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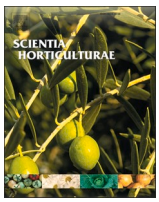

Musa species variation, production, and the application of its processed flour: A review

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ABSTRACT

Banana (*Musa* spp.), an evergreen perennial crop belonging to the *Musaceae* family, is one of the world's most important tropical and subtropical fruits. It is characterized by a wide variation in production, composition, and usefulness due largely to the cultivar, planting method, climate, as well as the availability of nutrients. Bananas are a rich source of essential minerals such as potassium, magnesium, and phosphorus, vitamins such as vitamins A, B_6, B_{12}, and C, and phytochemicals such as phenolic acids, flavonoids, tetrapenoids and catecholamines. The Cavendish group including cultivars like Grand Nain, Williams, Chinese, and Valery, is preferred over other cultivars due to a high yield potential and marketability both in the domestic and international markets. However, incomplete identification of cultivars used in producing flour, developing innovative products as well as postharvest losses, are key issues hindering the expansion of banana production. Identification of suitable cultivars and determining the applicable maturity stage of unripe banana is thus crucial for various food and industrial applications. This review therefore provides information on the taxonomy of bananas, their diverse cultivars, and elaborates on the composition of unripe banana flour required in various food applications.

1. Introduction

Banana (*Musa* spp.) is a non-grass, perennial plant, well known for its edible fruits as well as its contribution to food security and income generation for most communities around the world. Bananas have been cultivated in subtropical and tropical regions of the world with annual production levels estimated to be over 102 million tonnes of fresh fruit (Vu et al., 2018). The OECD-FAO Agricultural Outlook 2023 – 2032 (OECD/FAO, 2023) reported a decline in the production and export of banana from 20.5 million tonnes in 2021, to 19.6 million tonnes in 2022. However, the production figures are envisioned to rise to above 700% in the coming decade, barring negative weather conditions and disease attack (OECD/FAO, 2023). Edible banana fruit cultivars are a manufactured genetic complex based on two wild diploid species originating from South-East Asia namely *Musa acuminata* (AA) and *Musa balbisiana* (BB) (Heslop-Harrison and Schwarzacher, 2007). Presently, over 100 banana cultivars have been developed, including new cultivars and selections from breeding programs around the world (main genome groups of AA, AB, AAA, AAB, and ABB) (Creste et al., 2003; Heslop-Harrison and Schwarzacher, 2007; Arvanitoyannis and Mavromatis, 2009). amongst the developed cultivars, the Cavendish sub-genome group is the most significant sub-genome group of edible bananas, dominating the world trade due to their superior agronomic and disease resistance characteristics (Arvanitoyannis and Mavromatis, 2009). Commercialization and usage of high yielding banana cultivars such as the cavendish sub-genome groups have resulted in the limited application of indigenous and unpopular banana cultivars. This has led to the indigenous and unpopular cultivars being replaced by common commercial cultivars that are cultivated in monocultures (Hapsari et al., 2017).

Bananas exhibit climacteric patterns in both ethylene production and respiration rate which renders them susceptible to immediate deterioration as substantial volumes are lost during storage period and prior to postharvest processing (Bi et al., 2017). A particular objective of

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reducing postharvest loss is to preserve the quality of perishable fruits with a potential of expanding international marketing opportunities (Aurore et al., 2009; Anyasi et al., 2013). An important economic strategy therefore is to dehydrate unripe bananas and process banana flour into various innovative products that will promote banana intake, ensure food security and contribute to human health (Ovando-Martinez et al., 2009; Wang et al., 2012). Pico et al. (2019) stated that raw unripe banana flour contains a high concentration of dietary fibre, with a significant fraction of resistant starch (the fraction of starch that reaches the large intestine). Banana at its mature unripe stage, maintains a high carbohydrate content (mostly starch), minerals, protein levels and phenolic compounds (Arvanitoyannis and Mavromatis, 2009; Sarangi and Gaurav, 2014; Khoozani et al., 2019a). Starch, a key ingredient in unripe banana, undergoes major changes as the fruit ripens. When banana ripens, the total starch content decreases from 70% to less than 1% of the dry weight, while sugar (mainly sucrose) increases to more than 10% due to enzymatic activity (Sarangi and Gaurav, 2014). Starch is a useful raw material for modifying the texture and consistency of food. However, the quality of carbohydrates including starch and other polymers have been observed to vary according to the different cultivars in the existing genome groups (Kumar et al., 2019; Bi et al., 2019; Borges et al., 2020). Similarly, banana pulp and peel have been shown to contain polyphenols and other secondary metabolites with beneficial health properties (Qamar and Shaikh, 2018; Pico et al., 2019; Hikal et al., 2022).

Banana cultivars are extremely diverse in terms of plant stature, size, shape, colour, and pigmentation of the fruits (Singh et al., 2016). Considering that not every cultivar is popular amongst farmers, it is essential for farmers to assess the cultivars that are readily available to serve their needs (Khoozani et al., 2019b). Identification of these cultivars is highly critical as a foundation for future evaluation, development, and use for prospective banana breeding programs, conservation management, as well as processing and valorization in different food applications. Furthermore, the processing of banana flour from cultivars with market associated development characteristics of appropriate products, can lead to higher demand driven incomes (Pillay and Tenkouano, 2011). Although literature abound on the different banana genotypes, there is paucity of information on the variations that exist amongst these cultivars in relation to their starch composition, pulp and peel phenolic compounds profile and utilization in food applications. This review therefore provides information on the variations in the different *Musa* spp genotypes, banana production practices and the utilization of its processed flour.

2. Taxonomy, nomenclature, and genetic variation of banana

The edible banana fruit has been reported to have originated in the tropical regions of South-East Asia, and were also located from India to Polynesia (Simmonds, 1962). The fruit is now cultivated in about 135 countries in tropical and subtropical regions of the world (Pereira and Maraschin, 2015; Singh et al., 2016; Vézina, 2020). *Musa* spp. includes all edible cultivars, which are divided into four sections, *Australimusa, Callimusa, Eumusa*, and *Rhodochlamys* according to the number of chromosomes. The genome with eleven chromosomes (2n=22) is characteristic of *Eumusa* and *Rhodoclamys*, while ten chromosomes (2n=20) is observed in *Australimusa* and *Callimusa* (Robinson, 1996; Mohapatra et al., 2010; Pereira and Maraschin, 2015). However, Hakkinen (2013) based on the DNA of the banana groups, further restructured *Musa* species into two sections, *Musa* (a combination of *Eumusa* and *Rhodochlamys*) and *Callimusa* (a combination of *Callimusa* and *Australimusa*). Banana species were earlier classified as *Musa* x *paradisiaca* Lambert and *Musa* x *sapientum* (Müller-Wille and Scharf, 2009). Although revisions from botanists concluded that the classification of edible banana cultivars were from two wild species of banana (section *Eumusa*): *Musa acuminata* Colla and *Musa balbisiana* Colla (Pereira and Maraschin, 2015).

Polyploidy and hybridization of genomes arose from the two wild diploid species *M. acuminata* (El-Khishin et al., 2009) and *M. balbisiana* (Ravinder et al., 2018) (Fig. 1). These genomes are either diploid (AA, AB, BB), triploid (AAA, AAB, ABB, BBB), and tetraploid (AAAA, AAAB, ABBB, AABB) hybrids comprising *M. acuminata*, and between *M. acuminata* and *M. balbisiana* sub species (Robinson, 1996; El-Khishin et al., 2009; Pereira and Maraschin, 2015). There are other cultivars that exist naturally or developed by hybridization from these genomes, which have different nomenclatures (Robinson, 1996; Mohapatra et al., 2010). The seedless and parthenocarpy characters of bananas are the result of several hybridization events and mutations, whereby hybridization is still used in the production of new diverse and parental combinations of cultivars (Heslop-Harrison and Schwarzacher, 2007). In contrast to *M. acuminata*, parthenocarpy did not evolve in *M. balbisiana* as its seedy forms are substantially less variable than *M. acuminata*. Manzo-Sánchez et al. (2015) reported on four genomes present, which corresponds to the genetic conditions of four wild *Musa* species, which are *M. acuminata* (A-genome), *M. balbisiana* (B-genome), *M. schizocarpa* (S-genome), and *M. textillis* (T-genome). However, there are no edible diploid BB cultivars of *Musa* species.

There are about 35 species in the genus *Musa* (Deka and Neog, 2021) of which three most common species of *Musa* (*M. cavendishii, M. parasidiaca,* and *M. sapientum*) are widely cultivated in the world. Edible *Musa* variations include dessert bananas (AA, AAA, AAB), and cooking bananas (AAB, ABB, BBB) (Pereira and Maraschin, 2015). Dessert bananas are eaten raw (yellow and sweet) when fully matured. However, cooking bananas are prepared for consumption at various stages of maturity and are less sweet when uncooked due to unpleasant texture with a granular and hard feel in the mouth. A pure triploid *M. acuminata* (AAA genome group) and *M. cavendishii*, is sweeter and less starchy than *M. paradisiaca*, while *M. sapientum* is usually eaten raw (Mohapatra et al., 2010; Pereira and Maraschin, 2015). Both *M. paradisiaca* and *M. sapientum* belong to the AAB genome group (Mohapatra et al., 2010; Pereira and Maraschin, 2015), and are characterised by higher starch content when compared to pure *M. acuminata* species. Cooking bananas that fall under ABB (Pisang Awak, Bluggoe) and BBB (*Kluai Lep Chang Kut* banana) genome group, consist predominantly of the *M. balbisiana* species (Robinson, 1996; Mohapatra et al., 2010).

The most prevalent cultivated tetraploids are the result of breeding initiatives. There are no natural AAAA genome group bananas and only a few natural AAAB, AABB, and ABBB genome group exist. Tetraploids are the product of crosses between triploid female and diploid male parents (Nayar, 2010). In regions where banana diseases are widespread, a few promising cultivars are grown (particularly on several Pacific islands). The Fundación Hondureña de Investigación Agrícola (FHIA) tetraploids from Honduras are the most notable amongst the dessert bred tetraploid: FHIA-02 (AAAA genome group), FHIA-01 (also known as Goldfinger), FHIA-18 (both from AAAB genome group), and FHIA-03 (AABB genome group).

3. Banana production

Different banana cultivars have been developed to dominate in different locations of the world due to historical factors; however, the cultivar 'Williams' is popular, especially in the subtropics. Plant characteristics such as vigour, yield, fruit hardness, seedless fruit, and quality have influenced farmers selection for cultivated crops (Simmonds, 1962). Furthermore, hybridization and mutation has led to seedless and parthenocarpy attributes, which have occurred hundreds of times. Simmonds (1954) examined the origin and characteristics of the Cavendish subgroup (AAA genome group), a method which can still be used in the classification of the *Musa* genus. There was a degree of ambiguity in the nomenclature of Cavendish cultivars due to the classification of certain cultivars as synonyms in the West Indian Islands (Stover, 1988). The cultivars 'Grand Nain' and 'Williams,' for example, were classified under the Giant Cavendish genotype. Table 1 shows the origin of various

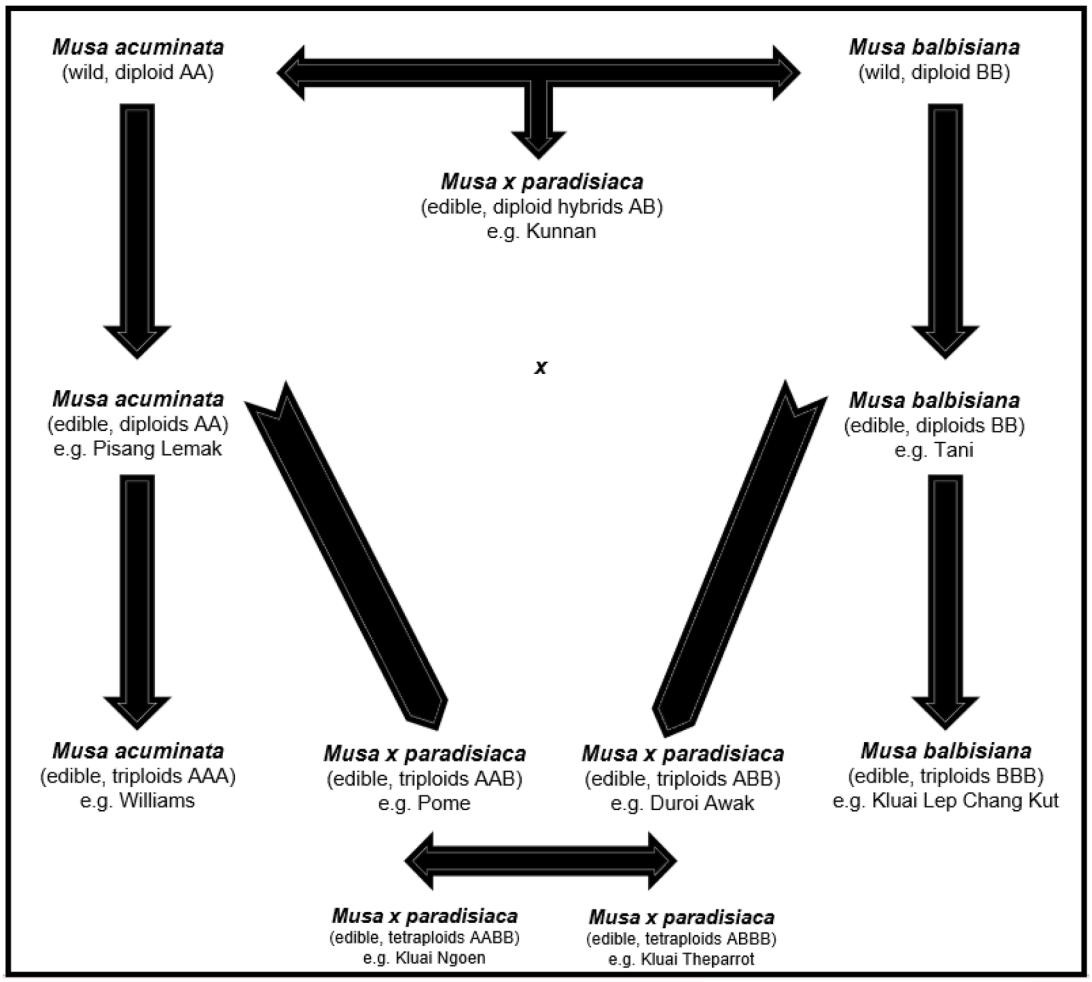

Fig. 1. Pathways leading to the development of edible banana hybrids.

hybrids of *Musa* genomes and synonyms in different parts of the world. In every banana-growing country, there are hundreds of duplicate names and close clonal relatives. It should be noted that some of these cultivars have been given ambiguous common names. The Lady Finger genotype, for example, has been used for the identification of at least four distinct AA, AB, and AAB clones (Ploetz et al., 2007). Recently, Maseko et al. (2022) determined that multi-elemental fingerprinting can be used in distinguishing sub-genomic and genomic groups of unripe banana flour.

3.1. Morphology

The banana tree is a perennial herb and starts growing by a false stem (main trunk), the "pseudo-stem", which is formed at the base of the tightly packed leaf sheaths (Fig. 2A). The underground rhizome, the aerial stem to which the leaves are attached and the peduncle to which the inflorescence is attached, make up the true stem. The shoot apex is found at the ground level and surfaces as a gigantic inflorescence leading to fruit production and lastly to shoot death (Barker and Steward, 1962). However, new offsets are formed at the base of the plant as corn or suckers. Hence, it is classified as a viable plant system that can be productive for up to ten years, with the sucker being cut off and used for propagating new plants. This process is prerequisite since banana plant never form seeds but multiply parthenogenically (Arvanitoyannis and Mavromatis, 2009) (Fig. 2F).

Appearance of the plant leaf takes between 7 – 14 days, with the number of leaves produced varying according to the cultivar, temperature, and growing procedures. All other parts of the plant are produced by the meristem of the true stem (Nelson et al., 2006). Fig. 3 illustrates the development process of banana fruits from a cluster, emergence of flowers, and the developed male hands and male bud. Each nodal cluster contains 12 - 20 flowers, which are grouped in two rows. A cluster's flower is usually functional as female or male (Fig. 3D), although they can also be hermaphroditic (both male and female) or neuter (neither male nor female). The first 3 - 9 clusters/hands, are female and produce edible fruits, which are commonly referred to as fingers. The subsequent clusters, situated away from the centre, have a male character and do not yield edible fruit (Brown et al., 2017).

The fruiting cycle takes up to two years, which includes the vegetative growth (lasting 6 - 12 months), and the period between emergence of the inflorescence and harvesting of the bunch (2.5 - 10 months). The cycle mainly depends on climate, cultivation conditions and the cultivar type (Brown et al., 2017). The banana fruit has a leathery outer peel comprising collenchyma (supporting plant tissue consisting of living elongated cells), which when unripe has bitter-tasting latex. The fruits are formed in layers called combs or hands (Arvanitoyannis and Mavromatis, 2009). Although the principal plant dies after bearing fruit, the entire plant is perennial in the sense that suckers replace the ageing aerial component without the need for replanting (Brown et al., 2017).

3.2. Banana cultivation

Bananas are cultivated all over the world in tropical and subtropical climates and require an evenly spread annual rainfall of between 90 – 250 cm depending on the length of the rainfall (Calberto et al., 2015). Banana cultivation can be challenging at altitudes above 1000 m due to

Table 1
The origin of various hybrids of Musa spp genomes, names, and synonyms.

Genome group	Origin	Genotype/ hybrid	Names and synonyms
AA	Malaysia	Sucrier/Nino	Lady Finger; Sugar; Dedo de Dama (Spanish)
	India	Chingan	Manniyilla Chingan (India)
AB	India	Ney Poovan	Safet Velchi; Apple; Farine France
	Southeast Asia	Kunnan	Golden Pillow
AAA	Martinique	Gros Michel	Bluefields (Hawaii); Criollo (Costa Rica); Ndizi (Tandzania); Anamala (Sri Lanka)
	China	Dwarf Cavendish	Dwarf Chinese; Governor; Pisang Serandah
	N/A	Gran Nain/ Grand Nain	Giant Chinese; Williams Hybrid (Australia); Harichal (India)
	N/A	Giant Cavendish	Williams (South Africa); Giant Governor (West Indies); Robusta (India)
	Philippines	Bungulan	Lacatan (Jamaica); Bungulan (Hawaii); Pisang Ambon (Indonesia)
	N/A	Dwarf/Red Tall	Red; Red Dacca; Pink Banana (Hawaii)
	Philippines	Lakatan	Pisang Barangan Merah (Indonesia and Malaysia); Kluai Ngang Phaya (Thailand)
AAB	India	Mysore	Kikonde Kenya (Zanzibar); Dwarf Waimea (Hawaii); Pisang Ceylan (South Africa)
	Pacific	Maoli	N/A
	Thailand	Thab Maeo	N/A
	N/A	Silk	Apple (Hawaii); Silk Fig (West Indies); Dwarf Cavendish (World); Latundan (Philippines)
	N/A	Pome	Lady finger (Australia); Prata (Brazil); Kijakazi (Zanzibar); Pome (Canary Islands)
	Brazil	Prata Ana	Dwarf Apple; Dwarf Brazilian; Santa Catarina (Hawai); Prata Santa Catarina (Brazil)
	Uganda	Sukali Ndizi	Sukari Ndizi; Sukari Ndiizi; Kamaramasenge (Rwanda); Kam22 (South Africa)
AAAB	Honduras	FHIA-01	Goldfinger (Australia, South Africa); Maravilha (Brazil); Goldi or Kabana 1 (Uganda)
	Honduras	FHIA-18	Bonanza or Bananza (Australia)
ABB	N/A	Bluggoe	Topocho (Venezuela); Mondolphin (Australia); Kivuvi (East Africa)
	Malaysia	Pisang Awak	Pisang Klotok (Indonesia); Ducasse (Queensland); Kluai Namwa (Thailand)
BBB	South-East Asia	Saba	Pisang Kebok (Indonesia); Pisang Nipah (Malaysia); Kluai Hin (Thailand)
AABB	Honduras	FHIA-03	Mona Lisa; Bahati or Kabana 2 (Uganda)
AAAA	Honduras	FHIA-02	Mona Lisa (Central America); Monalisa or Mbonwe (Uganda); SH-3486 (breeder's code)
	Honduras	FHIA-17	Kabana (Uganda)
	Honduras	FHIA-23	Kabana 4 (Uganda)
ABBB	Indo China	Kluai Theparrot	N/A

N/A: Not available. Source: Ploetz et al. (2007); Robinson and Saúco (2010); Karamura et al. (2012); Vezina and Bergh (2021).

the influence of altitude on temperature, rainfall, humidity, and light intensity (Robinson and Saúco, 2010; Adhikari et al., 2015). The banana plant produces fruit rapidly, necessitating fertilizer application on a regular basis. The weight of the bunch and the number of hands is determined by the type of growth the plant has within the first three to four months. As a result, it is important to give the best possible attention around this period (Al-Harthi and Al-Yahyai, 2009; Mustaffa and Kumar, 2012; Al-Busaidi, 2013). The most important factor in banana growth, production, and flowering is its optimal temperature, which should be between 21 and 33 °C (Lobo and Rojas, 2020). However, their development can be slowed by cold weather and prolonged drought. Crop growth and yield declines when the plant does not receive an adequate and regular supply of water (Adhikari et al., 2015; Ravi and Vaganan, 2016). Maintaining the plants water content is essential for photosynthesis, as well as improving the colour, flavour, and shelf life of the fruits (Deka and Neog, 2021). The capacity for growth and fruiting is determined during the establishment period and the early phase of the vegetative period, in addition to the water and nutrient supply required during these times. Edaphic factors such as mineral and humus content, pH, as well as soil water holding capacity, greatly influences banana growth as banana can be grown in a wide range of soil; however, the soil must be fertile and well-drained to thrive (Nelson et al., 2006). Deep, well-drained loams with a high water-holding capability and humus content, as well as a pH of 5 - 7, exhibit resilient soil. It is critical to maintain the ideal pH as higher or lower values result in mineral adsorption deficiencies. Diseases such as Panama and Fusarium wilt of banana can be caused by stagnant water around the plant field (Fey, 2010; Pegg et al., 2019). Similarly, leaf wetness aside from farm tools and insects, have been implicated as one of the modes of transmission of banana bacterial wilt disease (caused by the bacteria *Xanthomonas vasicola* pv. *musacearum*) which affects banana production in East Africa (Vezina and Bergh, 2020).

Plant growth requires the intake of at least 14 elements (Weinert and Simpson, 2016). The concentration of various elements such as nitrogen (N), potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg), sulphur (S), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), chlorine (Cl), molybdenum (Mo), cobalt (Co), and boron (B) vary depending on the different sections of the banana plant (Oliveira et al., 2007; Weinert and Simpson, 2016). Within a leaf, concentration can also vary, particularly if the elements are mobile within the plant. As the elements migrate from the leaf to the fruit, their amounts will decrease in the leaf between flowering and harvest. The elements, N and K are required in higher amounts, forming the basis of the NPK fertilizer compounds (Baligar and Bennett, 1986). Deficiencies in these elements can result in leaf malformation, decreased growth and yield, and poor fruit quality (Mishra et al., 2016). When rainfall and the prevalence of pests or diseases are not limiting factors, *Musa* species grow best in the open sun. Banana plants located in deep shaded areas produce thinner pseudonym, lower leaves and suckers, smaller brunches, and delayed fruiting; therefore, a limit of 50% shade is recommended (Nelson et al., 2006; Radha and Mathew, 2007; Scaranari et al., 2009).

3.3. Banana plant nutrition program

Nutrients consisting of mineral elements are distributed in the soil and plant of banana plantations. A number of these elements are soluble, and some are found in the fruit that is harvested and removed from the plantation. As suckers grow, these elements are recycled from the harvested standing pseudo-stems. By six weeks following harvest, 50 – 60% of N and P in the mother plant would have migrated to the growing sucker and by ten weeks, the mother plant supplies 40% of total elements required for the sucker to mature. The elements K, S, Fe, Zn and B migrate to the sucker in smaller quantities, whereas Ca and Mg remain less mobile in the mother plant (Lahav, 1995; Weinert and Simpson, 2016). In addition, elements are recycled throughout the plantation through banana decomposition process. The decomposition process releases almost 70% of the N, P and Mg in banana trash into the soil nine weeks after harvest, making it available to the growing sucker. This recycling process is crucial when determining a nutrition program (Lahav, 1995; Ultra et al., 2005). During the propagation of a new plant, nutrient recycling does not occur, thus all the necessary nutrients must be provided for the plant crop and early growth (Malézieux and Bartholomew, 2003).

Fig. 2. Development stages of banana: A) Tree planting; B) Growth and fruit development; C) Harvesting of banana fruit; D) Shoot death and removal; E) New plant fruit production; F) Subsequent sucker selection and growth.

Fig. 3. Development process of banana fruits: A) A cluster; B) Partial emergence of cluster flowers; C) Fully emerged cluster flowers; D) Subsequent female hands and male bud.

3.3.1. The role of macro and micro elements in banana plant development

Several factors influence banana fruit quality, including the individual and cumulative effects of elements (Hailu et al., 2013). Nutritional deficiencies can significantly alter the growth and development of bananas with the different elements impacting a different role (Lahav, 1995). The banana plant development is stimulated by N content and its occurrence aids in the development of size and number of hands on the fruit. The highest demand for N in bananas is during leaf development (Turner, 1989). Activities such as the partitioning of N in photosynthetic enzymes, pigment concentration, and the composition of chloroplasts affect the leaf nitrogen content (Bassi et al., 2018). This essentially provides the carbohydrate necessary for plant growth and development, as well as yield and fruit quality (Mustaffa and Kumar, 2012; Senthilkumar et al., 2017). Nitrogen as a primary element is absorbed by banana roots in the form of the nitrate (NO_3^-) ion (Orr and Nelson, 2018) and when the root health is deprived, water availability is reduced or the plant becomes waterlogged (Turner, 1989). It should be noted that excess N results in rapid growth and weak pseudo-stem strength, causing the stems to buckle or fold under the weight of the bunch. This further results in slow flowering, production of small bunches and shortening of the shelf life of the banana fruit (Weinert and Simpson, 2016; Srivastava, 2013).

3.3.1.1. Macro-elements. Despite being a primary element, bananas have a low P requirement for development. Phosphorus is essential for growth and development of all organisms as it serves as a vital structural component of nucleic acids, phospholipids, sugar-phosphate intermediates for glycolysis, respiration, and photosynthesis (Wang et al. 2017; Wang et al. 2021). Phosphorus exists both as an organic and as an inorganic form in form in soil (Wang et al. 2017). Plants usually take up inorganic phosphate (orthophosphate) as their main source of P even though it forms complexes with metal ions in soil which hinders its absorption (Wang et al. 2021). The banana plant quickly absorbs P during the first five months after planting, which is absorbed by the roots mainly in the form of orthophosphate ($H_2PO_4^-$). Since P is required in high concentrations at the growing points of roots and shoots, adequate P levels are particularly necessary during active growth periods. The first signs of deficiency appear in older leaves, turning to dark green with purple/brown flecks on the leaf edges. Reduced development in both mother and daughter trees, as well as shorter leaves, are other symptoms of phosphorus deficiency (Weinert and Simpson, 2016).

Potassium is the most essential component of banana production and serves a variety of functions. Potassium is crucial for cell division and expansion at all stages of development, more especially during fruit development (Senthilkumar et al., 2017; Mustaffa and Kumar, 2012). Potassium is vastly mobile in the soil and in plants, and it is ingested during the later vegetative growth stages, just before bunching. Banana fruit size is determined by the mechanisms of cell division and expansion. Although K does not directly affect plant cell structure, it is essential as it catalyzes important reactions such as respiration, photosynthesis, chlorophyll formation and water regulation (Mustaffa and Kumar, 20122). The macro-element also regulates the opening and closure of the stomata, which governs water intake and hence the absorption of other nutrients (Hasanuzzaman et al., 2018). Stomates are leaf structures that enable gas exchange for photosynthesis as well as water movement from the roots to the leaves. Reduced bunch and fruit size is a symptom of K deficiency, which is induced by a decrease of photosynthesis and sugar transportation (Weinert and Simpson, 2016). Potassium deficiency can instigate buoyancy reduction, interfering with postharvest production line operations, and causing the fruit to sink when dipped in water during washing or hot water treatment (Mustaffa and Kumar, 2012).

Calcium is essential for plant strength and structure. Calcium supports cell division and development in the leaves, fruit and root tips. It helps to reinforce plant cell wall, making them more resistant to heat stress and disease, and aiding the absorption of other nutrients. As Ca is required for all stages of development, it must be available all year (Hepler, 2005). Young roots and root tops passively absorb Ca as Ca^{2+}, binding with B in cell walls. Calcium is reserved in the soil more intensely than K, Mg, or Na (Lahav, 1995). Calcium levels in the leaf reflect the overall amount of Ca in the soil as well as the cation steadiness of Mg and K. The low Ca levels in the leaves may mean an abundance of these two minerals. Deformed fruit, poor fruit quality, and skin cracking are signs of Ca deficiency (da Silva and Williams., 2007; Weinert and Simpson, 2016).

Magnesium is a secondary macro-element absorbed as Mg ions (Mg^{2+}) in the soil. It is the most abundant mineral element for contributing to photosynthesis, and phloem-mediated sucrose transport and distribution of photo-assimilates within the plant (Shaul, 2002). Magnesium controls the absorption of other nutrients, while also playing a role in disease tolerance and drought resistance (Huber and Jones, 2013). When K treatment on the plant is beyond the required levels, it can deplete the amount of Mg available in the plant, resulting in Mg deficiency. Magnesium is one of the mobile elements that can move from the lower to upper leaf blade when plants are deficient in Mg. It has been recognized that symptoms of Mg deficiency develop on lower leaves of the banana plant, of which this deficiency essentially affects photosynthesis and carbohydrate partitioning in crops (Wang et al., 2020). After N and K, Mg is the most widespread deficiency in subtropical banana plantations (Weinert and Simpson, 2016) which has been reported to impact plants throughout the world and influencing agriculture productivity, quality, and forestry.

Sulphur is a secondary plant macro-element that is required for protein formation. Sulphur functions as a constituent of the three amino acids: cystine, cysteine, and methionine (Grimble and Grimble, 1998); is essential for chlorophyll production as well as the activity of adenosine triphosphate ATP-sulfurylase. These crucial functions allow for the growth of healthy, productive plants, which are necessary for high yields and quality (Komarnisky et al., 2003; Vidyalakshmi et al., 2009).

3.3.1.2. Micro-elements. Boron plays a variety of functions in plant nutrition. It is essential for both new cell growth and division as it affects plant hormones and carbohydrate movement, significant for the fruit set quantity, size, and shape (Shireen et al., 2018). Boron, along with Ca is a structural part of the cell wall, aiding Ca's movement to the plant's cell wall. Boron is highly soluble and readily leached from soil, where it is trapped in the cell wall of plants and is not mobile (Fleischer et al., 1998). Minute quantities are needed at all stages of growth, but the majority are needed during the early stages of fruit production. As B is required in such minute concentrations, it is simple to progress from deficiency to toxicity. Boron deficiency is uncommon in bananas, but it is common in acidic soil (Brdar-Jokanović, 2020). Arunkumar et al. (2018) showed that B availability in agricultural soil varies from 0.4 – 5 mg/kg, whereas Brdar-Jokanovic (2020) stated that the concentration of B required for the plants normal growth and development is as low as 1 μg to 1 mg/g. A slight B deficiency can affect the shape and consistency of fruit bunch; however, an extreme deficiency will cause significant bunch deformation. Boron-deficient plants produce fruit that is much smaller at the tip and has a rough brown central core (Weinert and Simpson, 2016). Banana fruit that does not fill may also show signs of a boron deficiency (Lahav, 1995; Shkolnik, 2012).

Zinc deficiency is the most common deficiency reported in banana farms and the most essential trace element in bananas (Weinert and Simpson, 2016). Zinc functions by promoting leaf expansion and growth, improving fruit length and diameter and promotes bunch stem elongation. Zinc deficiency is characterized by smaller, thinner, and younger leaves that have a spearhead shape. Plants with Zn deficiency develops small, malformed bunches and the distance between the bunch hands is reduced, giving the bunch a compact appearance (Nelson et al., 2006; Jeyakumar, 2011). The availability of Zn decreases as soil alkalinity is increased. Zinc deficiency can also be caused by high P levels in the soil (Shkolnik, 2012).

Manganese is absorbed by the plant roots in the form of Mn ion (Mn^{2+}). Manganese is essential for dehydrogenases, decarboxylases, kinases, oxidases, peroxidases, and the functioning of other divalent cation activated enzymes (Alejandro et al., 2020). It is essential for photosynthesis, chlorophyll formation, the manufacture of amino acids and proteins and nitrate reduction (Millaleo et al., 2010). Manganese deficiency manifests as "comb-tooth" chlorosis (a comb form striated appearance in leaves), which begins on the leaf margins and progresses through the veins towards the leaf's midrib, with an occasional narrow green edge. Chlorosis essentially emerges first on the second or third youngest leaf (Shkolnik, 2012; Srivastava, 2013).

Lauer et al. (2012) showed that exposure to different concentration of copper increases or inhibits the activities of enzymes involved in glycolysis and Krebs cycle, implicated for important functions such as photosynthesis and respiration. Copper proteins have been linked to metabolic processes such as lignification, anaerobic metabolism, cellular defence and hormonal metabolism. Copper proteins are also known to exhibit electron transfer and oxidase activity (Deeth, 2010). Copper serves as an electron acceptor towards the end of the mitochondrial oxidative pathway. Deficiency symptoms include the major veins bending backwards, giving the plant an umbrella appearance, and the leaves turn to a yellow bronze colour (Pilon et al., 2006; Lauer et al.,

2012; Shkolnik, 2012).

4. Banana fruit distribution

While banana originated from Southeast Asia, India is reported as the world largest producer followed by China, Indonesia and Brazil (Voora et al., 2020). The OECD/FAO (2023) report showed that banana production is projected to increase to 140 million tonnes in the next 10 years with India the world leading producer projected to attain a production output of 35 million tonnes by 2032. Banana, being the second major fruit crop produced in the world, has about 1200 cultivars (Aurore et al., 2009). The Cavendish cultivar proves to be better adapted to international trade than other cultivars due to its resistance to physical shocks during transportation (Voora et al., 2020). The Food and Agriculture Organization (FAO) of the United Nations reported that in 2020 shipments from Latin America and the Caribbean, the world's top exporting area, increased by about 3.7% to a total of 16.5 million tonnes, increasing by 600 000 tonnes from 2019. The key driver for this strong performance was the strong supply growth in Ecuador, Costa Rica, and Colombia; three of the top five exporters in the region and globally (FAO, 2021). Latin America and the Caribbean account for over 80% of global exports of banana, with the crop providing income and jobs to almost 70 million people in Africa (Voora et al., 2020).

In Africa, subsistence banana consumption is prominent in several countries, such as Uganda, Rwanda, and Cameroon (Olumba and Onunka, 2020). However, in countries such as South Africa, bananas are cultivated for sale in neighbouring markets or for household consumption and only a fraction of all harvested banana are sold in the international market (DAFF, 2020). Voora et al. (2020) thus noted that the per capita consumption in these African countries can exceed 200 kgs per year, especially in rural areas, where the tropical fruit can account for up to 25% of an individual's daily caloric intake.

4.1. The Caribbean

In 2020, Caribbean exports were estimated to increase by 4.4% from 2019, to 420 000 tonnes with the Dominican Republic being the main reason for this growth. The FAO Banana Market Review report of 2020 showed that the recovery from hurricanes which previously hindered banana production in Dominican Republic from 2017 to 2019, contributed immensely to this growth (FAO, 2021). The Dominican Republic exports approximately 95% of bananas emanating from the Caribbean and specializes in the production and export of organic bananas, which accounted for approximately 75% of the country's overall exports in 2017 – 2018. The Netherlands, a major re-exporter within the European Union, and the United Kingdom remained the leading banana importers from the Dominican Republic in 2020, acquiring 100 000 and 125 000 tonnes, respectively (FAO, 2021).

4.2. Asia

Banana exports from Asia decreased by 11.7% (about 4.4 million tonnes) in 2020, attributable to the negative effects of the COVID-19 pandemic on banana production in the region. Approximately 90% of Asian banana exports originate in the Philippines, which is the world's second largest banana exporter behind Ecuador. Banana exports from the Philippines were affected by severe production problems caused by the spread of plant diseases, aggravated by movement restrictions imposed to combat COVID-19. Banana exports to China, the Philippines' largest market, dropped by 25% in 2020 (about 1.2 million tonnes). In 2020, exports to Japan, another significant export destination for Philippine bananas, decreased by 0.8% (about 1.4 million tonnes) (FAO, 2021). Asia is projected to remain the leading producer of bananas with an estimated production of over 70 million tonnes of banana in 2032 (OECD/FAO, 2023).

4.3. Africa

FAO (2021) stated that in the face of COVID-19-induced difficulties in the production, harvesting and transportation of bananas, Africa's exports declined by 1.8% in quantity in 2020 (about 630 000 tonnes). This decline in exports resulted in higher costs and a reduced ability by the continent to compete with cheaper bananas from Latin America. Côte d'Ivoire, the region's leading exporter, reported a 24.4% drop in exports in 2020 (just under 330 000 tonnes), due to the impact of the COVID-19 pandemic on previously agreed contracts with importers. Côte d'Ivoire exports primarily to the European Union and majorly to France, which receives 50 to 60% of total export quantities each year. Likewise, due to high unit values which averaged over USD 920 per tonne at import level, while exports from Cameroon the region's second leading exporter to the UK, decreased by 37% (about 23 000 tonnes) in 2020.

5. Unripe banana flour processing

5.1. Nutritional composition of unripe banana

The nutritional value and chemical composition of *Musa* spp differs with each cultivar, stage of ripeness, soil, cultivation practices (quality of water, pesticides, fertilizer application) and climatic conditions under which the fruits were cultivated (Adeniji et al., 2009; Arvanitoyannis and Mavromatis, 2009). Banana consists of a moisture content of 65% for dessert banana and 75% for cooking banana (Adewole et al., 2012). Wang et al. (2012) established that unripe banana flour contains starch (61.3 – 76.5 g/100 g dry basis), comparable to that in the endosperm of corn grain and the pulp of white potato. Thakorlal et al. (2010) further determined that unripe banana contains resistant starch type II, which is essential in the prevention of diabetes, cholesterol lowering, weight management as well as the modulation of glycaemic index. Resistant starch improves digestion health by resisting starch hydrolysing enzymes in the stomach. Resistant starch II breaks down into short chain fatty acids and raises the pH level of the large intestine thus creating adverse conditions for pathogenic bacteria while favouring the growth of beneficial ones (Bird et al., 2000; Brown, 2004). Short-chain fatty acids such as butyrate is formed as a result of the fermentation activities of the beneficial bacteria thereby inhibiting the development of malignant carcinogenic cells, while increasing faecal bulking which promotes colon health (Brown, 2004; Sharma et al., 2008; Topping et al., 2008; Fuentes-Zaragoza et al., 2010; Pragati et al., 2014). Butyrate also acts as a rehydrating agent for those suffering from diarrhoea (Raghupathy et al., 2006). Kumar et al. (2012) also stated that banana fruits in India were utilized against constipation, hangover (build-up of depleted blood sugar levels) and against stress conditions.

At maturity, both plantains and dessert bananas are reported to contain vitamins A (carotene), B (thiamine, riboflavin, niacin), B_6 (pyridoxine), C (ascorbic acid) and B_{12}, as well as minerals K, P and Mg (Méndez et al., 2003; Aurore et al., 2009; Pereira and Maraschin, 2015; Tsamo et al., 2015a). Davey et al. (2006) documented the existence of various carotenoids in the banana fruit whereby the cultivar genotype specifies the quantity of carotenoids (mostly pro-vitamin A compounds and lutein). Studies demonstrated that the pro-vitamin A and carotenoid content of bananas from commercial cultivars (Cavendish sub-genome group) exhibited low concentrations (Davey et al., 2009; Englberger et al., 2010; Mattos et al., 2010). Davey et al. (2009) eventually determined that the cultivars with the highest amounts of pro-vitamin A were identified in the two *Musa* sections: *Eumusa* and *Australimusa*, most likely originating in Papua New Guinea. The major-minerals (Na, K, Ca, Mg, and P) and minor-minerals (Fe, Cu, Zn, Mn, and B) available in bananas have been determined to be greatly influenced by the area of origin. Hardisson et al. (2001) and Forster et al. (2002) determined that the concentration of minerals in the same cultivars differed between the areas in which they were grown.

Volatile compounds inherent in banana such as esters (Pérez et al., 1997) and alcohols (Nogueira et al., 2003), play an important role in the aromatic properties of dessert bananas. These compounds can be degraded or oxidized during the drying process due to sensitivity to thermal treatment. The astringency of unripe bananas is caused by phenolic compounds, which decreases as the fruit ripens (Aurore et al., 2009; Arvanitoyannis and Mavromatis, 2009). The export Cavendish cultivars have received the most compositional investigation based on the phenolic component concentration of the pulp ranging from 30 - 60 mg/100 g (fresh matter) (Aurore et al., 2009). Bennett et al. (2010) stated that banana fruit pulp contains significant levels of cell wall bound phenolics (ethyl acetate-soluble cell wall phenolics) and water-soluble cell wall phenolics. Cell wall-bound phenolics exhibit significant effects on the inhibition of cancer cell growth, key enzymes involved in carbohydrate metabolism, and the regulation of inflammatory processes. This is in addition to their antioxidant activity and bioactivity after being released from food (Santos-Zea et al. 2019). Phenolic acids, the principal bioactive compounds known for exerting health effects are reportedly present in bananas; however, the percentage of phenolic compounds available in banana peel has been observed to be higher than in the pulp (Bennett et al., 2010; Khoozani et al., 2019b). Gallic acid, catechin, and naringenin 7-O-neohesperidoside have all been reported as soluble phenolics present in banana fruit pulp (Aurore et al., 2009). Someya et al. (2002) showed that gallocatechin was more abundant in the peel than in pulp of commercial banana (Cavendish) from Philippines. However, Melo et al. (2006) opined that the fruit pulp of the cultivars 'Pacovan' (*M. acuminata*) and 'Comprida' (*M. paradisiaca*) commonly consumed in Recife, eastern Brazil, have considerable amounts of bioactive phytochemicals. Table 2 details the different phytochemicals present in the pulp and peel of banana cultivars and their health benefits. Unripe bananas have been shown to possess moderate antioxidant capacity when compared to other fruits such as orange, papaya, passion fruit and water melon (Ovando-Martinez et al., 2009; Shruthi, 2019; Jideani et al. 2021). Within the commercial and non-commercial cultivars, Anyasi et al. (2015) demonstrated that several non-commercial cultivars ("Luvhele", "Mabonde" and "Muomva-red") possessed higher antioxidant contents than the commercial cultivars.

5.2. Processing of banana fruit pulp

There are different factors that are involved in the production of unripe banana flour, and they include, banana ripening stage, postharvest treatments and the drying process (Zhang et al., 2005; Haslinda et al., 2009; Tribess et al., 2009; Hoffmann Sardá et al., 2016). The ripening process of banana is associated with biochemical and physical changes (Hoffmann Sardá et al., 2016). Biochemical changes include starch hydrolysis to simple sugars (Hoffmann Sardá et al., 2016), increase in osmotic potential in the pulp due to an increase in reducing sugars (fructose and glucose), the subsequent loss in turgor pressure in the peel cells, and water displacement from banana peel to pulp due to the fruit softening. Whereas physical changes include change in colour from green to yellow (beginning from the centre of the banana extending to its tips) and changes in the surface features (Ringer et al., 2018). It is essential to identify the applicable banana fruit ripening stage needed to produce flour with high resistant starch content (Zhang et al., 2005; Hoffmann Sardá et al., 2016). Besides starch degradation and the hydrolysis of sugar, other biochemical reactions such as synthesis of ethylene and the change in bioactive compounds occur during banana ripening. Three parameters can be used in evaluating unripe banana maturity stage prior to unripe banana flour production: peel colour, pulp hardness, and total soluble solids (TSS) content (Hoffmann Sardá et al., 2016; Amarasinghe et al., 2021; Watharkar et al., 2021). The most visible change during banana ripening is the change in peel colour modification, which is essential in defining the seven ripening stages used for industrializing banana fruits (Campuzano et al., 2018). Fig. 4 illustrates the seven ripening stages of banana fruits.

The basis of colour analyses of the fruit peel is done by considering the Von Loesecke scale (grading 1: green; 2: light green; 3: half yellow–half green; 4: three quarters yellow with green; 5: yellow with green tips; 6: full yellow; and 7: yellow with brown spots) (Marin et al., 1996). A texture analyser can be used in performing the firmness analysis, whereas a refractometer for determining the TSS (Hoffmann Sardá et al., 2016). Tribess et al. (2009) and Hoffmann Sardá et al. (2016) determined that the unripe banana (stage 1 of Fig. 4) had an average value for firmness at 25.8 and 31.4 N, a TSS value of 3.5 and a 2.8 °Brix content. Bananas are not consumed raw as fruits between stages 1 to 3 since they are green, very hard, astringent, and high in starch. After stage 7, bananas are overripe with a muddy texture (Aurore et al., 2009). Neither the time required for fruit development nor its size (diameter) has shown to be completely reliable predictors of its maturity stage. As a result, a more precise way of determining the physiological stage of the fruit is required especially in preventing premature ripening of the fruit (Marin et al., 1996).

To produce unripe banana flour, the fruits should be harvested at three-quarters of the well-developed, mature stage 1 (fully green) of Fig. 4 and processed within 24 h. If less mature fruits are used, the flour may taste slightly astringent due to the tannin content (Horie et al., 2020). It should be noted that amongst bananas of the same production stage and genomic group, physiological maturity does not necessarily occur at the same time. Different factors, such as the time of the year, Sigatoka leaf spot diseases, or other environmental conditions, might influence physiological maturity (Marin et al., 1996). Furthermore, the selection of genomes with the desired technofunctional properties as well the processing methods ultimately influences the flour quality. Before the drying process of banana during flour production, the fresh-cut fruit pulp can be pre-treated by subjecting it to treatments such as sulphite, citric acid, or saline solution to inactivate oxidases that leads to enzymatic browning (Deng et al., 2019). The implementation of Hazard Analysis and Critical Control Points (HACCP) should also be taken into consideration for the proper handling of fresh-cut products (Motarjemi and Warren, 2014). DiPersio et al. (2004) and Kendall and Sofos (2007) stated that pre-treating with an acidic solution or sodium metabisulphite dip increases the elimination of potentially harmful bacteria such as *Escherichia coli* O157:H7, *Salmonella* spp., and *Listeria monocytogenes* during drying. Though the application of unripe banana flour in foods has been evaluated in several studies, there has been no specific legislation for unripe banana flour identification and quality standards (Hoffmann Sardá et al., 2016). Therefore, it is important to propose characterization parameters such as resistant starch content, water binding and oil holding capacity for unripe banana flours available.

5.3. Drying process of unripe banana pulp

Dehydration is the oldest and most widespread method of food preservation, often utilized in cultures where long-term storage is desired in food products. The postharvest processing of banana pulp to flour, in particular the drying step is critical in ensuring high nutritional quality flour in terms of resistant starch, vitamins, and minerals (Khoozani et al., 2019b). The drying temperature also influences the characterization, sensorial evaluation, and microbial quality of the flour. Drying is needed to remove excess water from fresh produce, with sun drying (Arun et al., 2019; Arun et al., 2020) and hot air drying amongst the most common drying methods for banana and plantain (Bezerra et al., 2013; Zabalaga et al., 2016). Other methods such as freeze-drying (Savlak et al., 2016; Ahmed et al., 2020), spray drying (Izidoro et al., 2011; Verma and Singh, 2015), microwave oven drying (Pandya et al., 2014; Omolola et al., 2015) and drying on a spouted bed (Bezerra et al., 2013) have been reported. Table 3 highlights the drying methods used in banana processing and the characteristics of the obtained products.

Table 2
Banana pulp and peel phytochemicals and their health benefits.

Banana fruit part	Phytochemicals	Phytochemical classification	Phytochemical subclass	Health Benefits*	Reference
Peel	α-Carotene	Tetrapenoids	Carotenoids	Scavenges reactive species and radicals.	Hikal et al., 2022
Pulp and peel	β-Carotene	Tetrapenoids	Carotenoids	Supresses inflammatory responses, assist in the modulation of cell signalling and	Qamar and Shaikh, 2018; Hikal et al., 2022
Pulp and peel	Lycopene	Tetrapenoids	Carotenoids	induction of apoptosis, assist in cardiovascular protective activities, cancer,	Qamar and Shaikh, 2018
Peel	Lutein	Tetrapenoids	Carotenoids	gastrointestinal disorders, and obesity.	Qamar and Shaikh, 2018; Hikal et al., 2022
Peel	Isolutein	Tetrapenoids	Carotenoids		Hikal et al., 2022
Peel	Auroxanthin	Tetrapenoids	Carotenoids		Hikal et al., 2022
Peel	Neoxanthin	Tetrapenoids	Carotenoids		Hikal et al., 2022
Peel	Stigmasterol	Triterpenoids	Sterols	Essential components of the immune system. Important for the synthesis of prostaglandins	Qamar and Shaikh, 2018; Jideani et al., 2021; Hikal et al., 2022
Peel	β-sitosterol	Triterpenoids	Sterols	and leukotriene. Cholesterol lowering	Qamar and Shaikh, 2018; Hikal et al., 2022
Peel	Campesterol	Triterpenoids	Sterols	effects, anticancer, anti-inflammation, and	Qamar and Shaikh, 2018
Peel	24-Methylenecycloartanol	Triterpenoids	Sterols	anti-atherosclerosis properties	Hikal et al., 2022
Pulp and peel	Dopamine	Catecholamines	Amines		Qamar and Shaikh, 2018; Wongwaiwech et al., 2022; Hikal et al., 2022
Peel	L-dopa	Catecholamines	Amines		González-Montelongo et al., 2010; Vu et al., 2018
peel	noradrenaline	Catecholamines	Amines		Qamar and Shaikh, 2018
Pulp and peel	Ferulic acid	Phenolic acids	Hydroxycinnamic acids	Undertakes antioxidant activities and inhibits the oxidative damage induced diseases such as cancer, cardiovascular diseases and stroke. Possesses therapeutic potential against Alzheimer's diseases,	Agama-Acevedo et al., 2016; Kumar et al. 2016; Pico et al., 2019; Kumar and Goel, 2019; Bashmil et al, 2021; Hikal et al., 2022; Wongwaiwech et al., 2022; Li et al., 2023
Peel	Ferulic acid-hexoside	Phenolic acids	Hydroxycinnamic adis	increases sperm viability, enhances the stability of cytochrome C as well as inhibits	Tsamo et al., 2015b; Vu et al., 2018; Kumar and Goel, 2019
Pulp and peel	Caffeic acid	Phenolic acids	Hydroxycinnamic acids	apoptosis induced by cytochrome C. Exhibits antimicrobial, anti-inflammatory, antiallergic, antithrombotic, antiviral and	Bashmil et al, 2021; Hikal et al., 2022; Agama-Acevedo et al., 2016; Pico et al., 2019
Peel	Glucocaffeic acid	Phenolic acids	Hydroxycinnamic acids	herpatoprotective activities. Inhibition of α-glucosidase and α-amylase, enzymes	Tongkaew et al., 2022
Pulp and peel	ρ-coumaroyl glycolic acid	Phenolic acids	Hydroxycinnamic acids	responsible for the break down of dietary carbohydrates into glucose.	Bashmil et al, 2021
Pulp and peel	ρ-coumaric acid	Phenolic acids	Hydroxycinnamic acid		Li et al., 2023
Pulp	Chlorogenic acid	Phenolic acids	Hydroxycinnamic acid		Wongwaiwech et al., 2022; Pico et al., 2019; Tongkaew et al., 2022
Peel	Quinic acid	Phenolic acids	Hydroxycinnamic acid		Tongkaew et al., 2022
Peel	Sinapic acid	Phenolic acids	Hydroxycinnamic acid		Tsamo et al., 2015b; Vu et al., 2018
Peel	Sinapic acid-hexoside	Phenolic acids	Hydroxycinnamic acid		Tsamo et al., 2015b; Vu et al., 2018
Peel	Triferuloyl-dihexose	Phenolic acids	Hydroxycinnamic acid		Tsamo et al., 2015b; Vu et al., 2018
Pulp and peel	Gallic acid	Phenolic acids	Hydroxybenzoic acids	Undertakes antioxidant activities and inhibits the oxidative damage induced diseases such as cancer, cardiovascular diseases and stroke. Exhibits antimicrobial,	Pico et al., 2019; Kumar and Goel, 2019; Majaliwa et al., 2021; Jideani et al., 2021; Hikal et al., 2022; Wongwaiwech et al., 2022; Li et al., 2023
Peel	3,4-*O*-Dimethylgallic acid	Phenolic acids	Hydroxybenzoic acids	anti-inflammatory, antiallergic, antithrombotic, antiviral and	Bashmil et al, 2021
Peel	ρ-Hydroxybenzoic acid	Phenolic acids	Hydroxybenzoic acid	herpatoprotective activities. Inhibition of α-glucosidase and α-amylase, enzymes	Li et al., 2023
Peel	Salicylic acid	Phenolic acids	Hydroxybenzoic acid	responsible for the break down of dietary carbohydrates into glucose.	Li et al., 2023
Pulp	Ellagic acid	Phenolic acids	Hydroxybenzoic acid		Wongwaiwech et al., 2022
Pulp	Vanillic acid	Phenolic acids	Hydroxybenzoic acid		Pico et al., 2019
Pulp and peel	Catechin	Flavonoids	Flavanols	Free radical scavenging activities by stabilisation of the reactive oxygen species; disease combating activities by reducing the harmful effects of diabetes; exerts immune-regulatory activity; reduced risk of	Qamar and Shaikh, 2018; Pico et al., 2019; Zeng et al., 2019; Majaliwa et al., 2021; Jideani et al., 2021; Hikal et al., 2022; Wongwaiwech et al., 2022; Li et al., 2023
Pulp	Epigallocatechin	Flavonoids	Flavanols		Majaliwa et al., 2021
Pulp	Epigallocatechin gallate	Flavonoids	Flavanols	hypertension and cardiovascular diseases;	Majaliwa et al., 2021
Pulp and peel	Gallocatechin	Flavonoid	Flavanols	and chemo preventive activity against cancer cells	Qamar and Shaikh, 2018; Majaliwa et al., 2021; Wongwaiwech et al., 2022; Hikal et al., 2022
Pulp and peel	Epicatechin	Flavonoid	Flavanols		Majaliwa et al., 2021; Li et al., 2023; Pico et al., 2019; Anyasi et al., 2018; Panche et al., 2016

(*continued on next page*)

Table 2 (*continued*)

Banana fruit part	Phytochemicals	Phytochemical classification	Phytochemical subclass	Health Benefits*	Reference
Peel	(+)-gallocatechin 3-*O*-gallate	Flavonoids	Flavanols		Bashmil et al, 2021
Pulp	Gallocatechin gallate	Flavonoids	Flavanols		Wongwaiwech et al., 2022
Pulp and peel	Delphinidin 3-*O*-(6″-acetyl-galactoside)	Flavonoids	Anthocyanins	Suppress lipid peroxidation in caco-2 cells and undertakes anticarcinogenic activities.	Bashmil et al, 2021; Jideani et al., 2021;
Pulp and peel	Cyanidin 3,5-*O*-diglucoside	Flavonoids	Anthocyanins	Prevents nitric oxide synthase as well as reduction in nitric oxide and prostaglandin	Bashmil et al, 2021
Peel	Malvidin 3-*O*-(6″-acetyl-glucoside)	Flavonoids	Anthocyanins	E2 production.	Bashmil et al, 2021
Peel	Cyanidin	Flavonoids	Anthocyanin		Hikal et al., 2022
Peel	Delphinidin	Flavonoid	Anthocyanin		Hikal et al., 2022
Peel	Myricetin 3-*O*-rutinoside	Flavonoids	Flavonols	Anti-inflammatory activity: acting as preferential inhibitors of the isoform of the	Bashmil et al, 2021; Panche et al., 2016; Jideani et al., 2021;
Peel	Quercetin 3-*O*-xylosyl-glucuronide	Flavonoids	Flavonols	enzyme, cyclooxygenase (COX–2). Possess inhibitory activities against	Bashmil et al, 2021
Pulp	Quercetin	Flavonoids	Flavonols	acetylcholinesterase (AChE), thus serving as a therapy for mild to moderate symptomatic	Majaliwa et al., 2021; Wongwaiwech et al., 2022; Pico et al., 2019; Panche et al., 2016
Pulp	Quercetin 3-glucoside	Flavonoids	Flavonols	relief of Alzheimer's disease (AD).	Pico et al., 2019
Peel	Quercetin 7-rutinoside	Flavonoids	Flavonols		Tsamo et al., 2015b; Vu et al., 2018
Peel	Quercetin deoxyhexose hexoside	Flavonoids	Flavonols		Tsamo et al., 2015b; Vu et al., 2018
Peel	Isorhamnetin 3-*O*-glucoside 7-*O*-rhamnoside	Flavonoids	Flavonols		Bashmil et al, 2021
Peel	Isorhamnetin 3-rutinoside	Flavonoids	Flavonols		Tsamo et al., 2015b; Vu et al., 2018
Pulp and peel	Rutin	Flavonoids	Flavonols		Wongwaiwech et al., 2022; Hikal et al., 2022
Peel	Kaempferol 3-rutinoside	Flavonoids	Flavonols		Tsamo et al., 2015b; Vu et al., 2018
Pulp and peel	Kaempferol	Flavonoids	Flavonols		Li et al., 2023; Wongwaiwech et al., 2022
Peel	Kaempferol 7-rutinoside	Flavonoids	Flavonols		Tsamo et al., 2015b; Vu et al., 2018
Pulp	Myricetin	Flavonoids	Flavonols		Pico et al., 2019; Anyasi et al., 2018
Peel	Myricetin deoxyhexose hexoside	Flavonoids	Flavonols		Tsamo et al., 2015b; Vu et al., 2018
Peel	Laricitrin 3-rutinoside	Flavonoids	Flavonols		Tsamo et al., 2015b; Vu et al., 2018
Pulp	Apigenin 7-*O*-apiosyl-glucoside	Flavonoids	Flavones	Anti-inflammatory activity: acting as preferential inhibitors of the isoform of the	Bashmil et al, 2021; Panche et al., 2016; Jideani et al., 2021;
Peel	Chrysoeriol 7-*O*-glucoside	Flavonoids	Flavones	enzyme, cyclooxygenase (COX–2)	Bashmil et al, 2021
Peel	Chrysin	Flavonoids	Flavones		Hikal et al., 2022
Peel	Neoeriocitrin	Flavonoids	Flavanones	Anti-inflammatory activity: acting as preferential inhibitors of the isoform of the	Bashmil et al, 2021; Panche et al., 2016; Jideani et al., 2021;
Pulp and peel	Naringenin	Flavonoids	Flavanones	enzyme, cyclooxygenase (COX–2) Antimicrobial activity: serves as potent	Wongwaiwech et al., 2022; Hikal et al., 2022; Panche et al., 2016
Peel	Naringenin-7-*O*-neohesperidoside	Flavonoids	Flavanones	inhibitors of *Staphylococcus aureus* and counters the resistance of microbial enzymes	Qamar and Shaikh, 2018
Pulp and peel	Syringic acid				Li et al., 2023
Pulp and peel	Tannic acid	Tannin		Potential molecule for anti-obesity	Wongwaiwech et al., 2022; Hikal et al., 2022; Panche et al., 2016
Peel	Violaxanthin				Hikal et al., 2022
Peel	*β*-Cryptoxanthin				Hikal et al., 2022
Peel	*α*-Cryptoxanthin				Hikal et al., 2022
Peel	Cycloalkanol	Alkane			Hikal et al., 2022
Peel	Corticosteroids	Steroids			Hikal et al., 2022
Peel	Succinic acid	Dicarboxylic acid			Hikal et al., 2022
Peel	Palmitic acid	Saturated fatty acid			Hikal et al., 2022
Peel	12-Hydoxystearic acid	Hydroxy fatty acid			Hikal et al., 2022

* Health beneficial roles are grouped according to phytochemical subclass as majority of the phytochemicals in these subclasses undertake similar functions.

The principal aspects that influence the drying operations are temperature, air velocity, humidity, thickness, and size of the sample. During the drying process of banana, the moisture present in the banana pulp diffuses from the internal to the surface, evaporating into the air stream while heat is transferred from the air into the banana (Porciuncula et al., 2016). On removal of moisture, the volume of the product decreases, causing structure collapse and cell wall disruption thus successively affecting the diffusing distance of moisture moving from the inside to the outside (Thuwapanichayanan et al., 2011). The moisture content in food is of critical importance for freshness, shelf life and food stability, with the drying process directly interfering with the moisture of the final product (Cauvain and Young, 2009; do Prado Ferreira and Tarley, 2020; Hasan and Putri, 2020). The two significant processes during the drying operation include the movement of water from inside the material to the surface and the evaporation/release of surface water to the surrounding environment (Srikiatden and Roberts, 2007). Drying in general alters the top surface, changing the interior cellular structure of starches and influencing their properties, including reaction activity, gelatinization, retrogradation, and starch pasting properties (Grant, 1998).

The process of drying pastes and suspensions on spouted beds has been recommended as a cost-effective and high-quality alternative. It is commonly employed in the dehydration of heat-sensitive materials to preserve bioactive compounds, which has several advantages over other

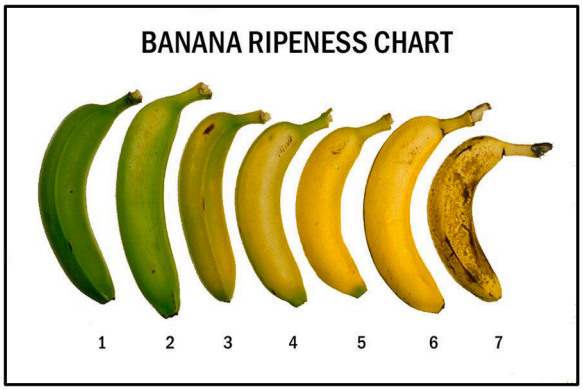

Fig. 4. The seven ripening stages of banana (© Don Edwards, UC Davis, Postharvest Technology center, California, USA).

drying processes, including faster drying times (Bezerra et al., 2013). Spray drying is the preferred method for thermally sensitive materials such as foods and pharmaceuticals. Spray drying is a method of rapidly drying a liquid or slurry with a hot gas in a single processing step to produce a dry powder. Spray drying removes moisture from food specimens through rapid evaporation on spray droplets exposed to high temperatures (Rezvankhah et al., 2020). All spray dryers employ an atomizer or spray nozzle to disperse the liquid or slurry into a controlled drop size spray (Verma and Singh, 2015; Izidoro et al., 2011). Dehydration using freeze-drying relies on the action of ice sublimation under low pressure. During freeze drying, excess water is removed, resulting in a lightweight product. When water is reintroduced, it prevents the survival of yeast and bacteria while retaining its taste, shape, and appearance. However, freeze-drying equipment is expensive and the process is time-consuming and labour-intensive (Verma and Singh, 2015). Although hot air drying is less expensive than freeze-drying and spray-drying, the quality of the products differs dramatically between the methods. As a result, a comparison of drying procedures and product quality should be conducted (Ahmed et al., 2020).

In the preservation of a product's organoleptic and physical characteristics, the drying temperature should generally not exceed 60 °C. This will minimize the loss of principal nutrients (Oliveira et al., 2016). Therefore, the drying process should be carefully selected to ensure a rapid inactivation of the hydrolases responsible for the starch conversion into reducing sugars during ripening. Specifically, α-amylase isolated from banana pulp have been reported to present an optimal activity between 8 and 38 °C, with denaturation commencing at 38 °C and completing at 100 °C after 5 min (Pico et al., 2019). Tribess et al. (2009) showed that resistant starch can be better conserved (up to 58.5 g/100 g) when using higher drying temperatures of between 52 – 58 °C; air velocities of 0.6 – 1.4 m s^{-1}; and at drying times of between 5.7 – 6.7 h. Dried food products are expedient since their lightweight, take up little space and do not oblige to refrigeration, thus enabling low transportation, exportation, and storage costs (Verma and Singh, 2015). Considering that banana flour is highly hygroscopic and susceptible to discoloration, moisture-proof packaging materials are essential upon drying for its storage (Cardoso and da Silva Pena, 2014).

5.4. *Carbohydrate quality of unripe banana flour from different genomic groups*

Starch has been implicated as the main carbohydrate present in unripe green bananas with 70 – 80% of the dry weight of whole bananas contributing to starch (Campuzano et al., 2018; Kumar et al., 2019). On the basis of its physicochemical properties, starch is divided into rapidly digestible starch (RDS), slowly digestible starch (SDS) and resistant starch (RS) (Jirapa et al., 2009). Both RDS and SDS can be digested by animals while RS is described as the fraction that evades digestion in the small intestine (Englyst et al. 1992). Compared to RDS, SDS provides a gradual increase of postprandial blood glucose level and can maintain blood glucose at a much longer period (Lehmann and Robin, 2007). Resistant starch acts as a fermentation substrate for beneficial microbes and possesses high concentration of amylose leading to its slow and resistant digestion nature (Hung et al., 2008). Banana starch comprises amylose content higher than those of corn, potato and wheat starch and BS is also known for its resistance to acid hydrolysis (Acevedo-Guevara et al., 2018). Utrilla-Coello et al. (2014) postulated that the amylose content contributes a crucial role in altering the diverse physico-chemical properties of starches especially as the amorphous fraction of starches consist mostly of amylose. Banana cultivars

Table 3
Drying methods of banana and the processed product characteristics.

Drying method	Product	Drying temperature	Drying time	Product characteristics	References
Conical spouted bed drying	Unripe banana paste	80 and 90 °C	N/A	Resistant starch (peeled 33.86 g/100 g d.b; unpeeled 40.14 g/100 g d.b), total starch (peeled 68.02 g/100 g d.b; unpeeled 73.07 g/100 g d.b)	Bezerra et al., 2013
Conventional oven drying	Unripe banana pulp and peel	40, 50 and 60 °C	5 h	Thermophysical properties: monolayer moisture content (5.5 g/100 g), equilibrium moisture content (1.4 – 4.7%), thermal conductivity (0.89 – 0.14 W/mK)	Zabalaga et al., 2016
	Unripe banana starch	50 °C	4 h	Moisture content (13.37%), resistant starch (79.89%)	Izidoro et al., 2011
Freeze drying	Unripe banana pulp	N/A	48 h	Moisture content (8.75 – 9.19%), TSS (0.52 – 0.74 °Brix), phenolic compounds (0.19 – 0.31 mg GA/g), bulk density (146 – 251 kg/m^3)	Savlak et al., 2016
		-47 to -50 °C	36 h	Moisture content (2.70%), resistant starch (37.87%), total starch (42.30%), thermal conductivity (0.12 W/mK)	Ahmed et al., 2020
Microwave oven drying	Ripe banana pulp	220 – 240 V, 50 Hz	12 min (300 W) 26 min (341 W)	Hardness (1.29 to 14.28 N at 341 W, and 0.45 to 9.28 N at 300 W)	Omolola et al., 2015
	Unripe banana pulp	N/A	N/A	Moisture content (3% w.b), fat content (2.19% at 40 W, and 1.42% at 80 W), ash content (0.81% to 0.87%)	Pandya and Yadav, 2014
Tray drying	Unripe banana pulp	55 °C	15 h	Moisture content (7.64%), resistant starch (25.77%), total starch (39.63%), thermal conductivity (0.18 W/mK)	Ahmed et al., 2020
Solar cabinet drying	Unripe banana pulp	48.5 °C	10 h	Moisture content after 1st day (16% for 0.03 kg/s and 22% for 0.015 kg/s of flakes), moisture content after 2nd day (6% for 0.03 kg/s and 10% for 0.015 kg/s of flakes)	Arun et al., 2019
Spray drying	Unripe banana starch	Inlet – 130 °C Outlet – 47 °C	Flow rate at 0.6 m^3/min	Moisture content (13.81%), resistant starch (68.51%)	Izidoro et al., 2011

N/A: Not available; TSS: Total soluble solids; d.b: dry basis; w.b: wet basis

belonging to different genome groups and cultivated in different regions of the world have been shown to exhibit varying starch concentration and composition.

Chang et al. (2022) reported a carbohydrate composition of 76.78 – 83.49% and a total starch composition of 58.01 – 68.74% for five Tanzania banana varieties: "Mzuzu" (plantains), "Malindi" (*Cavendish* sp.), "Mshale" (*Musa* AA Pisane litin), "Bukoba" (East African highland banana, *Musa* AAA), and "Moshi" (*Musa acuminata*). All banana cultivars used for the study showed B-type crystals, consistent with resistant starch characteristics of banana starch. Wang et al. (2019) demonstrated that seven banana cultivars: *Ensete glaucum* (Roxb.) Cheesm, *Musa* ABB cv. *dajiao, Musa* AAB cv. *Sikl* cv. *dalijiao, Musa* AAA cv. *Cavendish* cv. *baxi, Musa* ABB cv. *Pisang Awak* cv. *Fenjiao, Musa* AAA cv. *Red Dacca* and *Musa* AA cv. *Huangdijiao*, obtained from various locations in China had amylose content ranging from 22.59 – 38.40% with the banana cultivars exhibiting a mixture of the B- and C-type crystallinity. amongst the cultivars from different genomic groups examined by Kumar et al. (2019), the total starch content ranged from 68.97 – 81.66 g/100 g d.w. for Grand Naine (AAA), Nendran (AAB) and Popoulu (AAB) grouped as the dessert varieties, as well as Monthan (ABB) and Saba (ABB) which are grouped as plantains. The lowest total starch content of 68.97 g/100 g d.w. was recorded for the AAA genome (Grande Naine) while the highest total starch content of 81.66 g/100 g d.w. was recorded for Monthan belonging to the ABB genome. Similarly, the amylose content varied amongst the genome groups with Saba (ABB) exhibiting the highest amylose content of 24.21 g/100 g d.w. and Grand Naine (AAA) showing the lowest amylose concentration of 15.52 g/100 g d.w. Banana cultivars belonging to the genome groups ABB (plantains) recorded higher RS than those belonging to the AAB (dessert bananas) and the AAA (commercial Cavendish).

Borges et al. (2020) in their study on the nutritional value and antioxidant compounds in bananas and plantains cultivated in Brazil, postulated that the dessert and cooking banana genotypes with higher RS content were observed for cultivars in the *Musa* spp germplasm compared to the commercially available ones. In their study, 22 *Musa* spp made up of the diploid (AB), triploid (AAA, AAB and ABB) and tetraploid (AAAB, AABB, and ABBB) genotypes and consisting of the dessert, cooking bananas and plantains were analysed for their total starch (TS) and RS content. The TS content ranged from 42.3% (FC06–02, AABB) to 80.6% (Pelipita, ABB), while the RS content ranged from 22.9% (Namwa Khom, ABB) to 49.9% (Terra Ana Branca, AAB) amongst all the banana genotypes examined. Bi et al. (2019) opined that RS content of green bananas varies according to variety, with plantains exhibiting more RS content when compared with the commercial Cavendish bananas. However, Khoozani et al. (2019a) showed that drying methods were seen to affect the RS and amylose content of bananas belonging to the AAA genome (Cavendish group) with recorded higher values of RS and amylose for freeze dried bananas compared to the oven dried ones. Banana RS has been reported to be resistant to α-amylase and glucoamylase hydrolysis hence its classification as RS type II. Beneficial properties attributed to RS includes decreasing glucose and insulin responses, reducing the calories in food thereby leading to weight loss as well as promoting the proliferation of beneficial gut bacteria (Brown et al., 2001; Li et al., 2020).

Bi et al. (2017) opined that several factors such as chemical composition, granule morphology and molecular structure have been implicated as factors affecting the digestibility of starch. Starch digestion is affected by intrinsic factors including granule structure, starch source, granule size, crystalline structure, native α-amylase inhibitors, non-starch polysaccharides as well as amylose-lipid complexes; and extrinsic factors such as starch modification, mode of storage and processing method (Zhang et al., 2012; Bi et al., 2017). Starch digestibility has been directly related to granule size with larger granules exhibiting lower digestibility. Susceptibility to α-amylase which leads to starch digestibility is reduced by amylose-lipid complexes. Furthermore, starch from several plant sources are known to exhibit the A-, B- and C-type crystalline structure. The A-type structure are displayed by cereal starch; the B-type by tubers and fruits; while the C-type are exhibited by legume starch. The A-type are more easily digested than the B-type, while the C-type shows an intermediate digestion rate between the A- and the B-type starch (Bi et al., 2017).

5.5. Unripe banana flour application

Unripe banana flour serves as an important source of carbohydrates which is used as an excellent raw material for modifying the texture and consistency of foods (Arvanitoyannis and Mavromatis, 2009). Rodríguez-Ambriz et al. (2008) showed that unripe banana flour possesses the thickening and cooking properties almost like that of wheat flour. With bananas exhibiting a high starch content, the great biodiversity of banana fruits provides potential for varietal creation, to promote characteristics compatible with food expectations especially in relation to consumer health concerns. Unripe banana flour has been incorporated to produce slowly digestible cookies (Aparicio-Saguilán et al., 2007), high fibre bread (Juarez-Garcia et al., 2006; Aziah et al., 2012), and edible films (Sothornvit and Pitak, 2007). Unripe banana flour has also been applied (pilot scale) in certain food products, such as cereal bars (Santos, 2010), crackers (Fasolin et al., 2007), pasta (Agama-Acevedo et al., 2009), and noodles (Choo and Aziz, 2010; Hoffmann Sardá et al., 2016). Vernaza et al. (2011) stated that by banana flour was used in the development of products such as gnocchi, pâtés, and mayonnaise, due to its high starch-content biomass.

Bello-Pérez et al. (2000) isolated banana starch from cultivars 'macho' and 'criollo' (grown in Mexico) to determine their freeze-thaw stability. Banana starch has found application in multiple industries such as paper and textile industry as a binder, and as a disintegrant in the pharmaceutical industry (Kaur et al., 2020; Mohammed and Bin, 2020; Obioma et al., 2021). The natural abundance, biocompatibility, ease in structural reforms and polymerization matrix of banana starch features has caused researchers to adopt innovative procedures to work on. Orsuwan and Sothornvit (2017) improved the mechanical and water vapour permeability properties of banana starch nanotechnology-constituents embedded in packaging material synthesis through mini emulsion castings. For controlled delivery of bioactive constituents, Santoyo-Aleman et al. (2019) used nanotechnology to derive unripe banana starch matrix (< 250 nm) on modification to cross link pattern in assistance with citric acid loaded with β-carotene. However, the possibility of new and useful starch products resulting from the combination of different modifications with permissible reagents and levels of addition can also be expanded (Arvanitoyannis and Mavromatis, 2009). Chemical, physical, and biological modification methods have the potential to create new and more useful commercial banana starches.

Zhang et al. (2005) showed that several commercially available banana starches have been modified primarily through pre-gelatinization, to meet the needs of various industries. Similarly, the physical modification of banana starch achieved by citric acid treated gelatinization steps were seen to be effective in the reduction of body fat when administered as routine meals (Wu et al., 2020). Tibolla et al. (2019) synthesized banana starch nanocomposites with cellulose nano fibres of banana peel for the development of combo nanocomposite structures that do not possess hydrophilic characteristics thereby imparting better water barrier properties. Wu et al. (2018) used corona electrical discharge on raw banana starch obtained from Taiwan cultivars for the reduction in gelatinization enthalpy and pasting properties, with increased crystalline characteristics of the starch. Dual modification of banana starch using phosphorus oxychloride ($POCl_3$) cross linking and microwave irradiation increased the solubility, swelling, and water absorption extent of the starch (Carmona-Garcia et al., 2009). Carlos-Amaya et al. (2011) used esterified cross linking and cross-linked esterification methods which caused the modified starch to increase in slow digestible starch proportion. Currently, research is still being

conducted on improving banana starch properties to produce more stable and sustainable technological processes associated with food production.

Conclusions

Differences have been observed to exist in the nutritional composition of banana cultivars from known genomic groups. However, conventional techniques used in the preparation of banana flour are known to influence the physicochemical, functional properties and digestibility of both the flour and starch. Employing modification techniques will enhance the functional properties of banana flour including its starch and expand the range of applications for which it can be used in food formulations. Bananas are also noted to be a source of secondary metabolites inherent in both the fruit pulp and peel of its diverse cultivars. Engaged discussions on the availability of some of these banana cultivars at both the regional and national levels could provide a more unique approach of presenting information on the overlooked bananas. Studies on the utilization of phytochemicals present in banana peels while considering the fruit genotypes can further be explored. This will essentially promote banana end use and address the significant environmental challenges posed by banana waste all over the world.

CRediT authorship contribution statement

Kayise Hypercia Maseko: Writing – original draft, Conceptualization, Visualization. **Thierry Regnier:** Supervision, Conceptualization, Writing – review & editing. **Belinda Meiring:** Supervision, Conceptualization, Writing – review & editing. **Obiro Cuthbert Wokadala:** Supervision, Conceptualization, Writing – review & editing. **Tonna Ashim Anyasi:** Supervision, Conceptualization, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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