CHARACTERIZATION OF PARTICLE AND BULK SOLIDS OF ARABIC GUM POWDER AT DIFFERENT PARTICLE SIZES

By

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Chair : Professor, Ir. Yus Aniza Yusof, PhD
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The use of Arabic gum as a functional food ingredient is growing rapidly. Arabic gum is obtained in the form of gum nodules from the exudation of stems and branches of *Acacia Senegal* (L.). Particle size is an important factor influencing powder properties and the end product's quality. However, the food industry lacks information about the effects of particle size on the handling and processing of Arabic gum powder. Hence, this study investigated the particle size effects on Arabic gum powder's physicochemical, flow, rheological, and stability properties. The gum nodules were washed, dried, and cleaned before being ground, sieved, and fractionated into five particle size classes. The fractionation was classified according to its mean diameter (d_{50}), which ranged from 20 to 1000 µm. The proximate composition analysis confirmed that particle size significantly affected the moisture and fibre contents of gum powder. Smaller particles have a higher hygroscopicity, with values of 40%, indicating that they are more prone to absorbing moisture from their surroundings. The dissolution analysis discovered that smaller particles dissolve in water more slowly than larger particles. The swelling index and emulsion capacity results show that larger particles retained more water-swollen granules and had a more remarkable ability to form an emulsion with oil. Meanwhile, morphology analysis discovered that the gum powder had an irregular shape with rough granule surfaces. On the other hand, a reduction in particle size from 1000 to 20 µm tends to reduce powder flowability. The highest Hausner ratio and Carr's index values were found in smaller particles, indicating poor powder flowability. Larger particles caked more, which is due to powder segregation during the handling process, with the coarser fraction dominating the overall caking behaviour of the powders. Furthermore, the larger particles had the highest effective angle of internal friction values due to their interlocking effect. Smaller particles had the highest effective angle of wall friction values, indicating that they will have more difficulty moving along the wall surface. Rheological analysis discovered that all particle sizes exhibited shear-thinning behaviour at low shear rates (0.1–50 s^{-1}) and a viscosity plateau

at high shear rates (50–400 s^{-1}). Higher R^2 validates the best-fitting power-law model for describing the aqueous solution's flow behaviour (n) and consistency index (K). Furthermore, the dynamic mechanical spectra curves revealed that the storage (G') and loss (G'') moduli values increased with frequency, indicating that the highly concentrated gum exhibited solid-like rather than liquid-like behaviour. The isotherm curves had sigmoidal shapes and Type III behaviour, which is typical of sugar-rich products. The Peleg model fits the equilibrium moisture sorption of gum powder well. With SSE = 0.01, $RMSE$ = 0.014, P = 14.14%, and R^2 = 0.999, smaller particles provided the best fitting accuracy. To summarize, Arabic gum with coarse particles sized 208 to 414 µm demonstrated greater dissolution time, flowability, elasticity, and stability than other particle sizes. The ability to predict moisture content during storage under a variety of conditions can reduce product development costs and cycle time while also improving shelf life estimation. Furthermore, this comprehensive study of Arabic gum powder's physicochemical properties will aid in the development of food products with the desired texture by allowing for the selection of a specific particle size.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

PENCIRIAN PEPEJAL ZARAH DAN PUKAL SERBUK GAM ARAB PADA SAIZ ZARAH YANG BERBEZA

Oleh

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Penggunaan gam Arab sebagai bahan makanan berfungsi berkembang pesat. Gam Arab diperolehi dalam bentuk nodul gum daripada eksudasi batang dan dahan *Acacia Senegal* (L.). Saiz zarah adalah faktor penting yang mempengaruhi sifat serbuk dan kualiti produk akhir. Walau bagaimanapun, industri makanan ini tidak mempunyai maklumat mengenai kesan saiz zarah pada pengendalian dan pemprosesan serbuk gam Arab. Oleh itu, kajian ini menentukan kesan saiz zarah pada fisikokimia, aliran, reologi, dan sifat kestabilan serbuk gam Arab. Nodul gum dibasuh, dikeringkan, dan dibersihkan sebelum dikisar, disaring, dan dibahagikan kepada lima kelas saiz zarah. Pecahan dikelaskan mengikut diameter min (d_{50}), yang bersaiz antara 20 hingga 1000 µm. Analisis komposisi proksi mengesahkan bahawa saiz zarah dengan ketara menjejaskan kelembapan dan kandungan serat serbuk gam. Zarah-zarah yang lebih kecil mempunyai higroskopisitasi yang lebih tinggi, dengan nilai 40%, menunjukkan bahawa mereka lebih cenderung untuk menyerap lembapan dari persekitarannya. Analisis pembubaran mendapati bahawa zarah yang lebih kecil larut dalam air lebih perlahan daripada zarah yang lebih besar. Hasil indeks bengkak dan kapasiti emulsi menunjukkan bahawa saiz zarah yang lebih besar mengekalkan lebih banyak butiran yang bengkak air dan mempunyai keupayaan yang lebih luar biasa untuk membentuk emulsi dengan minyak. Sementara itu, analisis morfologi mendapati serbuk gam mempunyai bentuk yang tidak sekata dengan permukaan butiran yang kasar. Manakala, pengurangan saiz zarah daripada 1000 hingga 20 µm cenderung untuk mengurangkan kebolehaliran serbuk. Nisbah Hausner dan nilai indeks Carr tertinggi didapati pada zarah yang lebih kecil, menunjukkan kebolehaliran serbuk yang lemah. Zarah-zarah yang lebih besar terkumpul lebih banyak, yang disebabkan oleh pengasingan serbuk semasa proses pengendalian, dengan pecahan yang lebih kasar mendominasi kelakuan pengekkan keseluruhan serbuk. Tambahan pula, zarah yang lebih besar mempunyai sudut berkesan nilai geseran dalaman yang paling tinggi kerana kesan saling menguncinya. Zarah-zarah yang lebih kecil mempunyai

sudut berkesan nilai geseran dinding yang paling tinggi, menunjukkan bahawa ia akan mengalami lebih kesukaran untuk bergerak di sepanjang permukaan dinding. Analisis reologi mendapati bahawa semua saiz zarah menunjukkan tingkah laku penipisan ricih pada kadar ricih yang rendah (0.1–50 s^{-1}) dan dataran kelikatan pada kadar ricih yang tinggi (50–400 s^{-1}). Nilai R^2 yang lebih tinggi mengesahkan model undang-undang kuasa yang paling sesuai untuk menerangkan tingkah laku aliran penyelesaian berair (n) dan indeks konsistensi (K). Tambahan lagi, lengkung spektrum mekanikal dinamik menunjukkan bahawa nilai moduli penyimpanan (G') dan kerugian (G'') meningkat dengan kekerapan yang semakin meningkat, membayangkan bahawa gam yang likat dan pekat menunjukkan tingkah laku seperti pepejal dan bukannya seperti cecair. Lengkung isoterma mempunyai bentuk sigmoidal dan tingkah laku Jenis III, yang tipikal bagi produk kaya gula. Model Peleg sesuai dengan penyerapan kelembapan keseimbangan serbuk gam dengan baik. Dengan SSE = 0.01, $RMSE$ = 0.014, P = 14.14%, dan R^2 = 0.999, zarah yang lebih kecil memberikan ketepatan yang terbaik. Untuk meringkaskan, gam Arab dengan zarah kasar bersaiz 208 hingga 414 μm menunjukkan masa pembubaran, kebolehaliran, keanjalan, dan kestabilan yang lebih tinggi daripada saiz zarah lain. Keupayaan untuk meramalk kandungan lembapan semasa penyimpanan di bawah pelbagai keadaan dapat mengurangkan kos pembangunan produk dan masa kitaran di samping meningkatkan anggaran jangka hayat. Tambahan lagi, kajian menyeluruh tentang sifat fisikokimia serbuk gam Arab ini akan membantu dalam pembangunan produk makanan dengan tekstur yang dikehendaki dengan membenarkan pemilihan saiz zarah tertentu.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

*a**	Redness
a_w	Water Activity
ANOVA	Analysis of Variance
AOAC	Association of Official Analytical Chemists
*b**	Yellowness
BET	Brunauer, Emmett and Teller
CI	Carr's Index
DSC	Differential Scanning Calorimetry
EC	Emulsion Capacity
ES	Emulsion Stability
FAO	Food and Agriculture Organization
FESEM	Field Emission Scanning Electron Microscope
FTIR	Fourier Transform Infrared Analysis
G'	Storage Modulus
G''	Loss Modulus
GAB	Guggenheim-Anderson-De Boer
HG	Hygroscopicity
HPLC	High Performance Liquid Chromatography
HR	Hausner Ratio
JECFA	The Joint Expert Committee on Food Additives
K	Consistency Index
*L**	Lightness
n	Flow Behaviour
P	Average Relative Deviation

PFT	Powder Flow Tester
PFSD	Powder Flow Speed Dependency
R^2	Coefficient of Determination
RMSE	Root Mean Square Error
SSE	Error Sum of Squares
T_g	Glass Transition Temperature
WHO	World Health Organization
X_e	Equilibrium Moisture Content

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter summarizes the background of the study, including the importance of Arabic gum, primarily in the food and pharmaceutical industries. The food industry, in particular, requires hydrocolloid gums in the form of solid powders, which are added to various liquid or solid systems during processing to achieve the desired final product properties. Previous research that looked at the physicochemical properties of different types of powders and how they affected sensory properties is also reviewed in this chapter. This chapter also contained the problem statement, research gap, research scope, research objectives, research hypothesis, and thesis structure.

1.2 Research Background

1.2.1 Plant Gum Exudates

Various plant species are capable of producing complex polysaccharides known commercially as plant-based gums. A vast majority of plant gum exudates have been discovered and identified in the past several decades. Natural gums derived from plants are beneficial as acceptable food ingredients (Rana *et al.,* 2011). Plant gum exudates are derived from a variety of tree species with unique and varying physical properties (Srivastava and Kapoor, 2005). Plant gum exudates are water-soluble, complex acidic polysaccharides extracted from marine and land plants spontaneously or in response to mechanical injuries. On dehydration, the exudates harden into nodules or ribbons, forming a protective sheath against microorganisms. Often, non-carbohydrate contaminants naturally darken gum exudates, and the dry products are sifted and ground into powder.

Polysaccharide gums are considered one of the most abundant industrial raw materials and have been extensively researched compared to equivalent synthetic materials owing to their sustainability, biodegradability, and safety properties (Rana *et al.,* 2011). The term "gum" typically refers to a group of industrially valuable polysaccharides or their derivatives that hydrate in hot or cold water to form viscous solutions or dispersions at low concentrations (Whistler and BeMiller, 1973). Food-grade gums are sometimes referred to as hydrocolloids (BeMiller, 1996). In addition, gums are classified as natural and modified (Cottrell and Baird, 1980); natural gums include plant exudates (e.g., Arabic and tragacanth gums), seed-based or root-based gums (e.g., potato starch), seaweed extracts (e.g., alginates), and microbial fermentation gums (e.g., xanthan gum). On the other hand, modified gums are primarily composed of cellulose and starch derivatives, such as ethers and esters of cellulose.

Numerous studies on a variety of gums (mainly plant gum exudates and seed gums) have resulted in the identification of valuable natural sources of high-quality complex carbohydrate polymers. They are practical and beneficial for industrial applications, including those in the textile, cosmetic, food, and pharmaceutical industries (Mirhossein and Amid, 2013; Vieira *et al.,* 2007; Verbeken et al., 2003). Arabic gum, guar gum, and karaya gum have been used in the food and pharmaceutical industries for years; these gums are derived from plant exudates (Taha, 1993).

Arabic gum is the most extensively used exudate gum and an essential ingredient in food and other industries due to its excellent emulsion stability, encapsulation properties, and high solubility (Taha, 1993). Guar gum, containing several hydroxyl groups and displaying a polymeric structure, is one of the best thickening, emulsifying, and stabilising additives (Morris, 1995). Meanwhile, karya gum contains acetyl groups, resulting in its very strong swelling, high viscosity, and very poor solubility properties, limiting its applications in the cosmetics and pharmaceutical industries (Koocheki *et al.,* 2009; Silva *et al.,* 2003; Weiping et al., 2000). Arabic gum is the most commercially valuable and economically beneficial gum, making it the most extensively researched (FAO, 2015).

Almost every manufactured product goes through a powder, granular, or particulate phase during its production cycle, which means that a large amount of these materials are processed, handled, stored, and conveyed in bulk. The diameters of these bulk materials range from 30 µm to 5 mm. The relative movement of bulk materials in comparison to neighbouring particles, or along the wall of a storage container is defined as "flow." Inside the storage vessel, bulk materials form an arch, or rathole, preventing discharge and necessitating the use of hammering, vibration, aeration, or other methods to promote flow. Inconsistent or no flow of bulk materials from storage equipment is one of the problems with bulk solid handling. Flow interruptions cause production difficulties and inefficiencies, such as operators diverting from their primary tasks to hammer storage vessels.

In the food industrial sector, coffee powder is widely produced. The taste of coffee is influenced by a wide range of coffee beans, blends, and roasting techniques. The roasting of the beans, the size distribution of the powder, and the type and quality of preparation all contribute to the flavour of coffee. For an aromatic result, different grinds of coffee powder are required in the brewing and filtering processes. When roasted coffee beans are ground into powder, particle size distribution is critical because it affects the brewing and filtering properties, and thus the taste and aroma of the beverage (Severini et al., 2016). Monitoring the particle sizes and size distributions of ground coffee is essential for determining the optimal combination of these variables in order to produce perfectly brewed coffee.

Previous research has looked into the physicochemical properties of coffee powders and their impact on sensory properties (Oliveira et al., 2022; Bilge, 2020; Hargarten et al., 2020; Doğan et al., 2019; Fibrianto et al., 2018). The colours of the brewed coffees gradually darkened as the particle sizes of the ground coffee decreased and the grind became finer. The finer the coffee powder, the more ingredients can be extracted in less time. Furthermore, coffee powder exhibits difficult bulk material behaviour due to its high oil content, broad particle size distribution, and very irregular particle shape, i.e., the particles has a strong tendency to agglomerate, and the powder is difficult to pour or convey. This must be addressed adequately in mechanical and optical measurement methods.

Milk powder manufacturers invest heavily in research and development to ensure that their products have high sensory quality and a long shelf life. The chemical composition and physical properties of milk powders are the primary quality indicators. Powder particle size, particle size distribution, flowability, viscosity, and colour must all be measured because they are directly related to powder behaviour and physical properties. The raw material, different drying methods, and the numerous chemical reactions that could occur during storage due to temperature, relative humidity, and time all contribute to the variability of the milk powder's properties. Several studies on the properties of milk powder as influenced by particle size have been conducted (Nugroho et al., 2021; Ding et al., 2020; Abdalla et al., 2017; Boiarkina et al., 2016).

Pugliese et al. (2017) discovered that the particle sizes of spray-dried skim milk powders were significantly lower than those of whole milk powders, measured as volume and surface mean diameter, with the roller-dried sample having the largest particle size. This indicates that particle size has a significant impact on milk powder quality, which is critical when evaluating milk powder quality standards. Furthermore, the size of the milk powder particles used in the manufacture of various food products can influence the potential end-use behaviour of these products; for example, large particles of dry milk powder exhibit better wettability and dispersibility than small particles. Hence, a thorough understanding of the functional properties of milk powders may enable the dairy to tailor products to the user and assist the food processor in making a targeted choice based on the intended use.

The use of various additives such as thickeners, stabilisers, emulsifiers, and gelling agents is increasing and is highly demanded by many industries, including food, pharmaceutical, and cosmetic. In particular, the food industry requires hydrocolloid gums in the form of solid powders or splits that are added to various liquid or solid systems during processing to achieve desired final product properties (Rosell et al., 2007). One of the most important considerations in solid dosage manufacturing in the processing industry is the uniform flow of solid mixtures (Thalberg et al., 2004). Previous research has examined the flow properties of neem gum (Ogunjimi and Alebiowu, 2013), xanthan gum (Lee and Yoo, 2020), almond gum (Bashir and Haripriya, 2016), Zedo gum (Fadavi et al., 2014), and *Albizia procera* gum (Pachuau et al., 2012).

Furthermore, powder flow issues are prevalent in industries that handle fine powders. Powders with small and irregularly shaped particles, according to some studies, cause more flow issues than large, well-rounded ones. These irregular and elongated particles may mechanically interlock or entangle with one another, obstructing powder flow and lowering flowability. However, the current understanding of fine powder shear strength, which is the primary cause of hopper flow stoppages, does not take into account the influence of particle size distribution, particle shape, or powder storage in any systematic way. This is a significant issue because it has a negative impact on product quality, resulting in the rejection of large batches worth hundreds of thousands of dollars as well as expensive clean-up.

Some powders flow freely and easily into the mass flow regime, whereas others are cohesive and do not flow easily. When fine powders, for example, flow out of a storage bin or hopper, they may form a rathole. A rathole is a self-supporting vertical channel that runs from the outlet to the powder's top surface. This demonstrates that powder flow is governed by physical rather than chemical properties (Thalberg et al., 2004). Physical properties such as improper equipment geometry, particle size and shape, surface texture, size distribution, moisture content, compaction condition, storage time, and so on all have an impact on powder flow. Furthermore, inconsistency in particle size can lead to biomass degradation, material loss, flow obstruction, and a reduction in the powder's ability to flow well during discharge from storage equipment and structures. As a result, selecting the appropriate particle size will ensure that the material flows consistently for its intended use.

Besides that, moisture content and water activity are two of the most important quality control criteria in the industrial manufacturing of beverage powders because they affect handling properties and storage stability. In the processing industries, gum splits and powders were stored in gunny bags under ambient conditions, which are highly affected by the environmental conditions during storage. Water causes physical, chemical, microbiological, and enzymatic reactions in food materials and is the primary cause of deterioration and change in the material. Moisture sorption isotherms describe water's role in maintaining the stability of food and agricultural products during storage. Previous research has commonly studied some gums for moisture sorption isotherms, including babool gum (Saraugi et al., 2022), guar gum (Vishwakarma et al., 2011), Arabic gum (Zeinab and Abdelazim, 2014), xanthan gum (Basu et al., 2007), karaya gum (Saraugi et al., 2022), and carboxymethyl cellulose, guar, locust bean, tragacanth and xanthan gums (Torres et al., 2012). Due to their utility in industrial practise, many researchers are interested in measuring and modelling the sorption isotherms of food materials. This information is required for drying, mixing, packaging, and storing biological materials in order to maintain their quality over time.

1.2.2 Arabic Gum

Exudate gums are well recognized as one of the most important commercial polysaccharides compared with their counterparts. Exudate gums are produced as a result of certain plants' protection mechanisms against mechanical or microbial injuries (Rana et al., 2011). The gums are harvested from the stems and branches of the resource gum trees as dry exudates (FAO, 1995). Gums are obtained primarily from the trunk as natural exudates; however, other parts of the plant can also produce these exudates. For instance, when the stem is deliberately wounded by tapping wounds or fungal growth, the region between the bark and the cambial zone begins to produce gum. Arabic gum and other plant gums are important agroforestry resources in Nigeria.

The name "Arabic gum" is derived from its origin of export in the Arabian Peninsula, as the Arabs were important traders and vendors of this material in early history. Arabic gum is typically made from trees in the *Acacia* genus, the *Mimosoideae* family, and the *Leguminosae* family. This family contains over 500 species, which are found in the tropical and subtropical regions of Africa, India, Australia, Central America, and the American Southwest. The Expert Committee on Food Additives (JECFA) defines Arabic gum as a dried exudation obtained from the stems and branches of *A. senegal* (L.) Willdenow (FAO, 1999), which grows naturally throughout Africa's Sahelian region.

Over the past 5,000 years, Arabic gum has become an article of commerce and is known to be the oldest and best tree exudate gum (Whistler, 1993). It has been observed that gums of the same variety but grown in different locations produce gums that are noticeably different. Hence, it is critical to identify variations in species, varieties, and the environment when producing gums for unique and specific end uses (Yebeyen et al., 2009). Arabic gum uses the term "gum" to refer to its gummy characteristics and to the group of naturally occurring polysaccharides with various industrial applications (Phillips and Williams, 2000).

Two types of gum produced and marketed in Sudan but clearly separated in both national statistics and trade are *A. senegal* (*Hashab*) and *A. seyal* (*Talha*) (Verbeken et al., 2003). *A. senegal* and *A. seyal* gums have been scientifically investigated, commercially used, and compared to other species. Exudates from *A. senegal* and *A. seyal* have been extensively studied due to their high yield and availability compared to other *Acacia* species. Codex and JECFA have established guidelines and standards for *Acacia* gum, which state that any exudate gum obtained from sources other than *A. senegal* and *A. seyal* may not be established as *Acacia* gum.

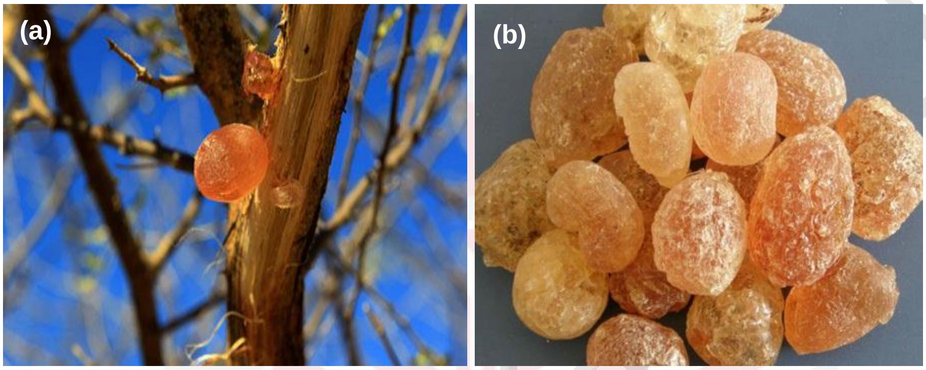

Figure 1.1 : (a) Branches of tree from *A. senegal* species (b) Gum nodules

Arabic gum exudes in the form of large nodules, or “tears,” with a 5-cm diameter from *A. senegal* trees. In order to expedite the exudation process, mature trees between the ages of 5 and 25 are tapped through incisions in their branches, with the bark stripped away (Eisa et al., 2008). The gums exuded from *A. senegal* trees are solid, pale to orange-brown, and break with a glassy fracture (Figures 1.1 (a) and (b)) (Sánchez et al., 2018). Generally, whole, orange-brown gums with round tears and a matte surface texture are considered to be among the highest grades. Moreover, it is well acknowledged that the locations, soil type, and age of trees significantly influence the physicochemical, functional, and toxicological properties of gum derived from *A. senegal* trees (Anderson et al., 1983).

Arabic gum is extensively used in the food industry as an emulsifier (Pua et al., 2007), a foaming agent (Jiang et al., 2013; Walsh et al., 2008), or an encapsulating material (Niu et al., 2018; Mosquera et al., 2012; Gabas et al., 2007). The physicochemical characterisation of polysaccharides is essential, contributing to the commercial value of gums. According to a literature review, no systematic comparative study has been conducted on the particle size characterisation of natural gums, such as Arabic and tragacanth gums, or modified gums such as hydroxyethyl cellulose. Numerous studies in this field have concentrated on cellulose, starch, and some of their convenient derivatives (Daniel et al., 1994).

1.3 Problem Statement

Equipment design and processing In the development of food process engineering require specific and thorough knowledge of both individual particles and the bulk properties of the powders. Due to the widespread usage of powders in a variety of industries and applications, the food industry has experienced a surge in powder production. As a result, information on handling and processing characteristics must be taken into account (Benković et al., 2013). Typically, powders and granular materials are classified according to particle size and mechanical application. Physical properties such as particle size, particle density, moisture content, and granular surface structure influence powder flowability (Barbosa-Cánovas et al., 2005).

Today's consumers demand food powders that dissolve and reconstitute rapidly and completely, which is critical for practical usage. Dissolution occurs when solid particles are introduced into the solvent phase and dissolved until a complete solution is obtained (Amiji and Sandmann, 2003). Moreover, dissolution is one of the most critical aspects of determining the quality of finished products for practical usage Previous studies have emphasised the role of particle size in the dissolution properties of food powders, reporting that particle sizes play a crucial role in influencing the powders' dissolution (Marques et al., 2014; McCarthy et al., 2014). Temperature, particle wettability, structure and surface exposure, dissolved material concentration, and stirring speed influence dissolution (Dokoumetzidis and Macheras, 2006).

Recently, the flowability of food powders has garnered considerable interest (Haas et al., 2020; Atalar and Yazici, 2018; Benković et al., 2017; Shenoy et al., 2015). Studies reported that size reduction significantly impacted powder's physical properties due to its varying particle sizes. Previous studies have emphasised the effect of particle size on the powders' flowability properties. They discovered that particle size and moisture content had a significant impact on powder flowability (Kudo et al., 2020; Ahmed et al., 2016; Jan et al., 2015). Furthermore, it has been reported that the flowability of particles exiting hoppers or feeders is highly dependent on their size (Fu et al., 2012). Only a few studies have looked into the effect of particle size and the morphological properties of gum particles on flowability. As a result, characterising changes in particle size and structural properties of gum powders would provide significant insight into how industries can overcome flow issues encountered during bulk handling.

The rheological properties of gum exudate play a significant role in the food industry as they govern the product development, design, and evaluation of the process equipment such as pumps, piping, heat exchangers, evaporators, and mixers (Rao and Anantheswaran, 1982). Rheological measurements are also thought to be an analytical tool for providing fundamental insights into the structural organisation of food. Essentially, rheological properties are determined by the gum's structural features and its conformation and configuration in the solvent phase and, in some cases, at the liquid-liquid interface. In many food products, especially sweetened foods, hydrocolloid gums have substituted sugars, and the rheological properties govern the quality of the end product. The common property of gums is that they impart viscosity or thickening to aqueous solutions or dispersions. Several studies have been reported on the rheological characteristics of Arabic gum individually or in food formulations (Miao et al., 2018; Niu et al., 2018; Li et al., 2011).

Food rheology, in general, may be exposed to a variety of environmental conditions (pH, ionic strength, heat treatment, and so on) as well as physicochemical properties (particle size, water activity, and so on) during processing, storage, transportation, and consumption. Ahmed (2014) and Ahmed et al. (2015, 2016) previously investigated the effect of particle size on the rheological properties of various flours including pumpkin, rice, and lentil. These studies confirmed the requirement for a detailed study of rheological properties with variation in their particle size for individual powders used in food products. However, no research has been done on the effect of particle size on rheological properties among different plant gums. As a result, the rheological study of Arabic gum influenced by particle size for use in processing and manufacturing will serve as a reference for other types of food hydrocolloids.

Meanwhile, powder processing is typically carried out in a controlled environment with controlled relative humidity and temperature to aid in the storage, handling, and operational processes as well as the design and optimization of industrial processes. Various changes in foodstuffs' physical, chemical, and/or biological properties occur throughout this process. Foods are exposed to varying relative humidity and temperature throughout the operation, causing them to seek equilibrium with the environment and adjust to the moisture level (Toneli et al., 2008). Thus, the relationship between a food product's water activity (a_w) and equilibrium moisture content (X_e) is known as the moisture sorption isotherm (Lomauro et al., 1985). Moisture sorption isotherms provide valuable information for predicting shell life, storage stability, and caking behaviour. Furthermore, the estimation of moisture sorption isotherms during storage under a variety of conditions reduces the cost and cycle time of product development and shelf-life estimation.

A thorough understanding of powder's physicochemical and functional properties is essential to determining industry-appropriate particle sizes. Many studies have been conducted on the hydrocolloids' physicochemical properties. Nevertheless, literature on particle size's effect on the powder system's final mechanical properties remains scarce. As a result, a deep understanding of the properties mentioned above would aid in understanding the handling applications, quality control, and other characteristics of Arabic gum, thereby avoiding potential flow issues and broadening its application in food products.

1.4 Research Gap

The general systematic relationship between primary properties (such as particle size and moisture content) and quantified flow properties (such as Hausner ratio and angle of repose) has not yet been investigated as per the literature review. According to the available literature, elongated and irregular-shaped foods and metal powders might cause mechanical interlocking between particles, reducing their flow properties. However, no quantitative research has been conducted on hydrocolloid powders in relation to the powder's elongated or irregular-shaped particles and the resulting flow properties. Furthermore, studies on the impact of particle size on the rheological behaviour of Arabic gum powder are lacking. This requires a better understanding of powder properties, which have a significant impact on rheological properties.

Numerous studies on food powders and other powders have been carried out. However, information in the literature regarding the effect of particle size on the rheology and stability of hydrocolloid powders remains limited. The effect of a wide particle size distribution on these properties is not precisely understood. More in-depth knowledge of the relationship between particle size and size distribution and the powder's physicochemical, flow, rheological, and stability properties may aid in eliminating potential flow and dissolution problems and in selecting the proper ingredients for manufacturing purposes. To the best of the author's knowledge, no study has been conducted on the particle size contribution to Arabic gum powder's physicochemical, flow, rheological, and stability properties.

1.5 Research Scope

The research established the effect of particle size on the powder's physicochemical, flow, rheological, and stability properties. For physicochemical analysis, Arabic gum powders in five different particle sizes were characterized using various methods, including laser diffraction, scanning electron microscope, pycnometry, and halogen moisture analyses. Meanwhile, compressibility index measurement determined gum powder's flow properties by means of the Hausner ratio and Carr index, angle of repose, powder flow analyzer, and annular shear tester. On the other hand, measurements of steady shear viscosity and frequency sweep tests of aqueous gum solutions in the rheological behaviour analysis of aqueous gum solutions were conducted using a stainless-steel cone plate rheometer. Subsequently, the static gravimetric technique assessed the water activity, demonstrating the moisture adsorption isotherms of gum powder. The non-linear least squares technique fitted the selected sorption isotherm models to the experimental data. Subsequently, the inter-relationship behaviour of physicochemical, flow, rheological, and stability properties was correlated to show its significant influence on gum powder properties. Evaluations of the properties and behaviour of Arabic gum are critical for a thorough understanding of a wide range of food products and their processing. Furthermore, this research would undoubtedly aid in the commercialization of Arabic gum, a well-known exudate gum that is an important ingredient in food and other industries.

1.6 Objectives of the Study

The knowledge gaps mentioned above led to the four research objectives listed below. The study's specific objectives were as follows:

1. To characterize the physicochemical properties of Arabic gum powder in a range of particle sizes.
2. To evaluate the flow properties of Arabic gum powder at various particle sizes using conventional and advanced methods.
3. To investigate the effects of particle size on the steady shear viscosity and dynamic viscoelastic rheological behaviour of Arabic gum aqueous solutions.
4. To assess the Arabic gum powder's equilibrium moisture sorption and model its sorption characteristics using various model equation.

1.7 Research Hypothesis

The study's hypotheses were as follows:

1. The physical and chemical properties of the powder may be affected by changes in particle size.
2. The particle size of the powder may affect its shelf life and stability.

1.8 Thesis Structure

The thesis structure presented an overview of the research. The first chapter provided in-depth information on Arabic gum sources, usage, and applications. This chapter includes the study's background as well as the problem statement, objectives, hypothesis, and study plan. The second chapter discussed a detailed review of the literature in order to obtain sufficient information for experimental analysis. The third chapter described the materials and methods used to examine the impact of particle size on the physicochemical, flow, rheology, and stability properties of Arabic gum. The fourth chapter focused on the study's findings. This chapter incorporates the proximate compositions, solubility, and thermal studies with regard to particle size. Powder flowability was evaluated using both traditional and advanced methods, and the relationship between these two methods is also presented and thoroughly discussed. The rheological behaviour of gum solutions at various concentrations was extensively investigated and discussed. This chapter also revealed the evaluation of the gum powder's stability using various empirical modeling techniques. Meanwhile, the fifth chapter summarizes the research findings, future recommendations, and implications, mainly for processing and product development.

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