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Review

Classification of potatoes by geographical origin and cultivar based on volatile compounds and proximate composition properties: A review

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Abstract: Potatoes exhibit substantial variability in chemical composition depending on cultivar, geographical origin, and environmental factors. This review summarizes compositional and volatile profiles of potatoes from Korea, Europe, China, and the Americas. Thermal processing such as boiling, baking, and frying alters volatile profiles through lipid oxidation and Maillard reactions. Variations in proteins, amino acids, starch, sugars, minerals, and lipids influence processing suitability and flavor development. Recent analytical approaches applying elemental and isotopic analyses, volatile profiling, and multivariate statistics have been used to discriminate potato cultivars and origins. Elemental and isotopic markers provide high accuracy, whereas volatile-based indicators have potential, particularly when used in combination with other compositional markers. Integrating compositional, isotopic, and volatile information offers an effective framework for reliable potato classification.

Keywords: potato; geographical origin; volatile compounds; non-volatile compounds; multivariate statistical analysis

1. Introduction

Potato (*Solanum tuberosum* L.) is one of the most important staple crops worldwide and serves as a major source of carbohydrates, vitamins, and dietary fiber in human diets. Global potato production has exceeded 390 million tons annually, with China and India being the largest producers, followed by several European countries.[1] Due to its high productivity and adaptability to diverse environmental conditions, potato is cultivated across a wide range of geographical regions. The proximate composition of potato tubers is strongly influenced by genetic background, cultivation environment, and postharvest conditions. Previous studies have reported that environmental factors such as temperature, precipitation, soil characteristics, and storage conditions can significantly affect the accumulation of starch, reducing sugars, volatile compounds and other metabolites in potato.[2,3] Consequently, potatoes produced in different region

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often exhibit distinct chemical profiles. These compositional differences are closely associated with geographical origin and agricultural practices, providing a scientific basis for origin discrimination.

In recent years, growing concerns regarding food authenticity and traceability have stimulated research on analytical approaches for determining the geographical origin and cultivar of agricultural products. Food authenticity is a critical issue in both quality control and food safety. In particular, geographical origin authentication has become an important component of food authenticity. It is increasingly recognized as a key quality criterion, partly driven by legislative protection of regional food products. Accordingly, accurate and standardized analytical methods for origin authentication are increasingly required.[4] To address this issue, compositional profiling has been widely applied to identify chemical markers associated with origin. Because the composition of agricultural products is influenced by environmental conditions, these products often develop distinct chemical profiles that can be used for origin discrimination.[2,5]

Beyond intrinsic compositional differences, thermal processing induces substantial changes in the volatile profile of potatoes. Various volatile compounds are generated through lipid oxidation, Maillard reactions, and carbohydrate degradation, contributing to the characteristic flavor of processed products such as chips, fries, and baked potatoes.[6] Volatile compounds, including aldehydes, alcohols, ketones, and sulfur-containing compounds, have been reported to contribute significantly to the sensory attributes of processed potato products.[2,7]

To investigate these compositional and processing-induced variations, advanced analytical techniques have been widely applied. Techniques such as inductively coupled plasma mass spectrometry (ICP-MS), gas chromatography–mass spectrometry (GC-MS), and metabolomics-based approaches are widely used to characterize chemical profiles. These analytical methods are often combined with multivariate statistical techniques, including principal component analysis (PCA), linear discriminant analysis (LDA), partial least squares–discriminant analysis (PLS-DA), and stepwise discriminant analysis (SDA), to support discrimination of geographical origin and cultivar. This review focuses on compositional characteristics and analytical approaches for potato origin and cultivar discrimination, with particular attention to volatile compounds formed during thermal processing and their relevance to food authentication.

2. Regional and Cultivar Diversity of Potatoes

2.1. Korea

Historical records indicate that potatoes were introduced to Korea in 1824 by Chinese immigrants who entered the Hamgyong-do region to harvest wild ginseng.[8] From that time until the late 1800s, detailed records of native potato cultivars were scarce. However, the publication of agricultural books after 1900 began to provide formal documentation, leading to the introduction of 'Irish Cobbler' in the 1930s. In the 1970s, the 'Superior' cultivar was introduced from the United States and has since been widely known by its local name, 'Sumi'. It was officially registered as a single-cropping cultivar in 1978, while 'Dejima' was introduced for double-cropping.[9,10] In the 1980s, 'Lemhi Russet' and 'Shepody' were registered as the demand for French fry processing grew. In the 1990s, the breeding system was established, and various cultivars were developed based on their growth types, farming methods, and uses. By 1995, 'Namseo' was developed, and 'Atlantic' was selected for potato chip production. In 1999, 'Gawon' was released as the first domestic cultivar for chips, along with a colored potato cultivar named 'Jasim'.[11] 'Arirang-1' is A notable Korean potato cultivar released in 2018. It grows well in high temperatures and produces a high yield of yellow potatoes. This cultivar exhibits greater drought tolerance than 'Superior' and is suitable for cultivation in both Korea and Central Asia.[12] Korean cultivars diversified according to cropping system and processing use, which may affect composition-related traits.

2.2. Europe

Europe has a long tradition of potato production and use, starting with the introduction of potatoes to Spain by explorers around 1570.[13] Shortly after, potatoes were spread as exotic gifts to Italy, Belgium, and Austria, reaching London, France, and the Netherlands by 1600.[14] From the 17th to the 20th century, the potato crop gradually developed from a basic primary dietary source to a major cash crop throughout Europe. [14] Currently, Germany, France, the Netherlands, the United Kingdom (UK), and Belgium are the five largest producers in the European Union, accounting for approximately 45 % of the total potato cultivation area in Europe.[13] Major European producers currently cultivate a wide range of potato cultivars tailored to specific end-uses. In Belgium, the cultivar ‘Fontane’ dominates the sector, accounting for 35.1 % of the total area due to the strong influence of the processing industry.[13] Germany shows high varietal diversity with 228 registered cultivars, including ‘Kuras’ for starch production, ‘Belana’ for fresh consumption, and ‘Fontane’ for processing.[13] While ‘Maris Piper’ has traditionally been the most widely grown cultivar in the UK, it is increasingly being replaced by newer cultivars designed for specialized purposes.[15] Similarly, the Netherlands and France strategically develop specific cultivars, such as ‘Spunta’ and ‘Innovator’, to meet global export and processing demands.[13,15] The strong specialization of European cultivars provides a useful background for comparing cultivar-dependent quality traits.

2.3. China

It is estimated that potatoes were first introduced to China between the late 16th and early 17th centuries, brought by maritime trade and explorers via European sea routes.[16-18] Initially, the crop arrived through southeastern coastal areas and spread to inland mountainous regions during the 18th and 19th centuries as a main food source to solve food shortages caused by rapid population growth.[19,20] Currently, China has grown into the world's largest potato producer, accounting for approximately 25 % of global planting area and total production.[19,20] The Chinese potato cultivars have developed based on the environmental characteristics of regions and industrial needs. Traditionally, cultivars like ‘Kexin-1’ have been the most widely grown for long periods due to their high adaptability.[16,17] Recently, introduced cultivars and their improvements have led the market, such as ‘Atlantic’ for industrial processing due to its high starch content and ‘Favorita’ for fresh consumption due to its high yield.[16,20] Since the “Potato as a Staple Food” policy was implemented in 2015, there has been active development of processing cultivars suitable for making noodles and bread, moving beyond simple fresh vegetable consumption.[19,20] Furthermore, cultivars are strategically developed for different environments, such as the single-cropping regions in the north and winter-cropping regions in the south, with current research focusing on enhancing disease resistance and nutritional value.[16,17] These diverse growing environments may contribute to region-related compositional variation.

2.4. The americas

Potatoes were first domesticated in the Andes Mountains of South America and subsequently distributed worldwide following their introduction to Europe in the late 16th century.[21] In North America, breeding efforts began in the 1850s and led to the establishment of the United States Department of Agriculture (USDA) potato breeding program in 1910.[22] The introduction of the ‘Katahdin’ cultivar in 1932 by public groups became the significant beginning of modern public potato breeding.[22] Since the 1920s, potato production in the United States increased six-fold per unit area, which was primarily due to better management and cultural practices.[22] The United States cultivars were classified into three major types based on their specific uses. Round-white types were utilized for chip processing and the fresh market, with ‘Atlantic’ and ‘Snowden’ serving as industry standards due to their high specific gravity and light chip color. Long-type (Long-white/Russet) potatoes were suitable for French fry processing, where ‘Russet Burbank’ remained popular for over a century despite its late maturity.[22] Additionally, ‘Russet Norkotah’

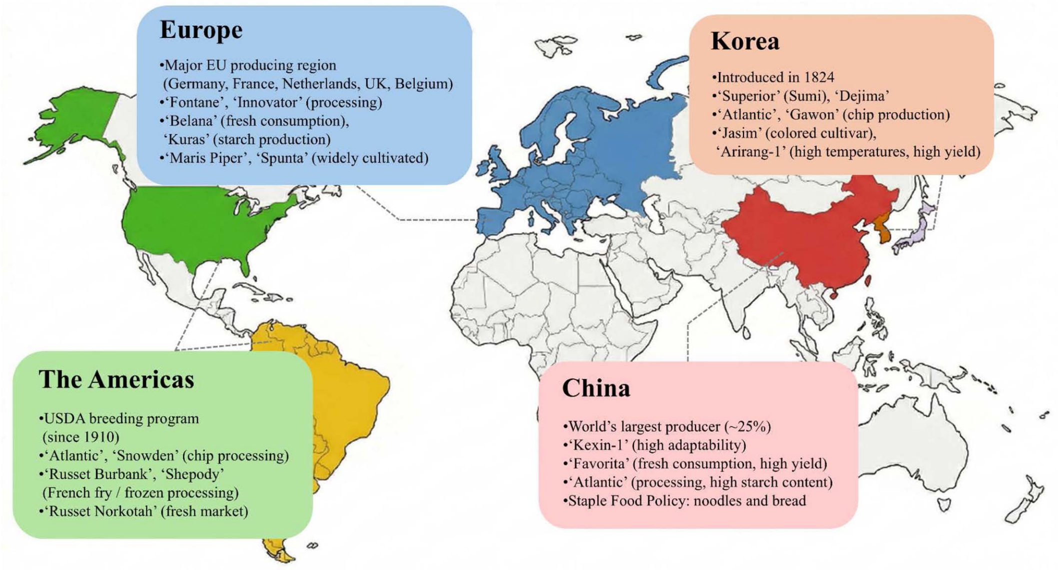

Fig. 1. Regional and cultivar diversity of potatoes.

was noted for its superior tuber-appearance ratings, while 'Shepody' was favored for its high specific gravity in frozen processing.[22] This grouping by end use is relevant because breeding targets may affect compositional and quality traits associated with cultivar classification (*Fig.* 1).

3. Physicochemical Profiling of Potatoes

Generally, potatoes have high water content (75–80 %) and are rich in carbohydrates (16–20 %), dietary fiber, and high-quality protein (2.5–3.2 %). In contrast, they contain only a small amount of fat (0.1–0.2 %).[23] Potatoes are also rich in micronutrients, notably Vitamin C.[24] However, these compositional traits may vary according to cultivar and growing regions, and such variation may be relevant to the classification of potatoes by geographical origin.

3.1. Protein and amino acid composition

Recently, potato protein has gained significant attention because it is allergy-free and has high nutritional quality. As a sustainable and gluten-free plant protein, it is widely used in various food products, such as meat and dairy substitutes for people with special dietary needs.[25] Raw potatoes provide a protein concentration of around 2 g per 100 g.[26]

In Korea, protein and amino acid levels showed distinct differences between cultivars. Kwon *et al.* reported that the crude protein content of five fresh potato cultivars ranged from 1.27 % to 1.64 %, with 'Namseo' having the highest level while 'Superior' and 'Jopung' showed the lowest.[27] The crude protein levels in 23 freeze-dried potato cultivars showed significant variation, ranging from the highest in 'Seohong' (9.07 %) to the lowest in 'Jayoung' (4.90 %).[9] Crude protein content in the freeze-dried powder of major domestic cultivars ranged from 4.13 % to 10.07 %, and specifically, new cultivars such as 'Geumnaru' (10.07 %) and 'Arirang-1' (9.99 %) showed the highest levels.[23] Regarding amino acids, cultivars such as 'Hongyoung' and 'Shepody' exhibited higher levels of glutamic and aspartic acids compared to the widely grown 'Superior'.[9] Essential amino acids such as leucine, threonine, and valine were confirmed as the major components, with the 'Seohong' cultivar showing the highest valine content at 47.8 mg/100 g.[23] In a comparative study, 'Jaseo' exhibited significantly higher levels of phenylalanine (24.1 mg/100 g) and tyrosine (20.8 mg/100 g) than other cultivars.[28] Furthermore, an analysis of potato powder showed that valine levels were highest to lowest in the order of 'Superior', 'Atlantic', and 'Jopung'.[10] These compositions were important factors that influenced flavor formation and browning by reacting with free sugars during high-temperature cooking.[9]

Within Europe, Spanish cultivars from Tenerife showed that methionine levels were the lowest, while leucine and phenylalanine were the most abundant.[29] Specifically, 'Palmera lagarteada' had the highest isoleucine (107 mg/100 g), leucine (156 mg/100 g), and phenylalanine (156 mg/100 g).[29] In particular, 'Colorada de baga' exhibited a total amino acid content of 1,520 mg/100 g.[29]

Regarding Chinese cultivars, a five-year study of nine major potato cultivars showed that average protein levels ranged from 1.67 to 2.43 g/100 g.[30] Processing cultivars 'Atlantic' (2.43 g/100 g) and 'Shepody' (2.35 g/100 g) exhibited the highest average protein content.[30] In addition, Xu *et al.* identified that the new colored cultivar 'Hongmei' contained a high crude protein content of 2.35 %, which was significantly higher than the typical range of 0.6–2.1 % found in many common cultivars.[31] 'Hongmei' also possessed a superior amino acid profile characterized by high concentrations of aspartic acid (23.28 %) and glutamic acid (15.40 %).[31] Among the essential amino acids, it contained significant levels of valine (5.28 %) and lysine (4.51 %), which could effectively compensate for the lysine deficiency in cereal-based diets.[31]

Across South American native species, '*Solanum andigenum*' (7.9 %) and '*Solanum stenotomum*' (8.0 %) showed significantly higher protein contents than the common cultivars grown in the United States.[32] In these potatoes, a major storage protein called patatin made up about 21.5 % to 41.7 % of the total protein, and a higher amount of patatin generally led to a better overall nutritional value.[32] South American cultivars from the Andes also had the highest average levels of lysine and histidine.[32] In particular, '*Solanum phureja*' registered the highest lysine (10.49 g/16 g N) and histidine (5.83 g/16 g N), and even its lower components, methionine (1.26 g/16 g N) and isoleucine (3.09 g/16 g N), were higher than other South American cultivars.[32] Protein and amino acid composition differs among cultivars and growing environment, but common markers have not yet been consistently established across studies.

3.2. Carbohydrate composition

Potatoes contain 13.9–21.9 % carbohydrates, with starch being the primary storage form at 10.2–17.5 %.[33] This variation in starch content serves as the most critical indicator for determining the processing suitability of each cultivar. Specifically, high-starch cultivars are ideal for crispy chips, whereas low-starch, high-moisture types are better for boiling due to their waxy texture.[33] Beyond its content, potato starch is identified by its large granule size and high phosphate content. Compared to cereal starches, potato starch contained lower levels of protein (0.08–1.18 %) and lipids (up to 0.34 %) but is richer in minerals (0.21–1.30 %), making it premium raw material for industrial use.[34]

3.2.1. Starch composition

Lee *et al.* reported that, in Korea, 'Goldenball' exhibited the highest total starch content (39.37 %), followed by 'Haryoung' (34.23 %) and 'Jayoung' (31.30 %).[23] In contrast, the 'Seohong' cultivar exhibited the lowest starch level at 18.91 % among the studied cultivars.[23] An analysis of 9 potato cultivars grown in Italy showed that 'Marabel' exhibited the highest starch content (18.63 g/100 g), while 'Agata' showed the lowest (12.22 g/100 g).[35] Furthermore, Xu *et al.* identified that the new Chinese colored cultivar 'Hongmei' showed a starch content of approximately 10.47 %.[31] This level remained lower than common commercial cultivars, which facilitated its suitability for raw consumption. The United States potato cultivars were bred to achieve high specific gravity and low reducing sugar levels to meet the needs of the processing industry in the mid-twentieth century.[36] The chipping cultivar 'White Pearl' showed the highest amylose content at 31.4 % and the largest starch granule size at 870.3 μm^2.[36] The French fry cultivar 'Russet Burbank' maintained a high specific gravity of 1.090 and an amylose content of 28.8% over a century of production, whereas 'Katahdin', a foundational cultivar for modern breeding, showed a relatively lower specific gravity of 1.078.[36,37] Additionally, 'Kennebec' recorded the lowest amylose content at 25.6 %, and the early-maturing 'Superior' exhibited the most rounded starch granules.[36] Notably, heirloom cultivars like 'Early Rose' (1.090) and 'Irish Cobbler' (1.084) already possessed high specific gravity values similar to those of modern cultivars.[36,37] Starch traits may contribute to cultivar classification, but their direct relevance to geographical origin discrimination remains less clearly established than that of element- or isotope-related variables. This is because potato starch properties are strongly influenced by genotype and growing environment, whereas origin discrimination has more often been supported by elemental and isotopic fingerprints.[2,38]

3.2.2. Free sugar composition

Reducing sugar content varies significantly among potato cultivars and serves as a key indicator of processing quality.[9] High reducing sugar levels during frying cause dark coloration and bitter taste due to the Maillard reaction. Therefore, cultivars with a reducing sugar content of 0.25 % or less are generally considered suitable for processing.[10]

In a study of 23 Korean cultivars, sucrose was found to be the most abundant free sugar.[9] 'Chugang', 'Jowon', 'Dejima', 'Jasim', and 'Hongyoung' showed high free sugar levels of 3.55 g/100 g or more. In contrast, 'Goun', 'Saebong', 'Gahwang', 'Superior', and 'Gawon' exhibited relatively lower levels below 2.50 g/100 g.[9] Lee *et al.* identified that 'Geumnaru' recorded the highest sucrose content (12.85 mg/g), whereas 'Jayoung' showed the lowest (1.67 mg/g).[23] 'Daegwang' had the highest glucose (6.14 mg/g) and fructose (5.95 mg/g) levels, whereas these sugars were not detected in 'Jayoung' and 'Goldenball'.[23] While 'Superior' contains very low sucrose, colored potatoes such as 'Haryoung', 'Jasim', and 'Jaseo' showed higher sucrose levels. In particular, 'Jasim' has also been reported to contain some maltose.[28]

Regarding European cultivars, Galdón *et al.* reported that sucrose was the most predominant sugar among 10 traditional Spanish potato cultivars.[29] In particular, 'Bonita' (9.33 g/kg) and 'Bonita negra' (7.96 g/kg) exhibited significantly higher levels than other cultivars. In contrast, reducing sugar concentrations were generally low in these cultivars. For instance, 'Borralla' and 'Peluca blanca' showed the lowest levels of glucose (0.13 g/kg) and fructose (0.10 g/kg), respectively. Similarly, Finotti *et al.* analyzed 9 Italian cultivars and found that while sucrose was most abundant in 'Marabel' (1.39 g/100 g), reducing sugars such as glucose and fructose recorded their highest levels in 'Arinda' (0.34 g/100 g) and 'Frinka' (0.18 g/100 g), respectively.[35] Overall, Korean potato cultivars tend to exhibit relatively higher levels of glucose and fructose compared to European cultivars.

Furthermore, Zhang *et al.* reported that reducing sugar levels in Chinese potato cultivars ranged from 0.08 to 1.36 g/100 g, with 'Atlantic' exhibiting the lowest level (0.17 g/100 g).[30] The highest total sugar concentrations were found in 'Favorita' (2.54 g/100 g) and 'Jizhang-12' (2.53 g/100 g). Beyond nutritional value, these compositions are key to forming flavor and browning (Maillard reaction) by reacting with sugars during high-temperature cooking.[9]

The free sugar content of United States potato cultivars showed significant variation depending on genetic factors, with 'Kennebec' and 'Fingerling Ozette' recording some of the lowest levels of fructose and glucose.[39] In contrast, 'Yukon Gold' exhibited the highest glucose concentration (34.73 mmol/kg), while large 'Red' potatoes showed the highest fructose levels (33.36 mmol/kg).[39] These differences in free sugar levels served as a key factor in determining browning and acrylamide formation during processing; consequently, modern chipping cultivars like 'Dakota Pearl' and 'Snowden' were bred to include cold-induced sweetening resistance to prevent sugar accumulation during storage.[36,39]

3.3. Mineral and vitamin composition

Cultivars in Korea present significant variations in the mineral content of its potato cultivars. According to Kwon *et al.*, the 'Namseo' cultivar exhibited the highest levels of potassium (16,095 ppm) and magnesium (1,044 ppm), while 'Superior' showed the highest calcium content (455 ppm).[27] In contrast, 'Atlantic' contained the lowest amounts of minerals.[27] Recent research further indicates that calcium levels in 'Jayoung' and 'Geumseon' are approximately twice as high as those in 'Superior', with 'Goldenball' recording the highest magnesium levels.[23] In colored Korean cultivars such as 'Rose' and 'Jasim', potassium accounts for over 90 % of all minerals, contributing to healthy blood pressure.[28] Regarding vitamins, 'Atlantic' recorded the highest vitamin C level (30.2 mg/100 g), followed by 'Namseo' and 'Superior'.[27] Another study reported that 'Superior' contained a high vitamin C level of 110.60 mg/100 g.[23] Vitamin B6 levels in Korean potatoes ranged from 0.61 to 1.09 mg/100 g, with 'Geumnaru' being the highest and 'Jayoung' the lowest.[23]

Europe provides various cultivars from Italy and Spain that demonstrate how mineral and vitamin levels differ by cultivar. In a study of Southern Italian potatoes, 'Everest' contained the highest potassium (3,067 mg/kg) and magnesium (236 mg/kg), while 'Antea' was richest in calcium (132 mg/kg) and 'Valeria' had the highest iron.[40] Additionally, an analysis of traditional cultivars from Spain reported that 'Bonita negra' (1.12 g/kg) and 'Bonita' (0.99 g/kg) contained the highest vitamin C levels, whereas the 'Borralla' cultivar showed the lowest concentration.[29]

China possesses potato cultivars such as 'Feiurita', 'Longshu-7', and 'Qingshu-9' with vitamin C contents ranging from 15.67 to 30.78 mg/100 g.[41] The vitamin C content in Chinese potatoes is influenced by both the cultivar and the growth period; as observed by Sim *et al.*, levels tend to increase during growth, reach a maximum value, and then decrease.[10]

The United States and South America are home to potato cultivars that show significant variation in mineral and vitamin contents based on their genetic backgrounds.[32,39] Among United States cultivars, 'Kennebec' and 'Russet' contained high potassium levels (400–500 mg/100 g), while 'Yukon Gold' exhibited a high iron content of 0.8 mg/100 g and the heirloom 'Fingerling Ozette' recorded 20–25 mg/100 g of magnesium.[32,39] Furthermore, 'Red' potatoes and 'Yukon Gold' from the United States reached high vitamin C levels of 15–20 mg/100 g.[39] Yellow-fleshed and colored cultivars, including those originating from South America, contained higher amounts of vitamin B6 and carotenoids compared to standard white potatoes.[32,36] Although these nutrients show regional differences, they are highly affected by

Table 1. Comparative physicochemical profiles of potato cultivars by geographical origin

Origin	Cultivar	Protein and amino acids	Carbohydrates and free sugars	Lipids, minerals, and vitamins	Reference
Korea	Namseo, Superior, Jopung, Seohong, Jayoung, Geumnaru, Arirang-1, Hongyoung, Shepody, Jaseo, Atlantic, Goldenball, Haryoung, Chugang, Jowon, Dejima, Jasim, Goun, Saebong, Gahwang, Gawon, Daegwang, Geumseon, Rose	- High protein content (Geumnaru, Arirang-1) - High valine levels (Seohong) - Elevated phenylalanine and tyrosine (Jaseo) - High glutamic and aspartic acids levels (Hongyoung, Shepody)	- High starch content (Goldenball, Haryoung) - Low starch content (Seohong) - High sucrose levels (Geumnaru) - High glucose and fructose levels (Daegwang)	- Fat content: 0.13-0.76% (Atlantic) - High unsaturated fats levels (Jopung) - High K and Mg content (Namseo) - High vitamin C content (Atlantic)	[9], [10], [23], [27], [28]
Europe	Marabel, Agata, Arinda, Frinka, Everest, Antea, Valeria, Palmera lagarteada, Colorada de baga, Bonita, Bonita negra, Borralla, Palmera lagarteada, Peluca blanca	- High total amino acids content (Colorada de baga) - High leucine and phenylalanine levels (Palmera lagarteada)	- High starch and sucrose content (Marabel) - High glucose/fructose levels (Arinda/Frinka) - Low glucose and fructose levels (Borralla, Peluca blanca)	- High K and Mg levels (Everest) - High Ca content (Antea) - High vitamin C content (Bonita, Bonita negra)	[29], [34], [41]
China	Atlantic, Shepody, Hongmei, Favorita, Jizhang-12, Feiurita, Longshu-7, Qingshu-9	- High total protein content (Atlantic, Shepody) - Superior amino acid profile (Hongmei)	- Low reducing sugar content (Atlantic) - High total sugar content (Favorita, Jizhang-12) - Low starch content (Hongmei)	- High vitamin C levels (Feiurita)	[30], [31], [35], [40]
The Americas	Kennebec, Russet Burbank, Yukon Gold, White Pearl, Katahdin, Early Rose, Irish Cobbler, Dakota Pearl, Snowden, Fingerling Ozette, Red, *Solanum andigenum*, *Solanum stenotomum*, *Solanum phureja*	- High protein content (*S. andigenum*, *S. stenotomum*) - High lysine and histidine levels (*S. phureja*) - High patatin levels (Andean cultivars)	- High amylose content and large granule size (White Pearl) - High specific gravity values (Russet Burbank, Early Rose, Irish Cobbler) - High glucose/fructose levels (Yukon Gold/Red)	- Low fat content (<0.1 g/100 g) - High K/Fe content (Kennebec/Yukon Gold)	[39], [36], [32]

environmental factors like soil and storage.

3.4. Lipid Composition

Potatoes generally have very low fat content, but crude fat levels still vary by cultivar. In Korea, research showed that crude fat content ranges from 0.06 % to 0.76 %, with 'Atlantic' being the highest and 'Goldenball' the lowest.[23] Kim *et al.* reported that the crude fat content of 23 domestic cultivars was between 0.26 % and 0.38 %.[9] In terms of fatty acid composition, 'Atlantic' showed significantly higher levels of saturated fatty acids, such as palmitic acid (32.2 %), stearic acid (9.43 %), and arachidonic acid (1.8 %), compared to other cultivars. In contrast, unsaturated fatty acids like oleic, linoleic, and linolenic acids were significantly higher in 'Jopung' and 'Shepody', indicating a higher degree of unsaturation.[27] About 60–80 % of potato lipids consist of unsaturated fatty acids, which contribute to the characteristic savory flavor during high-temperature cooking.[25,29] United States potato cultivars are characterized by a very low fat content, typically measuring less than 0.1 g per 100 g of fresh weight, which makes them highly valued as a low-fat food source (*Table* 1).[36,39]

4. Key Volatile Compounds in Raw and Processed Potatoes

The volatile profile of potatoes depends on tuber composition and processing intensity. Raw potatoes mainly contain compounds derived from endogenous metabolism and enzymatic oxidation. In contrast, boiling, baking, and frying shift the profile toward thermally generated volatiles.[42] This transition is analytically significant because potato volatiles reflect not only flavor characteristics but also cultivar, growing region, precursor composition, and processing history.[3,43]

As processing intensity increases, the volatile profile changes clearly (*Table* 2). Raw potatoes are mainly associated with aldehydes, alcohols and selected furans. Boiled potatoes are characterized by the appearance of methional (baked potatoes, bark, caramel, cooked potato, earth) alongside retained native volatiles. Baked and fried potatoes show a broader range of sulfur compounds, pyrazines, and thermally generated aldehydes. This pattern reflects the increasing contribution of the Maillard reaction, Strecker degradation, and lipid oxidation during heating. Several compounds, hexanal (apple, beany, cut grass), nonanal (beany, citrus, cucumber, fat), benzaldehyde (almond, berry, bitter, bitter almond, burnt), phenylacetaldehyde (berry, cherry, floral, flower, fragrant), and 2-pentylfuran (beany, butter, caramel, cream) were detected in both raw and processed potatoes. This suggests that they arise from common precursors and may persist under different heating conditions.

In raw potatoes, aldehydes and alcohols are generally dominant, and selected furans are also detected (*Table* 2). These compounds are primarily associated with endogenous metabolism and the enzymatic oxidation of fatty acids rather than intense thermal reactions.[3] Because heating has not yet strongly transformed the precursor pool, the raw volatile pattern serves as a more direct reflection of genotype and the growing environment.[3] A recent study has shown that potatoes from different cultivars and regions differ significantly in volatile composition and flavor scores.[44] However, the available evidence is still limited, and common volatile markers have not yet been consistently established across studies.

Boiling modifies the native potato volatile profile but does not fully replace it. This process is relatively mild because the aqueous environment limits temperature and reduces severe surface dehydration.[42] Under these conditions, part of the native volatile background is retained, while characteristic heat-derived potato flavors begin to develop (*Table* 2). Methional has been repeatedly identified as a key contributor to the characteristic flavor of cooked potato.[45]

Baking shifts potato flavor much more strongly toward thermally generated volatiles. Dry heat promotes moisture loss and increases the contribution of reducing sugars, amino acids, and lipid-derived precursors. As a result, the Maillard reaction, Strecker degradation, and lipid oxidation are promoted.[46] In baked potato, volatile formation is largely associated with lipid degradation and the Maillard reaction. Sulfur compounds

Table 2. Key volatile compounds identified in raw, boiled, baked, and fried potatoes

Volatile compound	Aroma description[1]	Processing type	Reference
Acids			
hexanoic acid	barnyard, cheese, fat, fecal	Boiled, Fried	[38], [45]
nonanoic acid	burnt, cheese, fat, fecal	Raw, Fried	[3], [38]
octanoic acid	almond, anise, barnyard, carrot	Raw, Boiled, Fried	[3], [38], [43], [45]
Alcohols			
1-octen-3-ol	earth, cucumber, fat, floral	Raw, Boiled, Baked	[3], [43], [45], [46]
3-methyl-1-butanol	balsamic, banana, burnt, cheese	Baked, Fried	[38], [46]
Aldehydes			
(E,E)-2,4-decadienal	coriander, cucumber, deep fried, earth, fat	Raw, Boiled, Baked, Fried	[43], [45], [46], [73], [74]
(E,Z)-2,4-decadienal	fat, flower, fried, green	Raw, Boiled, Baked, Fried	[43], [46], [59], [73]
benzaldehyde	almond, berry, bitter, bitter almond, burnt	Raw, Boiled, Baked, Fried	[3], [39], [43], [45], [46], [73], [74]
phenylacetaldehyde	berry, cherry, floral, flower, fragrant	Raw, Boiled, Baked, Fried	[3], [43], [45], [46], [74]
hexanal	apple, beany, cut grass, fat	Raw, Boiled, Baked, Fried	[38], [43], [45], [46], [73], [74]
nonanal	beany, citrus, cucumber, fat	Raw, Boiled, Baked, Fried	[3], [38], [43], [46], [73], [74]
Ketone			
2-heptanone	acorn, banana, bell pepper, blue cheese, cheese	Fried	[38], [74]
Sulfur compounds			
dimethyl disulfide	cabbage, cooked, garlic, meat, onion	Baked, Fried	[46], [74]
dimethyl trisulfide	cabbage, clove, garlic, meat	Baked, Fried	[46], [74]
methional	baked potatoes, bark, caramel, cooked potato, earth	Boiled, Baked, Fried	[45], [46], [74]
Pyrazines			
2,5-dimethylpyrazine	burnt, cocoa, coffee, grass	Baked, Fried	[46], [74]
2-ethyl-5-methylpyrazine	coffee, earth, fruit, green, nut	Baked, Fried	[46], [74]
2-ethyl-6-methylpyrazine	grass, green, nut, pyrazine	Baked, Fried	[46], [74]
methylpyrazine	burnt, cocoa, green	Baked, Fried	[46], [74]
Furans			
2-pentylfuran	beany, butter, caramel, cream	Raw, Boiled, Baked, Fried	[3], [38], [43], [45], [46], [73], [74]
furfural	almond, baked, baked bread, baked potatoes, bread	Baked	[46]

[1]Aroma character from https://www.vcf-online.nl/VcfHome.cfm

and pyrazines also contribute substantially to the final profile.[47]

Frying generates the most complex volatile matrix among common potato processing methods (*Table* 2). This profile results from severe heating, low surface moisture, and direct contact with hot oil.[48] Under these conditions, Maillard products and lipid-derived volatiles are formed simultaneously and interact strongly in the final volatile profile.[49] Fried potato products are commonly associated with pyrazines, furans, sulfur compounds, and unsaturated aldehydes such as 2,4-decadienal (fat, deep fried, fried, green). This compound is a typical fried-food odorant formed from oxidation of linoleate-derived intermediates.[50] Recent studies also showed that potatoes with different processing properties differed in the proportions of aldehydes, alcohols, furans, ketones, and hydrocarbons.[44] These results indicate that volatile formation is influenced by both tuber composition and processing conditions. Therefore, volatile profiles provide complementary information and have greater utility when used in combination with other compositional or elemental markers.

5. Analytical Approaches for Potato Geographical Origin and Cultivar Discrimination

5.1. Analytical platforms for potato geographical origin discrimination

Potato geographical origin studies have used a wide range of analytical platforms according to the target variables. Proximate or non-volatile components have been examined by conventional physicochemical methods or by LC-MS-based metabolite analysis.[51] Mineral and trace element profiles have been determined by ICP-based elemental analysis, including inductively coupled plasma-atomic emission spectrometry (ICP-AES)[52], ICP-MS[53,54], and inductively coupled plasma-optical emission spectrometry (ICP-OES)[55,56], as well as by flame-based methods such as flame atomic emission spectrometry (FAES) and flame atomic absorption spectrometry (FAAS).[57] Stable isotope ratios have been measured primarily by isotope ratio mass spectrometry (IRMS).[54,55,58] In some studies, site-specific natural isotope fractionation by nuclear magnetic resonance (SNIF-NMR)[55], carbon, hydrogen, and nitrogen analysis (CHN elemental analysis)[56], and attenuated total reflectance-fourier transform infrared spectroscopy (ATR-FTIR)[59] have also been used to obtain complementary compositional or spectral information for geographical discrimination. Together, these approaches capture different layers of potato chemistry, including non-volatile metabolites, mineral and trace elements, stable isotope ratios, and spectral features. Each analytical platform offers distinct advantages depending on the target compounds, with LC-MS-based methods generally suited for non-volatile metabolites, ICP-based techniques for mineral and trace element profiling, and isotope ratio analyses for capturing region-specific environmental signatures.[51-56,58]

For volatile analysis, several extraction techniques have been applied to potato samples, including solvent extraction, solvent-assisted flavor extraction (SAFE)[60], simultaneous distillation-extraction (SDE)[60], and headspace solid-phase microextraction (HS-SPME).[38,47,60] Conventional methods such as SAFE and SDE are effective for isolating volatile compounds, but they often require solvent use and additional concentration steps.[61] In addition, the high temperature used in SDE may degrade thermally unstable compounds and generate artifacts that are not originally present in the sample.[62] These methods are generally more suitable for semi-volatile and high-boiling compounds but less effective for highly volatile and thermally labile compounds.[60-62]

Among these approaches, HS-SPME coupled with GC-MS has emerged as one of the most widely used methods for profiling volatile compounds in raw potatoes as well as in processed products.[3,38] In HS-SPME, volatile compounds are adsorbed onto a coated fiber in the headspace and then thermally desorbed in the GC injector for GC-MS analysis.[61] Because extraction occurs in the headspace, HS-SPME can reduce thermal degradation and artifact formation compared with distillation-based techniques.[62] Accordingly, HS-SPME is particularly effective for low-molecular-weight volatile compounds that contribute to the overall volatile composition.[61,62]

SPME-Arrow was developed to improve conventional SPME. It has a larger sorbent phase and a more stable structure than conventional fibers.[63] Kim *et al.* reported that SPME-Arrow contains about 6-20 times more sorbent phase than conventional SPME fibers.[61] This feature improves extraction capacity and reproducibility. Among commercial coatings, DVB/CAR/PDMS is widely used for volatile analysis because it can recover a broad range of compounds.[64] Its frequent use stems from its ability to extract low- and intermediate-molecular-weight compounds, including aldehydes, alcohols, ketones, acids, and sulfur-containing volatiles.[65] This coating also provided good analytical performance in complex food matrices. Nam *et al.* reported high peak responses, and Min *et al.* reported acceptable analytical performance for DVB/CAR/PDMS SPME-Arrow.[66,67]

These analytical choices directly affect the range and reliability of volatile compounds detected in potato samples. Therefore, standardized volatile profiling platforms are important for improving the comparability of origin- and cultivar-related datasets.

5.2. Compositional and isotope-related analysis for potato geographical origin discrimination

Compositional variables such as starch, sugars, protein, amino acids, and lipids may contribute to potato classification. They may also help explain compositional differences associated with geographical origin. However, in potatoes, these variables are generally more useful as supportive compositional markers than as standalone markers for direct geographical origin discrimination. Therefore, their interpretation is stronger when they are combined with elemental, isotope-related, or volatile data.

Compositional analysis provides a useful starting point for potato geographical origin discrimination.[68] This approach is meaningful because regional background can influence tuber composition before thermal processing.[69] In potatoes, compositional origin studies have mainly relied on elemental and isotope-related variables rather than proximate composition alone.[58] A representative example is the study of organically cultivated potatoes from four macro-regions of Slovenia, namely Alpine, Dinaric, Mediterranean, and Pannonian regions.[70] Opatić *et al.* combined stable isotope analysis of major bioelements with element profiling, including rare earth elements.[70] The Slovenian potato samples were successfully classified according to the four macro-regions, and rare earth elements were identified as major contributors to the model.[70] Proximate compositional traits are typically treated as supportive variables. However, Lee indicated that they may still contribute to geographical classification when combined with volatile profiling and multivariate analysis.[71]

5.3. Volatile analysis for potato geographical origin discrimination

Studies directly addressing potato geographical origin through volatile compounds are still limited. However, available reports indicate that regional variation can be detected from volatile compounds and related chemical variables. This point is important because origin discrimination requires markers that reflect regional background rather than only cultivar-dependent differences. Longobardi *et al.* compared Italian potatoes grown in Sicily, Apulia, and Tuscany (*Table* 3).[2] They reported significant regional differences in 15 volatile compounds and in all isotopic parameters. They also applied discriminant function analysis (DFA), a supervised multivariate method that maximizes separation among predefined groups. Using DFA, both the volatile dataset alone and the combined volatile–isotope dataset achieved 100 % classification. The study also reported a leave-one-out cross-validation accuracy of 91.7 %. This means that each sample was classified using a model built from all

Table 3. Multivariate analytical approaches used for potato geographical origin discrimination

Sample	Analytical method	Volatile analytical method	Discriminant markers	Multivariate analysis	Reference
Potatoes from authenticated sites in the United States and Canada (n=608)	ICP-AES	–	Elemental composition, including K, Mg, Ca, Sr, Ba, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Mo, S, Cd, Pb, and P	PCA, CDA, and DFA	[52]
Potatoes from the Fucino basin and other Italian regions (n=60)	ICP-MS	–	Mg, Cr, Mn, Fe, Ni, Cu, Zn, Sr, Cd, and Ba	LDA	[53]
Three cultivars from three Italian regions over two years	CHN elemental analysis and ICP-OES	–	Carbon, nitrogen, and mineral element composition of tubers and soils	PCA	[56]
Three cultivars from three Italian regions	HS-SPME-GC-MS and IRMS	HS-SPME-GC-MS	Volatile compounds and isotopic ratios	DFA	[2]
Galician and non-Galician potatoes	FAES and FAAS	–	Li, Na, K, Rb, Ca, Fe, Mg, Mn, Cu, and Zn	PCA and HCA	[57]
Five cultivars from five Korean regions	IRMS	–	Stable isotope ratios of C, N, O, and S bio-elements	PCA and OPLS-DA	[58]
Organic potatoes from four Slovenian macro-regions (n=36)	Stable isotope analysis, energy-dispersive X-ray fluorescence spectrometry, and ICP-MS	–	$\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, $\delta^{34}S$, and multi-element profiles, including rare earth elements	MDA	[70]
Potatoes from different cultivars and regions in China (n=18)	HS-SPME-GC-MS	HS-SPME-GC-MS	Volatile flavour compounds and relative odor activity values	PCA and PLS-DA	[3]
Romanian and imported potatoes from the Romanian market (n=100)	ICP-MS and IRMS	–	Multi-elemental and isotopic fingerprints; $\delta^{13}C$bulk, $\delta^{2}H$water, and Sr were identified as key markers	LDA	[54]
Cypriot Spunta and other European potatoes (n=118)	SNIF-NMR, IRMS, and ICP-OES	–	(D/H)II, $\delta^{18}O$, R, and Cu	OPLS-DA	[55]
Two new Korean cultivars from three South Korean locations	Proximate composition analysis and HS-SPME-Arrow-GC-MS	HS-SPME-Arrow-GC-MS	Proximate traits and candidate volatile markers selected by Tukey's HSD test and VIP > 1.0	PLS-DA, LDA, and SDA	[71]

the remaining samples. These results indicate that volatile compounds were not only different among regions but also sufficiently structured to support robust group separation. They further suggest that isotope-related variables can strengthen regional interpretation when used together with volatile data.

A similar regional trend was observed in China under a shared cultivar background. Zhang *et al.* examined the cultivar Qingshu 9 grown in five Chinese regions.[44] This design is meaningful because it reduces cultivar effects and allows regional effects to be interpreted more clearly. The study identified characteristic regional markers, including 2-pentylfuran in Shanxi-grown Qingshu 9, methyl cyclopentane in Yunnan-grown Qingshu 9, and ferulic acid in Inner Mongolia-grown Qingshu 9. It also reported that 3-ethyl-2-methyl-1,3-hexadiene, 2-pentylfuran, cis-2-(2-pentenyl)furan, and 2-(E)-octenal contributed to regional separation. These findings indicate that regional differentiation was driven by specific compounds rather than by broad chemical classes alone. The authors related these differences to environmental factors such as soil pH, sunlight, and moisture. They also suggested that regional differences in flavor precursor metabolism contributed to variation in volatile formation. This interpretation links statistical separation to plausible biochemical and environmental causes. Together, these studies indicate that potato origin discrimination is associated with region-dependent differences in volatile compounds and related chemical variables.

Although common volatile markers for potato geographical origin have not yet been consistently established across studies, Lee reported strong discrimination of new cultivars and proposed several candidate markers, including heptanal, nonanoic acid, hexanal, (E,E)-2,4-heptadienal, benzaldehyde, and (E)-2-pentenal.[71]

5.4. Multivariate statistical analysis for potato geographical origin discrimination

Potato datasets are chemically complex and multidimensional. Therefore, multivariate statistical analysis is important for data interpretation (*Table* 3).[3] PCA and hierarchical cluster analysis (HCA) are unsupervised methods. They are used to examine clustering patterns and sample similarity.[57,58] In contrast, LDA, SDA, PLS-DA, and orthogonal partial least squares-discriminant analysis (OPLS-DA) are supervised methods. They maximize separation among

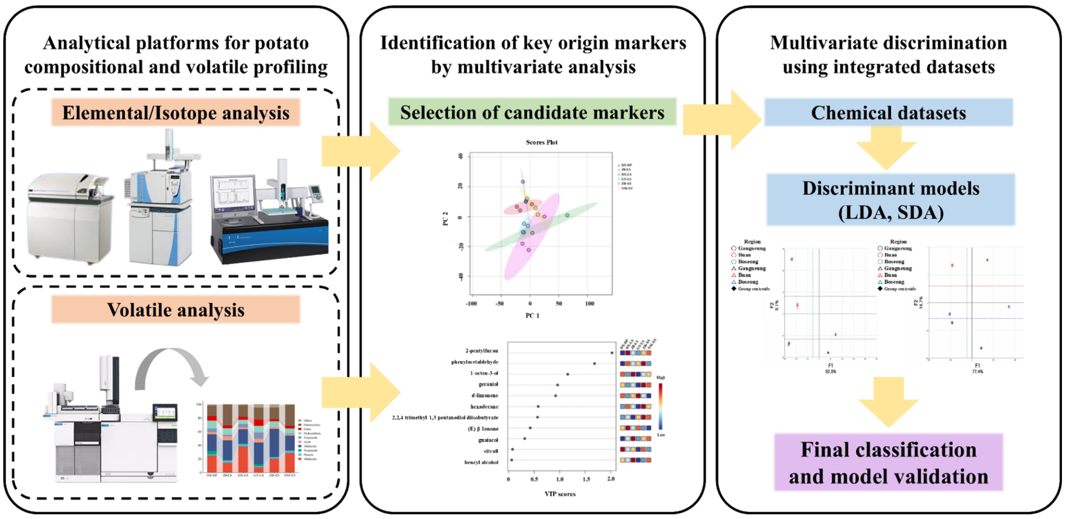

Fig. 2. Candidate markers were selected from volatile datasets using partial least squares-discriminant analysis (PLS-DA) and variable importance in projection (VIP) scores. Final discrimination was performed using linear discriminant analysis (LDA) and stepwise discriminant analysis (SDA). The PLS-DA- and VIP-based marker selection scheme was adapted from [3], whereas the LDA and SDA plots were generated from [71].

predefined groups.[3,53-55,58,71] SDA reduces the number of variables through stepwise selection.[71] OPLS-DA separates predictive variation from orthogonal variation for clearer interpretation.[58] In potato studies, PCA and PLS-DA have been used to compare samples according to cultivar, region, and processing properties.[3] LDA and SDA were also applied to Korean potatoes using proximate composition and volatile compounds.[71] OPLS-DA has been used for isotope-based discrimination of potato cultivation regions.[58] These methods are useful for potato classification (*Fig.* 2). However, supervised models require proper validation to reduce overfitting.[72]

These studies suggest that volatile data alone may be insufficient in many cases. Classification performance is likely to improve when volatile profiles are interpreted together with mineral, isotope-related, or other compositional variables.

6. Conclusion

Potato composition varies according to cultivar, geographical origin, and growing environment. These differences are reflected in proteins, amino acids, starch, sugars, minerals, lipids, and volatile compounds. They also influence processing suitability and final product quality. Raw and processed potatoes differ markedly in volatile profile. Raw potatoes are more closely associated with aldehydes and alcohols, whereas baked and fried products contain larger amounts of sulfur compounds, pyrazines, and thermally generated aldehydes. Current studies indicate that compositional and volatile traits can support potato classification. However, the reported patterns are not yet sufficiently consistent to define universal markers across studies. In particular, evidence for volatile-based geographical origin discrimination in potatoes remains limited, although several recent studies have reported promising candidate compounds. Among the reported variables, stable isotope ratios ($\delta^{13}C$, $\delta^{15}N$, and $\delta^{18}O$) and elemental profiles currently provide the most reliable markers for geographical origin discrimination. In contrast, several volatile compounds, including hexanal, heptanal, nonanal, benzaldehyde, (E,E)-2,4-heptadienal, and 2-pentylfuran, appear to be among the most consistently reported candidate markers. However, their discriminative power varies depending on cultivar, environmental conditions, and processing factors, and no universal marker has yet been consistently established across studies. Element- and isotope-related variables currently provide more direct support for geographical origin discrimination. Overall, potato classification is likely to improve when volatile, compositional, and isotope-related data are interpreted together rather than separately. Future studies should include larger sample sets, wider regional coverage, and more standardized analytical conditions. These efforts will improve comparability across studies and strengthen the analytical basis for potato origin and cultivar classification.

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