco *et al.*, 2017b; Rachman *et al.*, 2020b; Tangthanantorn *et al.*, 2021b). These improvements are associated with the ability of the hydrocolloids to form a robust protein matrix by interacting with the starch granules (Zheng *et al.*, 2016). The mechanisms for improving quality parameters can be explained by ample analysis, such as microscopy, spectroscopy, and pasting properties.

Pasting properties are used to analyze the behavior of starch during the cooking process (Alessandra Marti *et al.*, 2014a). It has been suggested that incorporating the hydrocolloids into pasta influences its pasting properties (Chauhan *et al.*, 2017; Detchewa *et al.*, 2022a; Kaur *et al.*, 2015). Chauhan *et al.* (2017) found that guar gum (GG) increased the pasting properties of amaranth-flour pasta. Xu *et al.* (2022b) found that xanthan gum (XG) increased the pasting

properties of wheat-highland barley noodles. Increasing the inclusion levels of guar gum in pasta increases inter-molecular interaction or entanglement with the starch granules and increases the viscosity of the pasta (Chauhan *et al.*, 2017). The interaction of XG and gelatinized starch during dough formation is responsible for the increase in the peak viscosity of the pasta (Hong *et al.*, 2021; Javaid *et al.*, 2021; Xu *et al.*, 2022b). However, Aravind *et al.* (2012) found that the pasting properties of durum wheat spaghetti decreased as the inclusion levels of GG increased. Similar findings have been reported for rice flour noodles containing xanthan gum (Detchewa *et al.*, 2022b). Gums inhibit the viscosity of pasta by competing with the starch granules for available water (Aravind *et al.*, 2012; Detchewa *et al.*, 2022b). Detchewa *et al.* (2022b) also found that the viscosity of noodles containing egg white (EW) was lower than the rice flour pasta without hydrocolloids. Egg white (EW), which has high protein content, reduced the viscosity of the noodles by reducing the amount of water accessed by the starch granules and the quantity of available starch (Detchewa *et al.*, 2022b; Ertaş *et al.*, 2021; Alessandra Marti *et al.*, 2014a).

Gel texture properties have also been used to explain the influence of hydrocolloids on the texture of pasta (Kongolo *et al.*, 2017; Shahzad *et al.*, 2019). Gels are formed by crosslinked polymer molecules that form a tangled and interconnected molecular network immersed in water (Saha & Bhattacharya, 2010). It has been suggested that incorporating EW improved the gel firmness of wheat-barley highland noodles (Ding *et al.*, 2024). The firmness of wheat-barely highland noodles gels increased due to ionic bonds, hydrogen bonding, hydrophobic interactions, and disulfide bonds (Ding *et al.*, 2024). Similarly, Shahzad *et al.* (2019) found that gums increased in the gel firmness of potato starch. This increase was attributed to the development of hydrogen bonds and gum macromolecules (Saha & Bhattacharya, 2010; Shahzad *et al.*, 2019). Other mechanisms by which hydrocolloids increase the hardness of the gels are hydrogen bonding, cation-mediated crosslinking, proliferation of junction zones, and

hydrophobic association (Ding *et al.*, 2024; Kraithong & Rawdkuen, 2020; Saha & Bhattacharya, 2010). Studies have been conducted on the influence of egg whites (Rachman *et al.*, 2020b; Rachman *et al.*, 2019), guar, and xanthan gums (Tangthanantorn *et al.*, 2021b) on banana flour and other conventional flour. There is currently limited information on the combined effects of hydrocolloids on the pasting properties and gel texture of banana flour-based pasta. Hence, the present study assesses the combined effect of hydrocolloids (egg white, guar, and xanthan gums) on the pasting properties and gel texture of banana flour-based pasta.

4.2 Materials and Methods

4.2.1 Materials

The composition of the materials used in the present study and the supermarkets where they were purchased were as described in Chapter 3.

4.2.2 Pasta Preparation and Formulation

The formulations and methods used to prepare the pasta used in the present study were as described in Chapter 3.

4.2.3 Rapid Visco-Analysis

The pasting properties of the ground pasta samples were analyzed using A Rapid Viscoanalyzer (RVA) (4500, Perten Instruments, Sweden) equipped with (Thermocline, Newport Scientific) analysis software. The RVA analysis of the pasta was done following the procedures described by Hong *et al.* (2021) and Wood (2009) with modifications. In an aluminum container, four grams (4 g; 14% moisture basis) of milled pasta was added into 25 g of distilled water (adjusted to correct for sample moisture content) and mixed a paddle. The RVA curves/pasting properties of the pasta were calculated in terms of pasting temperature, breakdown viscosity, peak

viscosity, final viscosity, breakdown viscosity, and trough viscosity. The pasting properties of the milled pasta were analyzed using the standard one (1) method test, where the mixed samples were held for 1 minute at 50 °C, heated and kept at 95 ° C for 2.5 minutes. Thereafter, the samples were cooled down to and held for 1.5 minutes at 50 °C. The speed of the paddle 950 rpm for the first 10 seconds and kept at a constant speed of 160 rpm throughout the whole,

4.2.4 Gel Texture Analysis

Analysis of the texture of the RVA-cooked gels was done using the methods of Shahzad *et al.* (2019) and Kongolo *et al.* (2017) with slight modifications. The RVA-cooked pasta pastes were packed in tightly sealed plastic sample holders (diameter: 3.5 cm and height: 1.1 cm) and stored overnight at room temperature. The gel firmness (maximum) and adhesive force (maximum negative force) were analyzed using the texture analyzer (TA. XT Plus Texture Analyzer, Stable Micro Systems, UK) fitted with a cylinder probe (2 mm diameter) equipped with the TA. XT Exponent© software. The texture analyzer had the following settings: pre-test and test speed (1.0 mm/s), post-test speed (10.0 mm/s), and penetration distance (5 mm).

4.2.5 Statistical Analysis

The statistical tools, software, procedures, and methods used to analyze the pasting and gel texture of the banana flour-based pasta were as described in Chapter 3.

4.3 Results and Discussion

4.3.1 Pasting Properties of banana flour pasta

Rapid Visco-analysis (RVA)/pasting properties are used to study the potential behavior of starch during the cooking process (Alessandra Marti *et al.*, 2014b). The pasting properties of the banana flour-based pasta are presented in Table 4.1. The pasting properties of the pasta containing EW decreased in response to incremental levels of EW (Table 4.1). However, the

pasting properties of the pasta with the GG and XG, with the except pasting temperature and trough viscosity, increased as their inclusion levels increased. Similar findings were reported by Chauhan *et al.* (2017) and Xu *et al.* (2022b) who reported that the pasting properties of amaranth flour pasta and wheat barley noodles increased as the inclusion levels of GG and XG increased. The reduction in the pasting properties of the pasta containing EW may be due to the ability of egg whites to slow down water intake by the starch granules (Alessandra Marti *et al.*, 2014b). The increase in the pasting properties of the pasta containing GG and XG may be due to the interaction surface of hydrogen bonds of starch granules with xanthan interaction with xanthan gum (Xu *et al.*, 2022b); low synergistic interactions between gums leached amylose and gums, and increased intermolecular entanglement within the starch granules (Kraithong & Rawdkuen, 2020; Shahzad *et al.*, 2019). It has also been suggested that an increase in the viscosity of pasta could be due to the inability of the gums to transfer to the interior of the starch to prevent amylose leaching (Xu *et al.*, 2022b). The pasting properties showed linear responses ($R^2 = 0.0793 - 0.6898$; $p < 0.05$) as the inclusion of the hydrocolloids (EW, GG, and XG) increased (Table 4.2).

Pasting temperature is the temperature at which gelatinization of starch granules is initiated (Xu *et al.*, 2022b). The pasting temperature of the pasta containing EW increased as the inclusion levels of the hydrocolloid increased (Table 4.1). No significant differences ($p > 0.05$) were observed for the pasting temperature of the pasta containing EW. The pasting temperatures in the present study are significantly lower than those reported for jasmine flour noodles containing EW and (86 °C) (Detchewa *et al.*, 2022b). Egg white (EW) competes with other biopolymers for available water and reduces the amount of water the starch granules absorb (Alessandra Marti *et al.*, 2014b). Hence, the pasting temperatures of the pasta increased as the inclusion levels of EW increased, probably due to increased resistance to swelling, and suggests that higher temperatures may be required to gelatinize the starch granules.

However, the pasting temperatures of the pasta containing XG and GG decreased in response to the increment levels of the hydrocolloids (Table 4.1). The pasting temperature of pasta containing 0.5% GG was significantly greater ($p<0.05$) compared to pasta containing 1.5 – 4.5% GG. Furthermore, the pasting temperature of the pasta containing 0.5 – 1.5% XG was significantly greater ($p<0.05$) than containing 2.5 – 4.5% XG. The findings of the present study are similar to those made by Xu *et al.* (2022b) and Liu *et al.* (2023) who found that the pasting temperatures of wheat-based noodles decreased as the inclusion levels of the hydrocolloids (GG and XG) increased. The reduction in pasting temperature is attributed to reduced resistance to swelling and rupture by the starch granules (Xu *et al.*, 2022b), which may indicate low/reduced crystallinity (Kumar & Khatkar, 2017).

Peak viscosity is the extent to which starch granules can swell freely before they physically break down (Gull *et al.*, 2018) and is the equilibrium between swelling and polymer leaching (Aasima Rafiq *et al.*, 2017). It is suggested that higher peak viscosity is associated with a higher proportion of un-gelatinized starch in food products, and low peak viscosity is associated with starch degradation in food products (Aasima Rafiq *et al.*, 2017). The peak viscosity of the pasta containing 18 – 19% EW was significantly higher ($p<0.05$) than that of pasta containing 20 – 22% EW (Table 4.1). The peak viscosity reported in the present study is greater than that of rice flour noodles containing 5% EW (3 600 mPa.s) (Detchewa *et al.*, 2022b). This is probably due to differences in the types of flour used to develop the pasta products. The lower peak viscosity at higher inclusion levels is attributed to the high protein content of EW and low starch content (Detchewa *et al.*, 2022b). Egg white (EW) reduces the peak viscosity of pasta by competing with other biopolymers, such as starch, for available water (Alessandra Marti *et al.*, 2014b). Egg white (EW) also reduces the peak viscosity of the pasta by reducing the amount of water absorbed by the starch granules (Alessandra Marti *et al.*, 2014b). This

increases the resistance of the starch granules to swelling and rupturing, hence the decrease in the peak viscosity of the pasta containing EW.

However, the peak viscosity of the pasta containing 3.5% GG and XG was significantly greater ($p < 0.05$) than that of pasta containing 0.5 – 2.5% and 4.5% GG and XG (Table 4.1). The peak viscosity values for the pasta containing XG and GG are greater than those reported for wheat-based pasta and noodles (1656.67 - 2903.50 mPa.s) (Aravind *et al.*, 2012; Liu *et al.*, 2023; Xu *et al.*, 2022b). Increasing the inclusion levels of guar gum in pasta increases the inter-molecular interaction or entanglement with the starch granules and increases the peak viscosity of the pasta (Chauhan *et al.*, 2017). The increase in the peak viscosity of the pasta containing XG is due to the interaction of XG and gelatinized starch during dough formation/mixing of ingredients (Hong *et al.*, 2021; Javaid *et al.*, 2021; Xu *et al.*, 2022b).

Trough viscosity and breakdown viscosity are associated with the extent to which starch granules are damaged after gelatinization (Kongolo *et al.*, 2017). Higher trough and breakdown viscosity values imply that the food product will incur higher losses during processing (i.e., cooking) (Manoj Kumar *et al.*, 2019). The trough viscosities of all the pasta samples decreased as the inclusion levels of the hydrocolloids (EW, GG, and XG) increased (Table 4.1). The trough viscosity of pasta containing 18% EW was significantly greater ($p < 0.05$) than those containing 19 – 22% EW. The trough viscosity of pasta containing 0.5 – 1.5% GG was significantly higher ($p < 0.05$) than those containing 2.5 – 4.5% (Table 4.1). Likewise, the trough viscosities of pasta containing 0.5 – 1.5% XG were significantly ($p < 0.05$) greater compared to pasta containing 2.5 – 4.5% XG (Table 4.1). The present findings are similar to those made by Aravind *et al.* (2012) who reported that the trough viscosity of durum wheat spaghetti decreased as the inclusion levels of GG increased from 2.5 to 15%. The decrease in trough viscosity could be attributed to hydrocolloids competing with starch for available water and inhibiting the pasting or retrograding of the starch granules (Aravind *et al.*, 2012; Detchewa *et*

al., 2022b). It could also be attributed to the disruption of the starch/protein matrix by the soluble fibre present in banana flour (Aravind *et al.*, 2012). The trough viscosity values of pasta containing GG are higher than those reported for durum wheat spaghetti (1183 – 1080 mPa.s) (Aravind *et al.*, 2012), while the trough viscosity of pasta containing XG was comparable to those reported for wheat barley noodles (1338.50 – 1785.50 mPa.s) (Xu *et al.*, 2022b).

Table 4. 1 Effect of Hydrocolloids on the Pasting Properties of Banana Flour Pasta

Parameters	Inclusion of Levels of Hydrocolloids (%)					Significance		
						P-Linear	P-Quadratic	X _{min/max} (%)
	Egg White							
	18	19	20	21	22			
Pasting Temperature	50.13 (0.04) ^a	50.10 (0.0) ^a	66.72 (14.41) ^a	58.97 (13.28) ^a	69.63 (15.92) ^a	0.0650	0.886	
Peak Viscosity	9387 (869.74) ^b	9975 (689.81) ^a	4785 (523.29) ^a	5013.67 (1378) ^a	4992.33 (2324.43) ^a	0.0028	0.2676	
Trough Viscosity	3460 (1569.78) ^a	2528 (1189.05) ^{ab}	2641.33 (295.39) ^{ab}	1532 (869.20) ^b	2030 (537.14) ^{ab}	0.0626	0.4464	
Breakdown Viscosity	5927 (2439.52) ^a	7447 (1058.14) ^{ab}	2144 (321.11) ^b	3481.67 (2176.52) ^b	2962 (2607.87) ^b	0.0455	0.543	
Final Viscosity	9196.50 (622.96) ^b	7598 (2171.41) ^{ab}	5673.33 (483.45) ^a	6328 (1159.93) ^a	5693.67 (976.51) ^a	0.0093	0.1448	
Setback Viscosity	5736.5 (2192.74) ^a	5070 (2743.60) ^a	3032 (316.72) ^a	4796 (1971.23) ^a	3663 (690.18) ^a	0.2845	0.5107	
	Guar Gum							
	0.5	1.5	2.5	3.5	4.5			
Pasting Temperature	75.45 (0.64) ^b	54.68 (2.90) ^a	56.78 (11.49) ^a	50.27 (0.17) ^a	58.32 (13.84) ^{ab}	0.0311 (0.29)	0.0219 (0.0219)	3.00
Peak Viscosity	7447.50 (627.20) ^{ab}	5900.67 (1326.51) ^{ab}	7762 (1112.4) ^{ab}	9198.67 (835.55) ^b	7157.67 (3010.97) ^{ab}	0.324	0.6018	
Trough Viscosity	4899.50 (712.47) ^c	2487.67 (884.63) ^b	2140.33 (448.74) ^{ab}	1165.33 (399.15) ^a	1943 (924.71) ^{ab}	<0.0001 (0.55)	0.0017(0.23)	
Breakdown Viscosity	2548 (1340.67) ^a	3413 (2210.87) ^a	5621.67 (1320.69) ^{ab}	8033.33 (1166.97) ^b	5214.67 (3535.55) ^{ab}	0.0167	0.1054	

Final Viscosity	6472.50 (945.40) ^a	6335.33 (1161.02) ^a	7309 (1261.81) ^a	9310 (1890.32) ^a	7160 (3321.19) ^a	0.2114	0.4431
Setback Viscosity	1573 (231.93) ^a	3847.67 (1988.82) ^a	5168.67 (1573.05) ^{ab}	8044.67 (1758.79) ^b	5217 (3418.16) ^{ab}	0.0083	0.0632
Xanthan Gum							
	0.5	1.5	2.5	3.5	4.5		
Pasting Temperature	77.95 (0.49) ^b	67.72 (15.09) ^b	50.18 (0.11) ^a	50.13 (0.08) ^a	52,38 (2.65) ^a	0.0002 (0.63)	0.0240 (0.14)
Peak Viscosity	8549.5 (190.21) ^{ab}	6554 (2012.98) ^a	8710.5 (666.80) ^{ab}	9434 (840.95) ^b	7897 (1545.86) ^{ab}	0.2020	0.2689
Trough Viscosity	4935 (360.62) ^b	3749 (1375.44) ^b	1109 (73.54) ^a	1259 (1089.2) ^a	1227 (97.02) ^a	0.0001	0.0650
Breakdown Viscosity	3614.5 (170.41) ^b	2805 (1306.8) ^a	7601 (741.05) ^a	8175 (1032.35) ^a	6670 (1606.53) ^a	0.0025	0.1830
Final Viscosity	7747 (144.25) ^a	7263 (2027.85) ^a	9269 (663.27) ^a	5843.67 (5232.37) ^a	7422.67 (791.83) ^a	0.8084	0.8817
Setback Viscosity	2812 (504.87) ^a	3514 (1428.43) ^{ab}	8159.50 (737.51) ^b	4584.67 (4181.58) ^a	6195.67 (747.08) ^{ab}	0.0851	0.3676

*Values in brackets are standard deviations

*Means with a different letter in each row are significantly (p<0.05) different.

[‡]X_{min/max} = the value of x that maximizes or minimizes the response parameter

The breakdown viscosity of the pasta containing 20 – 22% EW was significantly low ($p < 0.05$) compared to pasta containing 18 – 19% EW (Table 4.1). This suggests increasing the inclusion levels of EW improved the starch's structural integrity and shear resistance. Egg white (EW) reduced the breakdown viscosity of the pasta by interacting with the starch granules to form a physical barrier, which hinders the denaturing and swelling of the starch granules (Zheng *et al.*, 2016). However, the breakdown viscosity of the pasta containing XG and GG increased in response to the incremental levels of the hydrocolloids (Table 4.1). The breakdown viscosity of pasta containing 3.5% GG was significantly greater ($p < 0.05$) than that of the pasta containing 0.5 – 2.5% GG and 4.5% GG (Table 4.1). Furthermore, the breakdown viscosity of pasta containing 2.5 – 4.5% XG was significantly greater ($p < 0.05$) compared to the pasta containing 0.5 – 1.5% XG (Table 4.1). The breakdown viscosity of pasta containing gums increased due to the gums' high water absorption capacity and inability to transfer into the interior of the starch to prevent the leaching of amylose (Xu *et al.*, 2022b). This contradicts the suggestion by Shahzad *et al.* (2019) that gums reduce the viscosity of pasta by providing a protective layer on the surface of the starch granules, thereby restricting the swelling of the starch granules. The breakdown viscosity values reported in the present study are significantly higher than reported for rice flour noodles containing EW (900 mPa.s) and wheat-based pasta and noodles containing GG and XG (191 – 1 118 mPa.s) (Aravind *et al.*, 2012; Detchewa *et al.*, 2022b; Liu *et al.*, 2023; Xu *et al.*, 2022b).

Final and setback viscosity is related to the reordering of starch molecules, following gelatinization, and leaching out of amylose from broken starch granules (Kongolo *et al.*, 2017). The final and setback viscosity of the pasta containing EW decreased in response to the incremental levels of the hydrocolloids (Table 4.1). The final viscosity of the pasta containing 18% EW was significantly higher ($p < 0.05$) compared to pasta containing 19 – 22% EW. There was no significant difference ($p > 0.05$) in the final viscosities of the pasta containing GG and

XG (Table 4.1). No significant differences ($p>0.05$) were apparent in the setback viscosity of the pasta containing EW. The setback viscosity of the pasta containing 3.5% GG was significantly higher ($p<0.05$) than those containing 0.5 – 2.5% GG and 4.5% GG (Table 4.1). Likewise, the setback viscosity of pasta containing 2.5% XG was significantly higher ($p<0.05$) compared to pasta containing 0.5 – 1.5% and 3.5 – 4.5% XG (Table 4.1).

The low final and setback viscosity at higher inclusion levels of EW is attributed to the interaction of the egg white and hydrocolloids, which inhibits amylose chains (Chauhan *et al.*, 2017; Kraithong & Rawdkuen, 2020). However, the final and setback viscosity of the pasta containing GG and XG increased as the inclusion levels of the hydrocolloids increased (Table 4.1). The increase in the final and setback viscosity of pasta containing GG and XG is attributed to the distinct molecular structures of XG, the inability of gums to interact with amylose, and the flexibility of the gum chains (Shahzad *et al.*, 2019). The lack of interactions between gums and amylose increases the final viscosity by forming a strong network (Shahzad *et al.*, 2019). Increasing setback viscosity of the pasta is associated with short-term retrogradation and reduction in pasting temperature, indicating reduced resistance of starch granules to rupture and swelling (Xu *et al.*, 2022b). Some studies have also suggested gums increase the setback viscosity of foods by promoting the retrogradation of amylose (Shahzad *et al.*, 2019). The final and setback viscosity reported in the present study is higher than those reported for rice flour containing EW (1750 mPa.s) and durum wheat-based noodles and pasta (1836 – 3175 mPa.s; 756 – 1539 mPa.s) containing GG and XG (Aravind *et al.*, 2012; Detchewa *et al.*, 2022b; Liu *et al.*, 2023; Xu *et al.*, 2022b).

The pasting properties are said to give information about the behavior of the starch granules during the cooking process. Hydrocolloids compete with starch granules for available water (Aravind *et al.*, 2012; Detchewa *et al.*, 2022b). This implies that more time will be required to gelatinize the starch granules as less water will be supplied to starch granules. Hence, the

cooking time of the pasta increased in response to incremental levels of EW, GG, and XG. Furthermore, protein-rich hydrocolloids such as EW are said to compete with starch granules for available water and reduce the amount of starch available for gelatinization (Alessandra Marti *et al.*, 2014a; Saleh *et al.*, 2017). It has also been suggested that EW cannot form the bonding necessary to protect the swollen granules from rupture (Saleh *et al.*, 2017). Hence, the pasting properties of the pasta, except for pasting temperature, decreased as the inclusion levels of EW increased. It has been suggested that a low pasting temperature implies that less energy and time are required to gelatinize the starch granules (Kumar & Khatkar, 2017). This suggests that the cooking time of the pasta containing EW is attributed to the prolonged time required to gelatinize starch granules in the banana flour. The effects of EW on the pasting properties are associated with its ability to reduce the amount of water accessed by the starch granules and the total amount of starch available for retrogradation. In addition, the pasting properties of the pasta, except trough viscosity and pasting temperature, increased in response to incremental levels of GG and XG. This trend was due to increased molecular interaction, competition for available water with starch granules, the interaction of gums and starch during dough formation, and their lack of synergized interactions with leached amylose. The findings of the present study suggested that the effects of the hydrocolloids on the functional characteristics of the pasta may be related to the inherent properties of the hydrocolloids and their interactions with the flour. Therefore, research may be warranted to unravel the specific mechanisms by which each hydrocolloid influences the pasting properties of banana flour-based pasta.

Table 4. 2 Effect of Graded Levels of Hydrocolloids on Pasting Properties of the Banana Flour Pasta

Pasting Properties	Hydrocolloid s	Equation	R ² Linear	P-Linear	Significance R ² Quadratic	P-Quadratic	X _{min/max} (%)
Pasting Temperature (°C)	Egg White (EW)	$y = -2.14 + 4.20x$	0.2761	0.0650	0.0013	0.886	3.00
	Guar Gum (GG)	$y = 82.78 - 20.76x + 3.41x^2$	0.2393	0.0311	0.2786	0.0219	
	Xanthan Gum (XG)	$y = 90.75 - 22.17x$	0.6292	0.0002	0.1421	0.0240	
Peak Viscosity (mPa.s)	EW	$y = 43941 - 3238.58x$	0.5426	0.0028	0.0504	0.2676	
	GG	$y = 5935.77 + 1090.53x$	0.0793	0.324	0.0215	0.6018	
	XG	$y = 34026 - 18448x$	0.1297	0.2020	0.0955	0.2689	
Trough Viscosity (mPa.s)	EW	$y = 13800 - 1021.68x$	0.2697	0.0626	0.0392	0.4464	
	GG	$y = 6310.47 - 2937.43x$	0.5536	<0.0001	0.2258	0.0017	
	XG	$y = 6138.88 - 2464.46x$	0.6868	0.0001	0.0865	0.0650	
Breakdown Viscosity (mPa.s)	EW	$y = 30141 - 2216.90x$	0.3086	0.0455	0.0238	0.5438	
	GG	$y = -374.70 + 4027.96x$	0.3385	0.0167	0.1346	0.1054	
	XG	$y = 859.32 + 3220.59x$	0.5373	0.0025	0.0718	0.1830	
Final Viscosity (mPa.s)	EW	$y = 36444 - 2735.03x$	0.4235	0.0093	0.1055	0.1448	
	GG	$y = 5107.77 - 1654.07x$	0.1213	0.2114	0.0438	0.4431	
	XG	$y = 7323.16 + 211.31x$	0.0056	0.8084	0.0021	0.8817	
Setback Viscosity (mPa.s)	EW	$y = 22644 - 1713.35x$	0.0995	0.2845	0.0363	0.5107	
	GG	$y = 1167.35 + 4545.78$	0.3812	0.0083	0.1601	0.0632	
	XG	$y = 1184.44 + 2675.48$	0.2315	0.0851	0.0571	0.3676	

$x_{\min/\max}$ = the value of x that maximizes or minimizes the response parameter

4.3.2 Gel Texture of Banana flour pasta

The gel texture properties of the banana flour-based pasta are presented in Table 4.3. Gels are forms of matter and viscoelastic systems that are intermediate between solid and solids and whose storage modulus (G') is greater than the loss modulus (G'') (Aguilera, 1992; C. Deepa *et al.*, 2017). They are formed through crosslinking of polymers to create a rigid molecular network immersed in water (Saha & Bhattacharya, 2010). In the present study, the gels' firmness and gradient modulus increased in response to incremental levels of hydrocolloids (EW, GG, and XG) (Table 4.3). However, the negative force of the pastes decreased as the inclusion levels of the hydrocolloids increased (Figure 4.10). These trends are attributed to the crosslinking of the starch and hydrocolloids, which increases the gels' rigid structure and results in harder gels (Pongpichaiudom & Songsermpong, 2018; Saha & Bhattacharya, 2010).

The firmness of gels is caused by syneresis of water, retrogradations of the starch, and crystallization of amylopectin (Kongolo *et al.*, 2017; Sandhu *et al.*, 2010). However, some studies have argued that incorporating hydrocolloids reduces the hardness of the gel by inhibiting the reassociation of amylose chains (Xu *et al.*, 2022b). Hydrocolloids can increase the firmness of gels through hydrophobic association, cation-mediated crosslinking, and hydrogen bonding (Ding *et al.*, 2024; Kraithong & Rawdkuen, 2020; Saha & Bhattacharya, 2010). The firmness of the paste from pasta containing EW increased as the inclusion levels of the hydrocolloid increased from 18 – 21% (Table 4.3). No significant difference ($p > 0.05$) was apparent in the gel firmness of the paste from the pasta containing EW. The gel firmness of the paste from the pasta containing EW showed a linear increase ($R^2 = 0.4040$; $p < 0.05$) in response to incremental levels of EW (Table 4.4). The increase in the firmness of the paste is attributed to the high protein content found in egg whites (Detchewa *et al.*, 2022b; Ding *et al.*, 2024; Ertaş *et al.*, 2021). These proteins contain hydrophilic groups (NH_2 , $-\text{OH}-$, $-\text{COOH}-$ and $-\text{NH}-$), which form crosslink the starch and promote retrogradation of amylose to produce a rigid

paste (Detchewa *et al.*, 2022b). Ding *et al.* (2024) attributed the increase in the gel of the wheat highland barley noodles containing EW to ionic bonds, hydrogen bonding, hydrophobic interactions, and disulphide bonds.

The firmness of the paste from pasta containing GG increased as the inclusion levels of GG increased from 0.5 – 2.5% (Table 4.3). No significant differences ($p>0.05$) were observed in the gel firmness of the paste from the pasta containing GG. The gel firmness of the paste from the pasta containing GG showed a quadratic increase ($R^2 = 0.3474$; $p< 0.05$) in response to the incremental levels of GG (Table 4.4). Guar gum (GG) has a high molecular mass and can increase the hardness of the gels by interacting with the starch granules to form a rigid structure inside the gels. (Saha & Bhattacharya, 2010). Hence, the firmness of the gels increased in response to the incremental levels of GG (Table 4.4).

Furthermore, the firmness of the paste from pasta containing XG increased as the inclusion levels of the hydrocolloids increased from 0.5 – 3.5% (Table 4.3). The gel firmness of the paste from pasta containing 3.5% XG was significantly greater ($p<0.05$) than that of pasta containing 0.5 – 2.5% XG and 4.5% XG. The gel firmness of paste from the pasta containing XG showed quadratic responses ($R^2 = 0.0975$; $p>0.05$) in response to incremental levels of XG (Table 4.4). Xanthan gum (XG) is an anionic hydrocolloid that forms electrostatic complexes with some protein fractions in the pasta to form a more rigid 3D network of starch pastes (Pongpichaiudom & Songsermpong, 2018). Due to its rigid molecular structure, XG can reinforce the 3D structure of starch paste better than EW and GG (Pongpichaiudom & Songsermpong, 2018). Hence, the paste from pasta containing XG had the highest peak force (firmness) and gradient modulus compared to the paste containing EW and GG.

The increase in the firmness of the gels was corroborated by increasing gradient modulus values (Table 4.3). The increase in the gradient modulus of the paste implies that increasing

the inclusion levels of the hydrocolloids (EW, GG, and XG) increased the stiffness and hardness of the gels (Table 4.3). The present findings are similar to those made by Yu *et al.* (2022) who found that XG reduced the flexibility of soy-protein isolate gels. The gradient modulus of the paste from pasta containing EW showed a linear increase ($R^2 = 0.0776$; $p = 0.3327$), while those containing GG and XG ($R^2 = 0.3470$; $p = 0.0267$ and $R^2 = 0.974$; $p = 0.2524$) showed a quadratic increase to incremental levels of hydrocolloids (Table 4.4).

Some studies have suggested incorporating hydrocolloids reduces the adhesiveness of starch gels (Matia-Merino *et al.*, 2019). The decrease in the negative force values suggests that increasing inclusion levels of the hydrocolloids reduced the adhesiveness of the pasta (Table 4.3). The gel texture properties of the paste confirm the observations made on the texture properties (hardness, negative area, positive area, and area to peak) of the pasta, which are inclusion levels of the hydrocolloids and its internal structure.

Table 4. 3 Effect of Hydrocolloids on the Gel Texture Properties of Banana Flour Pasta

Inclusion Levels of Hydrocolloids (%)						Significance		
						P-Linear	P-Quadratic	X _{min/max} (%)
Parameters								
	Egg White							
	18	19	20	21	22			
Gel Firmness (g)	234.23 (13.39) ^a	282.24 (26.72) ^a	346.90 (196.41) ^a	390.18 (144.90) ^a	313.63 (143.61) ^a	0.0008	0.0010	
Negative Force (g)	64.81 (6.23) ^b	- 62.71 (15.68) ^b	- 68.19 (12.10) ^b	- 118.24 (35.71) ^a	- 57.46 (24.06) ^b	0.5219	0.2700	20.7
Gradient Modulus (g.sec)	22.85 (1.34) ^a	27.64 (4.62) ^a	34.09 (19.60) ^a	38.42 (14.46) ^a	30.78 (14.34) ^a	0.3371	0.3450	
	Guar Gum							
	0.5	1.5	2.5	3.5	4.5			
Gel Firmness (g)	171.13 (62.47) ^a	301.86 (187.1) ^a	475.14 (285.44) ^a	289.81 (88.57) ^a	174.11 (53.06) ^a	0.9834	0.0266	2.50
Negative Force (g)	-49.48 (20.89) ^a	- 62.38 (9.96) ^a	- 70.25 (3.25) ^a	- 53.98 (24.15) ^a	-45.35 (15.36) ^a	0.5687	0.0683	2.30
Gradient Modulus (g.sec)	16.54 (6.23) ^a	29.60 (18.69) ^a	46.91 (28.50) ^a	28.40 (8.85) ^a	16.84 (5.29) ^a	0.9854	0.0267	2.50

Xanthan Gum								
	0.5	1.5	2.5	3.5	4.5			
Gel Firmness (g)	207.85 (60.98) ^a	241.93 (6.49) ^a	330.52 (265.49) ^a	684.47 (3.10) ^b	242.91 (118.13) ^a	0.2596	0.2522	3.12
Negative Force (g)	- 64.67 (16.01) ^a	- 62.53 (1.28) ^a	- 60.06 (16.41) ^a	- 76.19 (4.65) ^a	- 68.47 (44.95)	0.6090	0.8595	
Gradient Modulus (g.sec)	20.21 (6.09) ^a	23.62 (0.65) ^a	32.43 (26.51) ^a	67.81 (0.31) ^b	23.71 (11.79) ^a	0.2598	0.2524	3.08

*Values in brackets are standard deviations

*Means with a different letter in each column is significantly ($p < 0.05$) different

[¥]X_{min/max} = the value of x that maximizes or minimizes the response parameter

Table 4. 4 Effect of Graded Levels of Hydrocolloids on Gel Texture Properties of the Banana Flour-Based Pasta

Gel Texture Properties	Hydrocolloids	Equation	R ² Linear	P-Linear	Significance		
					R ² Quadratic	P-Quadratic	X _{min/max} (%)
Gel Firmness (g)	Egg White (EW)	$y = 356.51 + 62.21x$	0.4040	0.0008	0.3822	0.0010	
	Guar Gum (GG)	$y = 25.46 + 303.49x - 60.82x^2$	0.0000	0.9834	0.3474	0.0266	2.50
	Xanthan Gum (XG)	$y = -115.14 + 457.77x - 73.30x^2$	0.0943	0.2596	0.0975	0.2522	3.12
Negative Force (g)	EW	$y = 375.37 - 45.05x - 1.10x^2$	0.0342	0.5219	0.1055	0.2700	20.7
	GG	$y = -40.50 - 22.32x - 4.80x^2$	0.1055	0.5687	0.2453	0.0683	2.30
	XG	$y = -63.65 - 0.93x$	0.228	0.6090	0.027	0.8595	

Gradient Modulus (g.sec)	EW	$y = -133.82 + 16.06x$	0.0776	0.3371	0.750	0.3450	
	GG	$y = 1.99 + 30.30x - 6.07x^2$	0.000	0.9854	0.3470	0.0267	2.50
	XG	$y = -12.00 + 45.08x - 7.31x^2$	0.0943	0.2598	0.974	0.2524	3.08

$\bar{x}_{\min/\max}$ = the value of x that maximizes or minimizes the response parameter

*Values in brackets and bold text represent R^2 values for a given parameter.

Gel formation is associated with a given food's inherent properties and retrogradation rate (i.e., flour) (Kongolo *et al.*, 2017; Shahzad *et al.*, 2019). Kongolo *et al.* (2017) found that banana flour tends to have higher recrystallization compared to most conventional flours due to its longer amylopectin chains, which can create crystallization junction zones. Junction zones are regions where two or more biopolymers meet and are formed by hydrogen bonding (Saha & Bhattacharya, 2010). Increasing the junction zones leads to a more compact three-dimensional recrystallized amylopectin chain (Saha & Bhattacharya, 2010). Some scholars have argued that the retrogradation rate of amylose and the incorporation of hydrocolloids influenced the gel texture properties of any given starch (Shahzad *et al.*, 2019). Hence, it may be concluded that the texture of the gels results from the inherent properties (starch molecular and supra molecular) of the starch granules of the banana flour and its interactions with the hydrocolloids.

4.4 Conclusion

The study showed that hydrocolloids influence the pasting properties and gel texture of pasta made from banana flour. Egg white (EW) decreased the pasting properties of banana flour pasta as its inclusion levels increased. However, GG and XG increased the pasting properties of the banana flour pasta as their inclusion levels increased. These variations are due to the unique way each hydrocolloid interacts with the starch granules present in the flour. The firmness of the gels increased in response to incremental levels of hydrocolloids (egg white, guar gum, and xanthan gum). This was attributed to retrogradation and interaction of the hydrocolloids with the starch granules, which increased the hardness/rigidity of the pastes. These variations demonstrate that the pasting and gel texture properties depend on the type, inclusion levels, and composition of a given hydrocolloid. There is currently limited knowledge on how hydrocolloids influence the pasting properties and gel texture of banana flour-based pasta. Hence, research is warranted to understand how the concentrations and types of hydrocolloids

influence the pasting properties and gel texture of banana flour-based pasta products. These studies will enable food processors and scientists alike to understand how incorporating hydrocolloids influences the behavior of the starch granules of banana flour-based pasta and its associated quality and functional characteristics. The inclusion levels for optimal gel texture properties (increased firmness/stiffness and reduced adhesiveness) are 20.7% egg white and 2 – 3% for guar and xanthan gums.

5. CHAPTER FIVE: GENERAL DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

Pasta is essential for human nutrition and the sustainability of food systems because it has a long shelf life, minimum cooking and transportation requirements, and is palatable (Amini Khoozani *et al.*, 2019; Camelo-Méndez *et al.*, 2018; Woomer & Adedjei, 2021). Pasta is rich in complex carbohydrates but lacks dietary fibre, resistant starch, and bioactive compounds (Pablo M Palavecino *et al.*, 2019; Torres Vargas *et al.*, 2021). However, climate change, declining wheat production levels, and the ongoing Ukraine-Russia war have threatened pasta production by restricting the export of wheat from Ukraine and Russia, since they are largest producers and suppliers of wheat (WEF, 2021). These changes have significantly contributed to the drastic price increase and reduction in the consumption of conventional pasta over the past years (WEF, 2021). Furthermore, the gluten found in wheat causes celiac disease and gluten sensitivity (Woomer & Adedjei, 2021). These disorders result in lifelong intolerance to gluten and inflammation of the small intestines, resulting in low nutrient absorption (Larrosa *et al.*, 2013; Myhrstad *et al.*, 2021; Saturni *et al.*, 2010). Gluten-related can only be treated by strictly adhering to a gluten-free diet (Saturni *et al.*, 2010). Gluten-related allergic reactions coupled with climate change and geographical jostles have necessitated the need to find alternative ingredients, such as flour from green bananas, to develop gluten-free pasta with similar quality and nutritional value as semolina pasta.

The conversion of bananas into flour reduces wastage, preserves the nutritional value, and improves the market value of bananas (Li *et al.*, 2020). Due to its high nutrient density (dietary fibre and resistant starch), banana flour is suitable for producing healthy foods such as pasta (Li *et al.*, 2020; Tangthanantorn *et al.*, 2021b; Yangilar, 2015). Banana flour can modulate and

prevent diseases such as diabetes, obesity, colorectal cancer, and cardiovascular diseases due to its abundant RS content (Dibakoane *et al.*, 2022). However, pasta made from banana flour has undesirable qualities such as high cooking losses, darker color, and poor textural quality (high adhesiveness, high stickiness, and less extensibility) (Padalino *et al.*, 2016; Rachman *et al.*, 2020b). These undesirable qualities are caused by the lack of hydrocolloidal properties and low protein content of banana flour (Rachman *et al.*, 2020b; Thakaeng *et al.*, 2021). Hence, ingredients that enhance the quality and functional characteristics of pasta made from banana flour must be evaluated. Ingredients such as hydrocolloids (egg white, guar, and xanthan gums) can enhance the quality and functional characteristics of gluten-free pasta such as banana flour-based pasta (Chauhan *et al.*, 2017; Motta Romero *et al.*, 2017; Tangthanantorn *et al.*, 2021b).

Hydrocolloids, polymers formed by a long chain of proteins and polysaccharides Castelo-Branco *et al.* (2017c) reported that tagliatelle pasta prepared with 15 - 30% banana flour and egg protein did not show any dark color. Tangthanantorn *et al.* (2021b) demonstrated that incorporating 1.0 and 1.5% guar gum and xanthan reduced the cooking losses of 30% dried banana noodles. Rachman *et al.* (2020b) reported that incorporating egg protein into banana pasta improved banana flour-pasta protein levels. In addition, Zandonadi *et al.* (2012) found that 47% banana pasta blended with egg protein, guar, and xanthan gum recorded higher acceptability compared to wheat-based pasta in terms of overall acceptability, texture, aroma, and flavor by both celiac and non-celiac patients. These improvements stem from hydrocolloids interacting with starch granules to form a stable protein matrix that restricts excess solids leaching and water penetration from/into the pasta (Rachman *et al.*, 2020b; Tangthanantorn *et al.*, 2021b; Widelska *et al.*, 2019; Zheng *et al.*, 2016).

Other studies have shown that guar and xanthan gums increased the pasting properties of amaranth flour pasta Chauhan *et al.* (2017); wheat-highland barley noodles (Xu *et al.*, 2022b). Increasing the inclusion levels of guar gum in pasta increases inter-molecular interaction or

entanglement with the starch granules and the viscosity of the pasta (Chauhan *et al.*, 2017). The interaction of XG and gelatinized starch that occurs during dough formation/mixing of ingredients is responsible for the increase in the peak viscosity of the pasta (Hong *et al.*, 2021; Javaid *et al.*, 2021; Xu *et al.*, 2022b). However, some scholars have found that egg white, guar, and xanthan gum reduced the pasting properties of durum wheat spaghetti Aravind *et al.* (2012) and rice flour pasta Detchewa *et al.* (2022b). Egg whites and gums reduce the viscosity of pasta by competing with the starch granules for available water to inhibit starch pasting and retrogradation (Aravind *et al.*, 2012; Detchewa *et al.*, 2022b). In addition, Shahzad *et al.* (2019) found that gums increased in the gel firmness of potato starch. This increase was attributed to the development of hydrogen bonds and gum macromolecules (Saha & Bhattacharya, 2010; Shahzad *et al.*, 2019). Ding *et al.* (2024) found that the firmness of the gels of the wheat highland noodles increased as the inclusion levels of EW increased. Increases in the firmness of the gels are attributed to the development of hydrogen bonds and gum macromolecules (Saha & Bhattacharya, 2010; Shahzad *et al.*, 2019) and ionic bonds, hydrogen bonding, hydrophobic interactions, and disulphide bonds (Ding *et al.*, 2024).

5.2 Influence of Hydrocolloids on the Quality of Banana Flour-Based Pasta

5.2.1 Cooking Time and Loss

Chapter 3 investigated the effects of varying inclusion levels of three types of hydrocolloids on the cooking quality, texture, and color of banana flour pasta. Increasing the inclusion levels of the hydrocolloids increased the cooking time of the pasta while significantly reducing the cooking losses. These increases are associated with the formation of a compact protein matrix formed by the interactions of the hydrocolloids and starch granules (Detchewa *et al.*, 2022b; A. Marti *et al.*, 2013; Rachman *et al.*, 2019; Zheng *et al.*, 2016). It has been suggested that incorporating more than one type of hydrocolloid in pasta significantly increases its cooking

time due to the formation of an even more compact internal pasta structure (Detchewa *et al.*, 2022b). A compact protein matrix formed by the interactions of the hydrocolloids and starch granules prevents excess leaching/loss of solids from the pasta (Detchewa *et al.*, 2022b; A. Marti *et al.*, 2013; Rachman *et al.*, 2019; Zheng *et al.*, 2016). Hence, the cooking loss of the pasta decreased in response to incremental levels of the hydrocolloids. The dose-response effect between the inclusion levels of the hydrocolloids and cooking quality followed a linear pattern with R^2 values ranging from 0.44 to 0.91. This suggests that the higher cooking times reported for the banana flour-based pasta may be due to increasing inclusion levels and interactions of the hydrocolloids with starch granules, which form an extensive and stable protein matrix in the pasta.

5.2.2 Texture

The hardness of the banana flour-based pasta increased in response to incremental levels of the hydrocolloids. The increase in the hardness of the pasta is associated with the formation of a compact protein matrix formed by the interactions of the hydrocolloids and starch granules (Detchewa *et al.*, 2022b; A. Marti *et al.*, 2013; Rachman *et al.*, 2019; Zheng *et al.*, 2016). Some studies have suggested that hydrocolloids improve the elasticity of pasta (Kraithong & Rawdkuen, 2020; Tangthanantorn *et al.*, 2021b). Hence, in the present study, the extensibility of the pasta increased as the inclusion levels of the hydrocolloids increased, as evidenced by decreasing gradient modulus values. Furthermore, increasing the inclusion levels of hydrocolloids reduces the adhesiveness of pasta by reducing its cooking losses (Bai *et al.*, 2022; Guo *et al.*, 2020). The adhesiveness of pasta containing GG decreased as the inclusion levels of the hydrocolloids decreased. The decrease in adhesiveness is attributed to the formation of a stable protein matrix, which prevents excess leaching of solids during cooking, resulting in less sticky pasta (Gasparre & Rosell, 2019; Tangthanantorn *et al.*, 2021b). However, the adhesiveness of the pasta increased as the inclusion levels of EW and XG

increased. The increase in adhesiveness of the fortified pasta is attributed to the high water absorption capacity of the xanthan gum and prolonged cooking times induced by the EW (Gasparre & Rosell, 2019; Thuy *et al.*, 2023; Xie *et al.*, 2020). Kaur *et al.* (2015) found that gums increased the adhesiveness of potato pasta by delaying the swelling of the starch granules and reducing interaction within the starch granules due to restricted amylose leaching.

5.2.3 Colour

The lightness of uncooked and cooked pasta increased in response to incremental levels of hydrocolloids. Hydrocolloids increase the lightness of pasta by formatting a compact granular structure, which prevents excess leaching of solids and high levels of water absorption by the starch granules (Detchewa *et al.*, 2022b; A. Marti *et al.*, 2013; Rachman *et al.*, 2019; Zheng *et al.*, 2016). The color of parameters of uncooked pasta increased in response to incremental levels of the hydrocolloids. However, the colour parameters of the cooked pasta, except lightness and hue angle, decreased in response to incremental levels of the hydrocolloids. The decrease in the colour parameters of cooked pasta is attributed to the degradation of pigments that occur at high temperatures (Baek & Lee, 2014; Kraithong & Rawdkuen, 2020; Motta Romero *et al.*, 2017). This suggests that the lightness and other colour parameters are influenced by the structure of the pasta and the inherent properties (colour) of the ingredients used to manufacture the pasta. Studies by Kraithong and Rawdkuen (2020) and Sanguinetti *et al.* (2015) suggested that hydrocolloids have a minimal effect on the color of the pasta compared to the inherent properties of the ingredients. Hence, Pablo Martín Palavecino *et al.* (2017) found that the lightness of white sorghum pasta was greater than black sorghum flour pasta, even though both pasta types were containing egg white and egg protein. Thus, it can be recommended that the positive effect of hydrocolloids on pasta products can be enhanced by compositing flours or ingredients with higher lightness.

5.3 Influence of Hydrocolloids on the Functional Properties of Banana Flour-Based Pasta

5.3.1 Pasting Properties

Regarding the mechanisms responsible for observations made in Chapter 3, chapter 4 assessed the influence of the hydrocolloids on the pasting properties and gel texture of banana flour-based pasta. The pasting properties (Final Viscosity, Peak Viscosity, Breakdown Viscosity, Trough Viscosity, and Setback Viscosity) decreased in response to incremental levels of EW. Protein-rich ingredients such as EW reduce the viscosity of pasta by competing with other biopolymers for available water, reducing water uptake/intake of the starch granules and the amount of starch available for gelatinization (Alessandra Marti *et al.*, 2014a; Saleh *et al.*, 2017). Hence, the pasting temperature of pasta increased in response to the incremental levels of EW, which signified that high temperatures and more time would be required to gelatinize the starch granules. This suggests that the cooking time of the pasta containing EW will increase as high temperatures and more time will be needed to gelatinize the starch granules.

The trough viscosity values decreased in response to incremental levels of EW, GG, and XG. The decrease in the trough viscosity values of the pasta is due to the fact that hydrocolloids compete with starch for available water and inhibit the pasting or retrogradation of the starch granules (Aravind *et al.*, 2012; Detchewa *et al.*, 2022b). It could also be due to the disruption of the starch/protein matrix by the soluble fibre present in banana flour (Aravind *et al.*, 2012).

The pasting properties (Final Viscosity, Peak Viscosity, Breakdown Viscosity, Trough Viscosity, and Setback Viscosity) of pasta increased in response to incremental levels of GG and XG. An increase in the inclusion levels of guar gum in pasta increases inter-molecular interaction or entanglement with the starch granules and increases the viscosity of the pasta (Chauhan *et al.*, 2017). Interaction of the XG and gelatinized during dough formation is responsible for the increase in the viscosity of the pasta (Hong *et al.*, 2021; Javaid *et al.*, 2021;

Xu *et al.*, 2022b). The breakdown viscosity of the pasta increased as the inclusion levels of the XG and GG increased. The breakdown viscosity of pasta increased due to the water absorption capacity of the gums and their inability to transfer into the interior of starch to prevent the leaching of amylose (Xu *et al.*, 2022b). The increase in the final and setback viscosity of pasta containing GG and XG is attributed to the distinct molecular structures of XG, the inability of gums to interact with amylose, and the flexibility of the gum chains (Shahzad *et al.*, 2019). The lack of interactions between gums and amylose increases the final viscosity by forming a strong network (Shahzad *et al.*, 2019). Increasing setback viscosity of the pasta is associated with short-term retrogradation and reduction in pasting temperature, which indicates reduced resistance of starch granules to rupture and swelling (Xu *et al.*, 2022b). Some studies have also suggested gums increase the setback viscosity of foods by promoting the retrogradation of amylose (Shahzad *et al.*, 2019).

5.3.2 Gel Texture

The gel firmness of the paste from the banana flour-based pasta increased in response to incremental levels of the hydrocolloids (EW, GG, and XG). This was corroborated by increasing gradient modulus values. The increase in the firmness of the paste is attributed to the high protein content found in egg whites (Detchewa *et al.*, 2022b; Ding *et al.*, 2024; Ertaş *et al.*, 2021). These proteins contain hydrophilic groups (NH₂, -OH-, -NH-, -COOH-) that form crosslink with starch to promote amylose retrogradation and produce a more rigid paste (Detchewa *et al.*, 2022b). Ding *et al.* (2024) attributed the increase in the gel of the wheat highland barley noodles containing EW to ionic bonds, hydrogen bonding, hydrophobic interactions, and disulphide bonds. Guar gum has a high molecular mass and increases the firmness of the gels by interacting with the starch granules to form a more rigid structure inside the gels (Saha & Bhattacharya, 2010). As an anionic hydrocolloid with a rigid and

conformational internal structure, XG increased the firmness of the gels by reinforcing the 3D structures of the gels (Pongpichaiudom & Songsermpong, 2018).

The increase in the gel firmness of the gels is due to the high retrogradation rate of banana flour relative to conventional flours. Kongolo *et al.* (2017) found that banana flour tends to have higher recrystallization compared to most conventional flours due to its longer amylopectin chains, which can create crystallization junction zones. Some scholars have argued that the retrogradation rate of amylose and the incorporation of hydrocolloids influenced the gel texture of any given starch (Shahzad *et al.*, 2019). Hence, the gel texture of the banana flour gels could be attributed to the inherent properties (starch molecular and supra molecular) of the starch granules of the banana flour and its interactions with the hydrocolloids. In addition, it has been suggested that incorporating hydrocolloids reduces the adhesiveness of starch gels (Matia-Merino *et al.*, 2019). The decrease in the negative force values suggests that increasing inclusion levels of the hydrocolloids reduced the adhesiveness of the pasta (Table 4.3). The gel texture results are consistent with the texture of the banana flour-based pasta and confirm that the texture of the pasta is influenced by the inclusion levels of the hydrocolloids and its internal structure.

5.4 Conclusions

This study demonstrated that hydrocolloids could improve the quality and functional characteristics of banana flour-based pasta. However, the redness, brightness, mean saturation index, and hue angle of the cooked pasta decreased as the inclusion levels of the hydrocolloids increased. Furthermore, the texture of the pasta improved in response to the increment levels of the hydrocolloids (EW, GG, and XG). However, the adhesiveness of the pasta increased response to incremental levels of EW and XG. The increase in the adhesiveness of pasta containing EW and XG is associated with longer cooking times and high-water absorption

capacity. This, therefore, demonstrates that longer cooking times may not be suitable for the texture and color of pasta; hence, there is a need to optimize the inclusion levels of the pasta.

Moreover, uncooked pasta had favorable colour attributes compared to cooked pasta. The colour of the cooked pasta seems to be heavily influenced by the pigmentation of the ingredients (i.e., flour) used to develop the pasta. In addition, the pasting properties of the pasta fortified EW decreased at higher inclusion levels, which indicated resistance to swelling of the starch granules present in banana flour. However, the pasting properties of pasta containing GG and XG increased at higher inclusion levels. These variations could be attributed to the unique way each hydrocolloid interacts with the starch granules present in the flour. Hence, more research on how hydrocolloids on the pasting properties of banana flour-based pasta may be warranted. The firmness of the gels increased in response to incremental levels of the hydrocolloids (egg white, guar gum, and xanthan gum). This was attributed to retrogradation and interaction of the hydrocolloids with the starch granules. There are currently limited studies on the effects of hydrocolloids on the pasting and gel texture properties of banana flour-based pasta. Hence, more studies are needed to elucidate the influence of hydrocolloids on the pasting properties and gel texture of banana flour-based pasta. These studies will enable food processors and scientists alike to understand how the incorporation of hydrocolloids influences the behavior of the starch granules of banana flour-based pasta and its associated quality and functional characteristics.

5.5 Recommendations

The increase in cooking time and decrease in colour parameters of the cooked pasta in response to the incremental levels of the hydrocolloids suggest that further research is needed to find optimal inclusion levels of the hydrocolloids in the pasta, given that research has demonstrated the influence of hydrocolloids on the quality of the pasta depend on their inclusion levels.

Furthermore, hydrocolloids should be combined with ingredients with high lightness values to improve the colour parameters of pasta. There is currently limited knowledge on the effects of hydrocolloids on the pasting properties and gel texture of banana flour-based pasta. Hence, more research is warranted to unravel how the inclusion levels and type of hydrocolloids influence the pasting and gel texture of banana flour-based pasta products. To optimize and enhance the quality (cooking time, colour, and texture) and functional (gel texture) characteristics of the pasta, the present study proposes that the recommended optimal inclusion levels of egg white should be 19 – 20% while those of guar gum and xanthan gum should be 2 – 3%. However, these inclusion levels have to be verified through Response-Surface Methodologies.

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