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Geo-Authentication of Indian *Moringa oleifera* Using AI and Soil Mineral Analysis: Concepts, Current Evidence, and Future Directions

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Abstract: Intrinsic chemical fingerprints (ICPs) enable geo-authentication of plant-based foods in a manner that will enable traceability, fraud prevention, and support origin-related quality assurance claims. Moringa oleifera is a plant-based food/superfood (technically a functional food) which is highly nutritious, a native plant to the Indian subcontinent, and extensively cultivated and exported by India. Despite this, there have been no scientifically validated methodologies pertaining to the verification of the geographic origin of Moringa oleifera. This review aims to describe and present the existing literature on the conceptual frameworks, soil mineral signatures, artificial intelligence (AI) geo-authentication techniques, and geo-authentication of M. oleifera from India, particularly the geo-authentication of Indian M. oleifera from India. Artificial intelligence (AI) geo-authentication techniques, soil mineral signatures, and geo-authentication of Indian M. oleifera from India have been the focus of this review. The interrelations of soil geochemistry, soil minerals, climate, soil mineralogy, and planting and cultivation (farming) practices establish region-specific stable elemental and isotopic and metabolome signatures. These signatures may be elucidated by employing an array of analytical methodologies (e.g., ICP-MS, XRF, spectroscopy, stable isotope ratio analysis, and untargeted metabolomics). There is ample evidence of similar crops (e.g. spices, tea, rice, grapes) indicating that origin classification from multiple geo-graphical zones is theoretically derived from the fusion of Machine learning (ML) and multivariate analytical techniques (MVA) to achieve elevated classification precision (e.g. Principal Component Analysis (PCA), Partial Least Squares Discriminant Analysis (PLS-DA), Support Vector Machine (SVM), and Random Forest (RF). There is a relatively great deal of literature pertaining to Moringa, from which there exist documented considerable differences in mineral and metabolite compositions from single localized sampling points. However, there exists a considerable gap in systematically obtained geo-referenced data from Indian locations. The review elucidates important gaps in research and suggests next steps like nation-wide soil–plant sampling, data fusion, AI model building, field-deployable tools, and digital traceability system integration. The trust of consumers can be augmented, regulatory requirements can be met, and zone-based branding can be achieved, along with the strengthening of the sustainability and competitiveness of India's Moringa sector by establishing a science-based geo-authentication framework for Indian Moringa oleifera.
Keywords: Moringa oleifera, geo-authentication, soil mineral fingerprinting, elemental analysis, stable isotopes, metabolomics, machine learning, food traceability, India.

I. INTRODUCTION

Moringa oleifera (drumstick tree) is a nutrient-rich superfood native to the Indian subcontinent. Its leaves and seeds are high in minerals (especially calcium and potassium), vitamins and bioactive compounds, and are widely used in powders, teas, oils and snacks. India is a leading producer and exporter of Moringa products, so verifying the claimed Indian origin ("geo-authenticity") is important for consumer trust, quality assurance and regulatory compliance (e.g., EU novel-food rules). Unlike documents or labels, geo-authentication uses the intrinsic chemical fingerprint of the plant (elements, isotopes, metabolites) to confirm provenance. This fingerprint arises because soil composition, climate and farming practices vary by region, and plants absorb soil minerals into their tissues.[1]. Ensuring that a "Punjab Moringa" or "Tamil Nadu Moringa" truly comes from its claimed region can protect honest farmers, validate nutritional claims, and prevent fraud (e.g., mixing with other species or foreign-origin material). This review examines the conceptual basis of geo-authentication, the chemical and analytical methods used (including AI models), existing studies relevant to Moringa, and future directions specifically for Indian *M. oleifera[2]*.

A. Soil Geochemistry as a "Fingerprint."

Soil naturally contains a unique mix of macro- and micro-elements and isotopes that depend on parent rock, climate, topography and farming practices. For example, soils over limestone bedrock will be rich in calcium, whereas those from volcanic terrain may have elevated trace metals. These geochemical profiles become imprinted in plants. In viticulture (grapes/wine) and other crops, studies have shown that "the geochemistry of [vineyard] soil plays a fundamental role" in what elements end up in the fruit. Likewise, Laureano *et al.* (2026) demonstrated in Portuguese vineyards that soil elemental properties and agricultural factors are "mirrored in agricultural products," creating a unique elemental fingerprint characterizing each terroir. In other words, the combination of elements taken up by the plant reflects its soil of origin.[3].

Because Indian agro-climates are diverse (from arid Punjab to wet Kerala), the soil mineral composition can differ markedly from one state to another. Mapping these differences – for example, higher calcium or rare-earth elements in certain Indian soils – sets the stage for region-specific Moringa fingerprints. Portable X-ray fluorescence (XRF) surveys or ICP-MS scans of Indian soils would likely reveal distinct element patterns that could later be traced in plant tissues.

B. Soil–Plant Mineral Transfer

Plants absorb elements through roots and mobilize them to leaves and seeds. Although uptake efficiency varies with plant physiology and soil chemistry (pH, organic matter, etc.), many studies document that plant elemental composition partly reflects soil content. For instance, a study on Chinese tea (Anji Baicha) combined soil and leaf analyses: they found strong correlations ($R^2>0.5$) between key element levels in tea leaves and those in the corresponding soils for elements like Rb, Mn, Pb, Mg and K. In that study, mineral profiling by ICP-MS/OES allowed a Support Vector Machine (SVM) model to correctly classify tea origin (94.9% train, 92.7% test accuracy) and identified Mo, Cu and Rb as the best geographic markers[4].

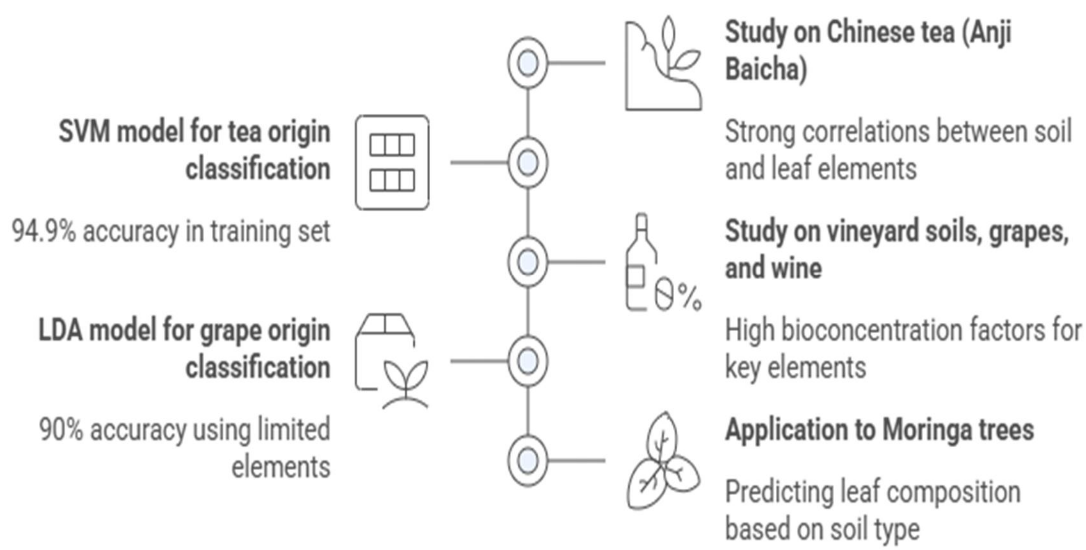

Figure 1: Conceptual representation of soil–plant mineral transfer and its application in geo-authentication.

In a similar study, Mousavi et al. (2022) analyzed the soil, grape, and wine samples from six regions in China and obtained the soil→grape bioconcentration factors for some selected elements. These include potassium (K), magnesium (Mg), zinc (Zn), rubidium (Rb), strontium (Sr), and barium (Ba), which showed high transfer. An LDA model based solely on the elements K, Sr, and Li classified the region with over 90% success. These studies exemplify the soil – plant transfer paradigm. The distinctive soil trace element and isotopic signatures (e.g., 87Sr/86Sr) provide a fingerprint to the plant tissues. In the case of Moringa, we hypothesize that trees cultivated in calcareous soils would be characterized by high concentrations of leaf calcium (Ca). In contrast, those cultivated in other soil types would be characterized by high concentrations of strontium (Sr), rubidium (Rb), and possibly other trace elements. The multi-element profile of leaf or seed powder provides a 'chemical snapshot' of the soil[5].

C. Chemical and Isotopic Profiling of Moringa

Spatial elemental analysis of Moringa can be done using the soil-derived fingerprint with the following methods:

1) Elemental Analysis: XRF and ICP-MS/OES are examples of techniques that can be used to assess dozens of macro (e.g., Ca, Mg, K) and trace elements (e.g., Fe, Zn, Sr, Rb, rare earth) found in leaves or powdered samples. These elements remain through the drying/powdering process. An example is an XRF study that was done on Chinese prickly ash (a spice), where the elements K, Ca, Mg, Sr and others (P, S, Fe, O, Si) were found to be the top elements that discriminated the region; with this alone, SVM was able to achieve 100%C on origin classification. We anticipate M. oleifera to have the same regional variability in its elemental composition. While published compositional studies have mentioned Moringa's Ca composition to be 1.3–2.6% (1320–2645 mg/100g) in leaf powder from Ethiopia, it has also been shown to have considerable amounts of K and Mg. Within a uniform region of Pakistan, Afzal et al. (2019) found significant variability among sites with respect to leaves Na, K, and Mg, where the range was (1.26–2.58%); whereas, Ca was consistently high (around 2.1–2.6%) and did not significantly differ. This implies that while it is likely that Moringa has a universal enrichment of Ca, the elements K, Na, and Mg are likely to show a greater variance among different geographical regions[6].

2) Stable Isotope Ratios: Geographic attribution studies employ powerful isotopic systems like radiogenic strontium (^87Sr/^86Sr), nitrogen (^15N/^14N = δ^15N), carbon (^13C/^12C = δ^13C), deuterium (^2H/^1H), and oxygen (^18O/^16O), as well as others. δ^13C shows the rainfall biomarker/aridity, while ^87Sr/^86Sr mirrors bedrock. Moringa studies incorporating the use of isotopes are sparse, but similar studies are common with crops and tea. In one of the tea studies conducted in China, δ^13C, δ^15N and δ^18O, alongside multivariate statistics, were used to evaluate the tea's origin. In general, isotopes mixed with other elements show improved discrimination. Given our background, we expect a range of isotopic signatures in Moringa leaves from various Indian growing regions differing in precipitation, sunlight, and soil. Analyzing isotopes using a gas source IRMS (Isotope Ratio Mass Spectrometer) should be conducted during future research[6].

3) Spectral fingerprints: Scanning solid and powdered leaves using spectroscopies such as NIR, Mid-IR, Raman, or LIBS is non-destructive and can be done rapidly. Scanning Solid and powdered leaves using NIR, Mid-IR, Raman, or LIBS is non-destructive and can be done rapidly. They provide a wide range of chemical fingerprints. They are notably less specific than elemental analysis, but are still able to tell matrix differences. FTIR and chemometrics were used to identify the authenticity of Moringa seed oil, as well as to identify the presence of other seed oils. NIR and hyperspectral scanning of Moringa leaves and seed oil can capture the presence of oils and water bonded to other chemical structures. The use of portable XRF and FTIR tools allows field-based measurements.

4) Metabolomic Profiles (Organic Compounds): Organic metabolites (e.g., flavonoids, glucosinolates, vitamins, and fatty acids) have been documented using (LC-MS/MS, GC-MS, and NMR). Compounds can be impacted by one's genetic composition and their environment. Recently, a multi-country study (Ceci et al., 2024) conducted untargeted LC-MS analyses of leaf extracts from 9 locations (India, Mexico, the UK, Colombia, Reunion, Fiji, and others). PCA/PLS-DA samples by country, for example, UK commercial powder and Colombian samples, clustered metabolically, separate from all the others, and for cryptochlorogenic and neochlorogenic acids and other mass key discriminating metabolites, included when varied strongly by place of origin. No significant differences were observed across the origins when tested for overall antioxidant capacity. The dataset suggested a shift in specific bioactive molecules depending on origin. Observable metabolomic changes demonstrate a geographic signal. Common-garden studies show that the plant's origin (previous environment and genetics)[7].

Data integration is often used in practice: combining elemental and metabolite profiles produces a higher-dimensional fingerprint. One can synthesize a dataset from ICP-MS elemental data and LC-MS metabolomics. The latest chemometrics can process this sort of multimodal dataset and capture both soil-driven elemental signatures and plant-driven organic signatures. Generally, elemental and isotopic signatures serve as anchors for soil fingerprints, and metabolomic and spectral signatures serve as anchors for plant fingerprints. Together, they form a geo-fingerprint[8].

II. MACHINE LEARNING MODELS FOR ORIGIN CLASSIFICATION

The previous datasets' richness and high dimensionality call for multivariate and machine learning (ML) approaches. For visualization and exploration of patterns, unsupervised methods, such as principal component analysis (PCA) and hierarchical clustering, are often used. In contrast, for origin predictions, supervised classifiers, such as partial least squares discriminant analysis (PLS-DA), support vector machine (SVM), Random Forest, and neural networks, are deployed. Typical methods are as follows.

Principal Component Analysis (PCA) is used to compress data into a smaller set of orthogonal components that account for the most data variance. Generally, origin clustering is often illustrated in PCA scatter plots. In the metabolomics study of Moringa, PCA and

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PLS-DA scatter plots showed that the UK samples were isolated from the rest. In contrast, samples from Reunion and Fiji made a separate group. These scatter plots made it easier to see the different clusters.[9].

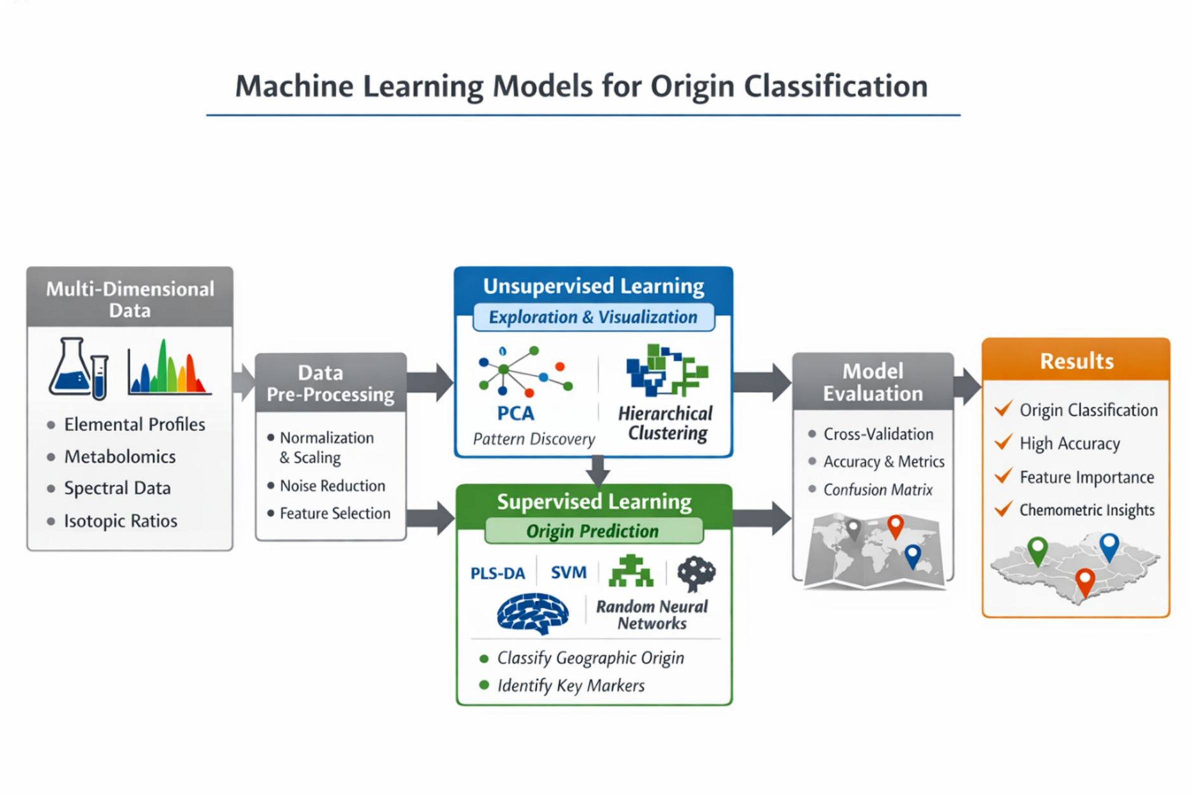

Figure 2: Schematic representation of unsupervised and supervised machine learning approaches applied to multi-dimensional chemical and spectral datasets for accurate geographic origin classification

Partial least squares discriminant analysis (PLS-DA) and OPLS-DA: These approaches use supervised methods to identify latent structure components that maximize the discrimination between a set of pre-defined classes (e.g., region labels). In the study of Anji tea, OPLS-DA was used following SVM and stated that Mo, Cu, and Rb were the most important to differentiate the Chinese provinces. In food traceability, PLS-DA is extensively applied as it is able to cope with collinearity and offers variable importance.
Support Vector Machines (SVM): SVM classifiers, which can capture complicated non-linear boundaries via kernel tricks, are frequently used and have high success in the origin studies for SVM. For instance, Zhang et al. (2023) stated that SVM attained 100% success in the classification of Chinese prickly ash spice samples with respect to region (using XRF elemental data). Similarly, SVM was also the leading performer in studies pertaining to the origin of rice: Saeed et al. (2022) applied ^1H-NMR metabolomics of white and brown rice and reported that SVM was able to obtain 99-100% success (Korea vs China). In the case of Anji tea, SVM obtained around 94 to 95% success as well. It also provided confidence measures and performed well with high dimensions.[10].

Random Forest (RF) and Tree Ensembles. RF consists of an ensemble of decision trees. It has built-in protection against overfitting and offers metrics for feature importance. In the XRF spice study, RF classified the most discriminant elements (K, Sr, C, Ca, P, S, Fe, O, Mg, and Si), which corresponded to the elements that PCA identified. These two methods (RF and gradient boosting) are widespread in their use because of their ability to withstand a high number of input features (elements or wavelengths) and their ability to capture complex interactions.[11].

Other Methods: These include Linear Discriminant Analysis (LDA), k-Nearest Neighbors, and a variety of models for Artificial Neural Networks (including deep learning) and Bayesian models. LDA, for example, reported 100% cross-validation accuracy for the study of isotopes in Chinese tea. In most cases, researchers use several algorithms and test them against cross-validation or hold-out testing to determine the best one for their data.[12].

During standard workflows, data is divided into two sets: training and test. Models are constructed and evaluated on the withheld samples (possibly via k-fold cross-validation). Performance is measured with metrics such as accuracy, confusion matrices, and ROC curves. Practitioners often begin with PCA / PLS-DA to visualize and simplify the dimensions before performing the final classification with SVM or RF. There is a widely accepted sequence of steps to be followed. (1) Collect geo-tagged samples. (2) Prepare multi-element, metabolite, and isotope data sets. (3) Preprocess the data sets (normalization and scaling) and reduce the number of features. (4) Use PCA to examine the data and identify groupings. (5) Construct the first iteration of the supervised models (PLS-DA, SVM, RF, etc.). (6) Validate the models using cross-validation and implement blind tests[13].

III. STUDIES ON COMPARATIVE GEO-AUTHENTICATION

Numerous proof-of-concept studies conducted on alternative food items have demonstrated the ability to identify the location of production using a combination of machine learning with elemental and metabolomic profiling. The following are representative examples.

Product / Study	Data Type	Analysis Methods	Outcome / Notes
Chinese prickly ash (spice)	XRF elemental (K, Ca, Mg, etc.)	PCA, PLS-DA, SVM, RF	SVM achieved 100% accuracy in region classification; RF identified the top 10 elements (K, Sr, C, Ca, P, S, Fe, O, Mg, Si) contributing most to differentiation.
White & brown rice (Korea vs China)	^1H-NMR metabolomics	PCA, PLS-DA, SVM	SVM best model: ~99% accuracy for white rice, 96% for brown in cross-validation; external validation accuracy 100% for both.
Anji Baicha tea (China)	ICP-MS elemental soil & leaf	OPLS-DA, SVM	SVM achieved 94.9% (train) and 92.7% (test) accuracy for authentic vs non-; OPLS-DA identified Mo, Cu, Rb as key geographic markers; strong soil–tea correlations for Rb, Mn, Pb, Mg, K.
Moringa leaves (multi-country)	LC-MS/MS metabolomics	PCA, PLS-DA	Samples clustered by origin (UK powder and Colombian samples formed distinct groups). Cryptochlorogenic/neochlorogenic acid isomers, rutin, and glucomoringin were among the metabolites varying with location. Total antioxidant capacity was similar across origins.

These illustrations highlight the successful ML origin classification coupled with rich chemical data. They also indicate that the type of data (elemental, metabolic, spectral) can be tailored to the particular product and its intended purpose. For example, Teixeira et al. avoided sample prep by using XRF for spices, while Saeed et al. used NMR for rice to circumvent the need for derivatization. Ceci et al. used LC-MS to analyze the unique metabolites of Moringa.[14].

A. *Recent Studies on Traceability of Moringa*

There is insufficient research on the geo-authentication of M. oleifera in India. The majority of studies involving Moringa are on nutrition, varietal chemistry, or adulteration, not on geographic origin. Current research in this area is summarized in the following points:

1) Mineral and Nutritional Analysis: There are studies analyzing the mineral and proximate content of Moringa in a single location. Most of these studies indicate the presence of very large amounts of calcium and considerable quantities of other constituent elements like Mg, K, Fe, etc. Gebregiorgis (2015), for example, analyzed Ethiopian leaf powder and reported the presence of Ca, K, and Mg in the following quantities per 100 g: Ca 2016–2620 mg, K 1817–1845 mg, and Mg 322–340 mg. Other studies reported similar findings; however, those studies did not analyze the same Ethiopian leaf powder. Afzal et al. (2019) analyzed the leaves of Moringa from 3 Pakistani districts (having similar climate) and reported site-to-site variation in Na, K, and Mg; however, they found no considerable or significant difference in the presence of Ca (2–2.6%) in the various sites. He, however, noted that the "local factors, even within the same ecological zone, are important in determining nutrient composition. This means that even though the presence of calcium would be considerably high, other elements would be low or negligible, depending on the site. These studies indicate that the mineral content of Moringa is the result of a combination of factors such as the genetics of the plant and environmental factors. The latter, as suggested, is critical in geo-fingerprinting[15].
2) Species Authentication: Confirming species' authenticity and identity is emerging as a critical need. A 2024 study (Sahi et al.) using traditional PCR showed that a variety of "Moringa" marketed products currently sold in EU commerce are 'impure' and

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are sold as mixtures with M. stenopetala (from Africa) and other Moringa species. The authors created a duplex PCR test with M. oleifera and other species targeting plastid markers. This response may begin to address some of the issues of species purity (a significant initial element); however, it fails to address the issues of the geography of the entity. It does, however, illustrate that fraudulent (mislabeling by species or adulteration) problems exist, which reinforces the need for chemical traceability to address this issue.

3) Variation of Metabolomics by Origin: The only study published to date that examined differences in Moringa by origin is the multi-country metabolomics study by Ceci and colleagues (2024) described above. The study noted different sample groupings/clusters by country and unique metabolites for specific origins. Among the samples, the UK (commercial powder) and Colombia were noted to be well separated from the other sample groupings. Concentration of metabolites and other Moringa metabolomics studies have focused on singular topical country agronomic (fertilizer or processing) differences, not geographical differences.
4) Phytochemical Screening: The Use of NMR and LC-MS to Catalog and Classify Moringa Bioactives (e.g., flavonoids, glucosinolates, fatty acids, etc.) with respect to cultivar or cultivation treatment differences. Most of these studies create reference libraries but do not relate these libraries to any geographical area. One could use some of the existing compound databases (e.g., Moringa) for rutin or chlorogenic acid to determine the existence of region-specific compounds. Still, the literature has not been compiled with geographical references. There is clearly a research gap: no detailed survey has integrated the sampling of Moringa leaves (and associated soils) from different states of India and analyzed them for geo-markers. The enormous agro-ecological diversity of India (Punjab vs Kerala vs Gujarat, etc.) suggests different and unique soil and climatic conditions impacting Moringa, but this is not documented. Within India, there are no published studies on Moringa regarding soil-plant transfer, or even on Indian geo-referenced data, or any machine learning models. Therefore, the geo-authentication of Indian Moringa is a promising yet unexplored field.

IV. NUTRITIONAL AND FUNCTIONAL IMPLICATIONS OF ORIGIN

Moringa is highly regarded for containing a wide range of nutrients and various phytochemicals such as calcium, vitamins, and antioxidants. Therefore, it is reasonable to hypothesize that the origin may have a subtle influence on these attributes.

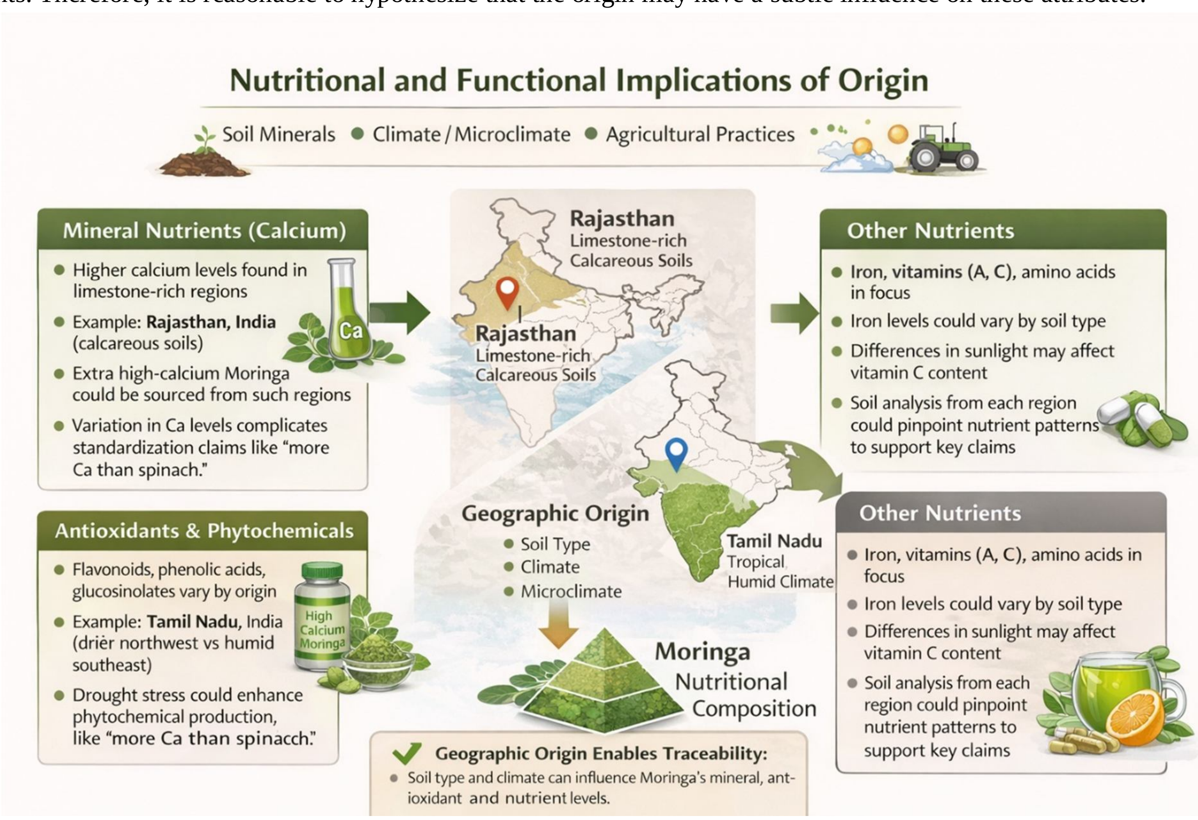


Figure 3: Schematic illustration showing how geographic origin, through variations in soil minerals and microclimate, can modulate mineral nutrients, antioxidants, and other functional components in Moringa leaves.

1) Mineral Nutrients (e.g., Calcium): Moringa marketing frequently mentions Moringa as a “high calcium” food. In an Ethiopian study, Ca in Moringa leaves was ~1.3–2.6%. Even in this single study and region, Ca values in Moringa leaves varied greatly (one sample 2645 mg/100g Ca vs another 1322 mg). Afzal et al. reported a similar situation with another Pakistani site where Moringa leaves contained 2.645% Ca (2645 mg/100g) and a different site with 2.164%. These variations may indicate that soils with a higher bioavailable Ca, like the limestone-rich area, are likely to grow “extra high-Ca Moringa.” For functional food products (e.g., Ca-fortified Moringa snack), harvesting from these limestone-rich soil areas may result in more Ca-fortified Moringa products. However, if “Calcium” is a marketing term stating “more Ca than spinach,” the geo-variability of Moringa leaves would give marketing a headache. A comprehensive sampling of the Indian subcontinent could answer the question of whether a state like Rajasthan (with calcareous soils) has Moringa leaves with a more significant Ca concentration than a state like Kerala.
2) Antioxidants and Phytochemicals: The presence of vitamins and other phytochemicals such as glucosinolates (glucomoringin), phenolic acids (chlorogenic acids), quercetin, and kaempferol (both flavonoids) in the leaves of Moringa contributes to the antioxidant activity of the leaves. In the multi-origin metabolomic study, the presence of cryptochlorogenic and/or neochlorogenic acids and rutin varied strongly based on geographic region. The study also mentioned, however, that the antioxidant capacity of the extracts was no different regardless of origin. This suggests that the specific profile of individual antioxidants was different and was likely due to microclimates or variations in the soil’s nutrients. The overall antioxidant capacity was reasonably comparable across geographic regions. It is well known that certain secondary metabolites are enhanced by environmental (drought, soil nutrients, UV) stress. In Moringa, varying rainfall or temperature will likely affect the levels of flavonoids. Drought stress, for example, is known to increase the presence of flavonoids in certain plant species. If the northwestern region of India is drier than Tamil Nadu, we might see slight variances in the spectrum of antioxidants present in Moringa[16].
3) Other Nutrients (e.g., Fe, Vitamins, Amino Acids): The phrases, ‘more iron than spinach’, ‘high in vitamin A', and alike, are vague. If the origin affects mineral uptake, levels of iron or zinc may differ due to the soil. Likewise, the plant’s genetics, plus the amount of sunlight, may affect the levels of vitamin C or β-carotene. There are no comparative studies to date. For future studies, it would be beneficial to analyze the levels of Ca, K, Mg, Fe, provitamin A, protein, and glucosinolates in the leaf powders of Moringa. India has several major growing regions for Moringa. If the nutrient data were correlated with soil data, it would be possible to make statements such as, ‘In this region, Moringa has, on average, 20% more iron.’ It is best to operate with the assumption that geo-authentication provides a primary level of traceability, and any nutritional differences may be more speculative than actual, or more like a guarantee that the batch meets the nutritional claim described in the text[17].

Geographic origin could affect the nutritional values of Moringa, but we need more data to show this. What is most important is that geo-auth indicates traceability concerning such nutritional aspects. For example, ‘This Moringa in this snack bar is from X plateau, which is well-known for the high calcium content.’ Without geo-auth, producers must rely on supply chain documents, which may be falsified. A geo-fingerprint provides the basis for any regional branding or health claim.

V. APPLICATIONS AND FUTURE DIRECTIONS

The development of dependable geo-authentication of Indian Moringa would be advantageous for various stakeholders.
1) *Industry and Brands:* Companies specializing in food and nutraceuticals would be able to sell Moringa products that are specific to particular geographical regions (similar to how companies sell “single-estate” tea or wine). They would be able to sell products at a higher price and gain the trust of consumers with labels of verified origins (for example: “Moringa from Kerala backwaters”). Companies would be able to test the quality of their incoming raw materials, as portable XRF or NIR analyzers that are customized to specific regions can be used to detect raw materials from regions outside of the “Indian” label that are inconsistent with Indian raw materials. Primary evidence of geo-authentication would be useful in meeting compliance for various export regulations (for example, the EU may require evidence of traceability to meet the criteria for novel food clearance or Geographical Indication (GI) applications). If the Moringa industry in India establishes a brand image for its products as ‘region of origin,’ then science-based geo-authentication would strengthen that brand image[18].
2) *Regulators and Certification:* Food safety and standards authorities may consider geo-authentication to combat fraud. Like olive oil and honey, market samples tested at random may show origin mismatches. For example, a powder labeled ‘India’ may be confiscated if it deviates from the elemental patterns of any Indian soil. Institutions, such as the Agricultural Research Institute and the GI (Geographical Indications) registry, may develop “reference” databases of geo-tagged elemental/isotope profiles for Moringa. Although India currently does not possess a GI for Moringa, this technology may help establish one.

Organic or fair-trade certifiers may consider geo-fingerprinting to authenticate that the laboratory data corroborate the claimed sources[19].

3) *Farmers and Rural Communities:* Farmers are likely to benefit from the validation of their regional identity. With a recognized label as \\"Punjab Moringa,\\" farmers from Punjab could form cooperatives to manage quality and gain bargaining power. Knowledge of soil signatures could lead to agronomic practices that manage and improve specific desirable nutrients. For example, if soil tests show low availability of Fe, farmers could apply Fe-enriching amendments to improve the iron content of leaves, and verify this through geochemical analysis. On the other hand, if it is proven that a specific geographic area consistently produces Moringa with higher nutrient content, farmers could use this as leverage when negotiating with customers. Geo-authentication could essentially value test traceability for smallholder farmers, as they would possess scientific evidence of the origin of their product, rather than just documents.
4) *Research and Data Infrastructure:* For all of this to happen, there is a need for a more focused type of research. The most immediate priorities are:

a) Systematic Sampling: In India\'s principal Moringa producing regions (Gujarat, Maharashtra, Karnataka, Tamil Nadu, Punjab, West Bengal, etc.), and across different management practices (organic vs. conventional) and seasons, collect paired soil and Moringa leaf/seed samples. Capture geo-referenced agronomic data.
b) Building Comprehensive Databases: plants and soils profiles for multi-element (ICP-MS or XRF) geo-chemical analysis and stable isotopes (δ13C, δ15N, δ18O, 87Sr/86Sr, etc.), along with metabolites (LC-MS/NMR) analysis, should be undertaken to quantify Calcium, Potassium, Iron, vitamins, and glucosinolates. Also, building a geochemical and metabolomic database correlated with specific geospatial locations will be essential.
c) Machine Learning: Origin classifiers, using geo-spatial ML databases, should be trained according to industry standards, including training/testing splits, cross-validation, and blind samples. Algorithms should be chosen based on the best practices for the analysis, e.g., PCA/PLS-DA for insight, SVM/RF for prediction, etc. Collaborate with other laboratories to strengthen inter-laboratory studies and reproducibility. An open reference database with industry-standard ISO methodologies for regulatory and industry use would be ideal.
d) Tools for the Field: Rapid response tools require the development of new calibration models. For example, Rapid field-testing devices like NIR or handheld XRF (“smartphone for soils”) could be trained on lab data to improve quality control (processing facilities).
e) Blockchain and Traceability Chains: Combine geo-authentication data with blockchain. Each batch of Moringa powder should be tagged with an authenticated origin fingerprint on a blockchain to provide retailers and customers with the ability to scan a QR code and authenticate the product source.
f) Integration with Genomics: Considering the genetic marker-chemical fingerprinting merger proposal, the locally adapted M. oleifera varieties may perhaps contain specific DNA variants, and the incorporation of genomics (such as SNP markers) with elemental profiles may improve differentiation accuracy across neighboring regions.
g) Remote Sensing Correlation: Determine the extent to which satellite-derived metrics (e.g., Soil type maps, Vegetation Indices) improve the value of ground data. For example, some geomorphic/tectonic units, which are sometimes visible from satellites, are known to contain high-calcium soils.
h) Future Research Needs: Since India is the leading producer of Moringa and with the increasing value of ‘traceable superfoods’, there is a need for grant funding and the formation of interdisciplinary teams among agronomists, chemists, and data scientists. Several research questions emerge: What is the variability in soil element profiles among Indian states? Which elements or metabolites are the best for differentiating regions within India for Moringa, and do nutritional claims (e.g., “high-Ca region”) vary? What is the least number of markers to achieve >95% classification success across all the major regions? Addressing these questions will make geo-auth a viable concept.[20].

VI. CONCLUSION

The geo-authentication of Indian Moringa oleifera, having the potential to enhance the value of the product through chemical fingerprinting, is still at an early stage. Extensive research in other foods has established that the signatures of soil minerals are incorporated into the tissues of plants and can be reliably detected by modern analytical and AI-based techniques.

Current research confirms that the mineral content of Moringa leaves is unevenly distributed across different locations and that the leaf metabolome has spatial signatures. Machine learning techniques such as PCA, PLS-DA, SVM, and RF, among others, have demonstrated high accuracy in the classification of the origin of analogous crops. The primary disadvantage of Indian conditions is the lack of data: M. oleifera requires extensive systematic sampling and modeling throughout India.

The development of authenticated origin databases will enhance traceability for exporters, regulators, and farmers. One would utilize validated AI models to predict the origin state of certain unknown samples based on measurable attributes (and possibly isotopes/metabolites). Such technology will support claims of nutritional quality, enforce geographic indications, and provide consumer confidence (e.g., that ‘Himalayan Moringa’ came from the Himalayan foothills). As geo-authentication becomes an integral component of quality control, India’s “miracle tree” will require it when entering additional international markets. M. oleifera will, in the coming years, become a superfood, and with the integration of soil science, plant chemistry, and AI, will also be a traceable one.

REFERENCES

[1] S. Sultana, “Nutritional and functional properties of Moringa oleifera,” Metabol. Open, vol. 8, p. 100061, Dec. 2020, doi: 10.1016/J.METOP.2020.100061.

[2] Z. Islam, S. M. R. Islam, F. Hossen, K. Mahtab-Ul-Islam, M. R. Hasan, and R. Karim, “Moringa oleifera is a Prominent Source of Nutrients with Potential Health Benefits,” Int. J. Food Sci., vol. 2021, p. 6627265, 2021, doi: 10.1155/2021/6627265.

[3] J. Wirth, D. Slaghenaufi, S. Vidal, and M. Ugliano, “Electrochemical Approaches for Rapid Characterization of Oxidizable Compounds in Different Oak Alternatives,” Beverages 2021, Vol. 7, Page 1, vol. 7, no. 1, p. 1, Dec. 2020, doi: 10.3390/BEVERAGES7010001.

[4] Z. Temerdashev et al., “Impact of Soil Profile Mineralogy on the Elemental Composition of Chardonnay Grapes and Wines in the Anapa Region,” Beverages 2026, Vol. 12, Page 1, vol. 12, no. 1, p. 1, Dec. 2025, doi: 10.3390/BEVERAGES12010001.

[5] X. Hao et al., “From soil to grape and wine: Geographical variations in elemental profiles in different Chinese regions,” Foods, vol. 10, no. 12, p. 3108, Dec. 2021, doi: 10.3390/FOODS10123108/S1.

[6] M. Zhang, Q. Xiong, C. Li, J. Hu, and X. Hou, “Classification and geographic origin discrimination of Chinese prickly ash using X-ray fluorescence and machine learning,” LWT, vol. 183, p. 114947, Jun. 2023, doi: 10.1016/J.LWT.2023.114947.

[7] M. Paolucci, M. Di Stasio, A. Sorrentino, F. La Cara, and M. G. Volpe, “Active Edible Polysaccharide-Based Coating for Preservation of Fresh Figs (Ficus carica L.),” Foods 2020, Vol. 9, Page 1793, vol. 9, no. 12, p. 1793, Dec. 2020, doi: 10.3390/FOODS9121793.

[8] R. Joshi et al., “Application of Fourier Transform Infrared Spectroscopy and Multivariate Analysis Methods for the Non-Destructive Evaluation of Phenolics Compounds in Moringa Powder,” Agriculture 2022, Vol. 12, Page 10, vol. 12, no. 1, p. 10, Dec. 2021, doi: 10.3390/AGRICULTURE12010010.

[9] A. Colantuono, R. Ferracane, and P. Vitaglione, “Potential bioaccessibility and functionality of polyphenols and cynaropicrin from breads enriched with artichoke stem,” Food Chem., vol. 245, pp. 838–844, Apr. 2018, doi: 10.1016/J.FOODCHEM.2017.11.099.

[10] V. Luzak, “Nuclear Condensates: New Targets to Combat Parasite Immune Evasion?,” Front. Cell. Infect. Microbiol., vol. 12, p. 942200, Jul. 2022, doi: 10.3389/FCIMB.2022.942200.

[11] H. Koguchi et al., “Application of Recombinase-Based In Vivo Expression Technology to Bifidobacterium longum subsp. longum for Identification of Genes Induced in the Gastrointestinal Tract of Mice,” Microorganisms, vol. 8, no. 3, p. 410, Mar. 2020, doi: 10.3390/MICROORGANISMS8030410.

[12] Y. Zhu et al., “Study on the origin identification of Anji Baicha based on mineral elements,” Food Chem., vol. 498, p. 147209, Jan. 2026, doi: 10.1016/J.FOODCHEM.2025.147209.

[13] O. Y. Rodionova, P. Oliveri, C. Malegori, and A. L. Pomerantsev, “Chemometrics as an efficient tool for food authentication: Golden pillars for building reliable models,” Trends Food Sci. Technol., vol. 147, p. 104429, May 2024, doi: 10.1016/J.TIFS.2024.104429.

[14] M. Zhang, Q. Xiong, C. Li, J. Hu, and X. Hou, “Classification and geographic origin discrimination of Chinese prickly ash using X-ray fluorescence and machine learning,” LWT, vol. 183, p. 114947, Jun. 2023, doi: 10.1016/J.LWT.2023.114947.

[15] R. M. Taylor-Gjevre, B. V. Nair, S. Jin, and J. Quail, “Higher mortality rates associated with rheumatoid arthritis in Saskatchewan, Canada, 2001–2019,” Can. J. Public Health, vol. 112, no. 4, p. 722, Aug. 2021, doi: 10.17269/S41997-021-00476-W.

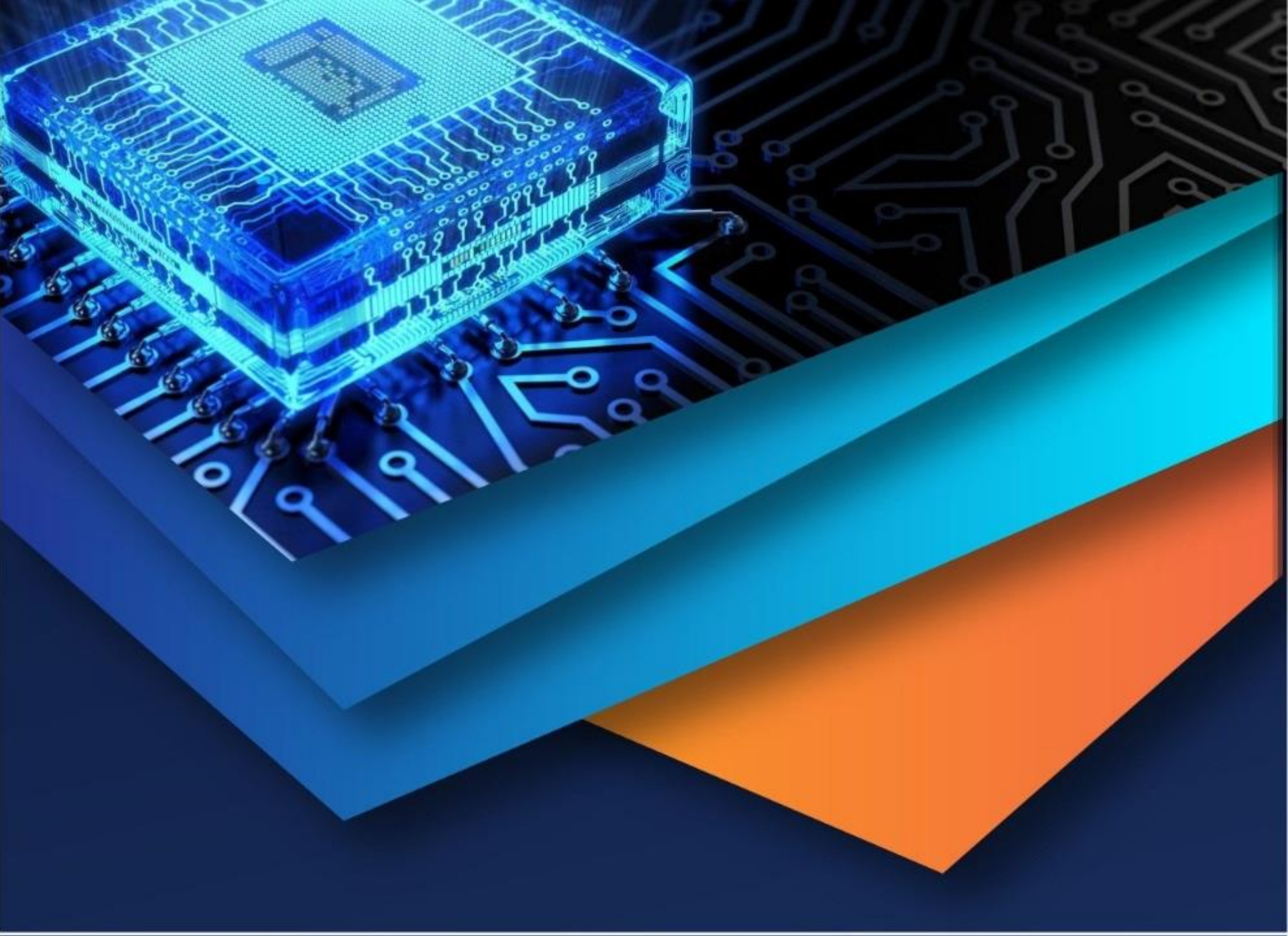
[16] R. Shinde, Y. Vinokur, E. Fallik, and V. Rodov, “Effects of Genotype and Modified Atmosphere Packaging on the Quality of Fresh-Cut Melons,” Foods, vol. 13, no. 2, p. 256, Jan. 2024, doi: 10.3390/FOODS13020256/S1.

[17] R. Ceci et al., “Comparative Metabolomic Analysis of Moringa oleifera Leaves of Different Geographical Origins and Their Antioxidant Effects on C2C12 Myotubes,” Int. J. Mol. Sci., vol. 25, no. 15, p. 8109, Aug. 2024, doi: 10.3390/IJMS25158109/S1.

[18] H. Koguchi et al., “Application of Recombinase-Based In Vivo Expression Technology to Bifidobacterium longum subsp. longum for Identification of Genes Induced in the Gastrointestinal Tract of Mice,” Microorganisms, vol. 8, no. 3, p. 410, Mar. 2020, doi: 10.3390/MICROORGANISMS8030410.

[19] M. Azarikia, R. Mahdavi, and L. Nikniaz, “Occurrence and dietary factors associated with the presence of aflatoxin B1 and M1 in breast milk of nursing mothers in Iran,” Food Control, vol. 86, pp. 207–213, Apr. 2018, doi: 10.1016/J.FOODCONT.2017.11.009.

[20] R. González-Domínguez, A. Sayago, and Á. Fernández-Recamales, “An Overview on the Application of Chemometrics Tools in Food Authenticity and Traceability,” Foods, vol. 11, no. 23, p. 3940, Dec. 2022, doi: 10.3390/FOODS11233940.



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