International Journal of Agriculture, Environment and Food Sciences

e-ISSN: 2618-5946 https://dergipark.org.tr/jaefs

DOI: https://doi.org/10.31015/2025.4.38 Int. J. Agric. Environ. Food Sci. 2025; 9 (4): 1379-1393

Multivariate Evaluation of Vitamin and Mineral Retention Across Diverse Foods and Processing Methods

Yusuf Durmus[1]

[1]Department of Gastronomy and Culinary Arts, Faculty of Tourism, Artvin Çoruh University, Artvin, Türkiye

Article History
Received: November 1, 2025
Accepted: December 22, 2025
Published Online: December 26, 2025

Article Info
Type: Research Article
Subject: Food Technology

Corresponding Author
Yusuf Durmuş
yusufdurmus@artvin.edu.tr

Author ORCID
[1]https://orcid.org/0000-0001-8286-4141

Available at
https://dergipark.org.tr/jaefs/issue/99001/1825680

DergiPark AKADEMIK

Abstract

This study aimed to elucidate the effects of food matrix and processing methods on nutrient retention by applying multivariate and dimensionality reduction analyses to retention factor data. The nutrient retention factor (RF) data for different foods and processing methods were obtained from the Australian Food Composition Database. A total of 261 RF values were analyzed for 16 nutrients, 30 food categories, and 57 processing types. Dimensionality reduction and clustering techniques, including principal component analysis (PCA), isometric mapping (ISOMAP), uniform manifold approximation and projection (UMAP), and hierarchical cluster analysis (HCA), were employed to explore relationships among nutrients, foods, and processing conditions. The results showed that nutrient stability varies substantially depending on the nutrient class, food matrix, and processing intensity. Minerals such as Zn, Fe, Ca, P, and Mg showed the highest mean RFs (>0.90), indicating strong thermal and oxidative stability, whereas water-soluble vitamins, including folic acid, vitamin B1, vitamin B6, and vitamin C, showed the lowest retention (<0.80). The highest nutritional losses occurred by moist-heat treatments, especially extended boiling while the most effective nutrient preservation was achieved by reheating and rapid preparation. Correlation and clustering analyses demonstrated that the nutrient retention patterns are significantly impacted by dietary matrix composition and processing intensity. Dimensionality reduction techniques revealed distinct grouping patterns among food categories, emphasizing the effects of the food matrix on nutrient retention. Legumes and pasta experienced extensive water-soluble vitamin loss due to leaching, while meats and dairy products exhibited moderate vitamin loss and stable mineral retention. Overall, this study offers a thorough multivariate evaluation of nutrient retention behavior, providing insightful information for improving processing and cooking techniques to raise food quality while minimizing micronutrient losses.

Keywords: ISOMAP, Mineral, PCA, Retention factor, UMAP, Vitamin

Cite this article as: Durmus, Y. (2025). Multivariate Evaluation of Vitamin and Mineral Retention Across Diverse Foods and Processing Methods. International Journal of Agriculture, Environment and Food Sciences, 9 (4): 1379-1393. https://doi.org/10.31015/2025.4.38

INTRODUCTION

Micronutrients, especially vitamins and minerals, are essential dietary components that support fundamental metabolic and physiological processes like antioxidant protection, immunological defense, energy production, and brain activity. However, throughout preparation, heating, and storage, foods' nutritional composition can alter dramatically. Retention factor (RF) is a popular way to represent how much nutrients are maintained or broken-down during processing. RF is the percentage of a nutrient that remains in a food product after processing in comparison to its initial concentration (Bognár, 1998). Therefore, accurate food composition databases, dietary evaluations, and the formulation of nutritionally balanced foods depend on an understanding of nutrient retention.

Food processing can induce various chemical, physical, and enzymatic transformations that affect nutrient stability. Water-soluble vitamins, such as vitamins C, folate, and vitamin B1, are particularly sensitive to heat, oxygen, and light exposure. This leads to substantial degradation during thermal and aqueous processing (Gregory, 2001; Lešková et al., 2006; Miglio et al., 2008). Fat-soluble vitamins (A, E, K, and carotenoids) are generally more stable at moderate temperatures, though they can still oxidize when exposed to air, during frying, or during storage (Murador et al., 2014; Rodriguez-Amaya, 2001). Minerals, on the other hand, are not destroyed by heat, but they can be lost through leaching into cooking water or by removing mineral-rich parts, such as the peel, germ, or drippings (Bognár, 2002; Murphy et al., 1975). The final outcome of nutrient retention is determined by the combined influence of temperature, moisture, pH, and matrix composition (Rickman et al., 2007).

Existing food composition databases incorporate RF values. These databases include the USDA Table of Nutrient Retention Factors (Release 6) and the Australian Food Composition Database (AFCD, 2023; USDA, 2007). They estimate the nutrient content of cooked or processed foods. This is done when analytical data are unavailable. The derivation of these RFs is from experimental measurements or empirical models, and they are critical for the translation of raw food nutrient data into realistic estimates of consumed nutrients (USDA, 2007). However, the majority of available RF datasets are limited in scope and frequently depend on data from a small number of foods or processing methods (Bognár, 1998). As a result, there is an increasing demand for comprehensive methods that assess nutrient retention patterns across various food categories, processing conditions, and nutrient groups.

Recent advances in data science highlight the value of multivariate and machine-learning–based approaches for analyzing high-dimensional food and nutrition datasets. Dimensionality reduction techniques such as principal component analysis (PCA) enable the identification of dominant variance structures and correlated nutrient behaviors under different processing conditions (Jolliffe & Cadima, 2016). However, nutrient retention patterns are often nonlinear due to threshold effects, matrix interactions, and process-specific responses. Nonlinear manifold learning methods, including isometric mapping (ISOMAP) and uniform manifold approximation and projection (UMAP), are increasingly used to uncover latent structures and clustering tendencies in complex biological and food systems where linear assumptions are insufficient (Tenenbaum et al., 2000; McInnes et al., 2018). Complementary to these approaches, hierarchical cluster analysis (HCA) allows foods, nutrients, or processing methods to be grouped based on similarity in retention behavior, facilitating interpretable classification of stability profiles (Ward, 1963). Applying such multivariate techniques to nutrient retention data provides insights that cannot be obtained from single-nutrient analyses. For example, nutrients that co-degrade under similar thermal or oxidative conditions, such as B-complex vitamins, may form distinct clusters reflecting shared sensitivity mechanisms (Ball, 2005; Ziegler & Filer, 1996). Similarly, minerals such as calcium, phosphorus, and magnesium often exhibit comparable retention patterns dominated by leaching rather than chemical degradation (Murphy et al., 1975; Rickman et al., 2007). At the food level, matrix properties strongly modulate nutrient stability. These properties include moisture content, fat content, and cellular structure. This leads to systematic differences between plant- and animal-based foods (Erdman Jr et al., 2012; Lee & Kader, 2000). Despite this potential, comprehensive multivariate evaluations of nutrient retention across multiple food categories and processing methods remain scarce. Most existing studies focus on specific nutrients or individual processing techniques, limiting generalization across food systems. Therefore, there is a clear need for integrative analytical frameworks that simultaneously consider nutrient type, food matrix, and processing intensity.

Nutrient preservation is significantly impacted by thermal processing, one of the most influential factors in this regard. Significant losses of water-soluble nutrients through leaching and oxidation are often the result of moist-heat methods such as boiling, stewing, and blanching (Miglio et al., 2008; Rehman & Shah, 2005). For example, boiling vegetables can cause vitamin C losses that exceed 50%, while heating time sharply increases vitamin B1 and folate degradation (Gregory, 2001; Lešková et al., 2006). In contrast, higher retention is typically produced by dry-heat treatments such as toasting, roasting, and short-time reheating, as leaching and oxidative reactions are limited by reduced water activity (Bognár, 1998; Choe & Min, 2007). The way nutrients interact with each other and how they are processed depend on the type of food. The stability of lipophilic vitamins and carotenoids can be enhanced by high-fat matrices, for instance, by an oxygen-limiting environment being provided (Erdman Jr et al., 2012; Shi & Maguer, 2000). On the other hand, plant matrices with high moisture content and polyphenol oxidases can speed up the loss of sensitive compounds, like vitamin C (Lee & Kader, 2000).

Numerous studies have examined the loss of individual nutrients during specific processes. However, systematic multivariate analyses that encompass multiple nutrients and food categories are scarce. Studying how nutrients are connected can show if certain vitamins or minerals have similar ways of breaking down. For instance, earlier studies have demonstrated robust positive associations among B-complex vitamins, implying that these compounds frequently co-degrade under comparable thermal or oxidative conditions (Ball, 2005; Ziegler & Filer, 1996). In addition, minerals such as magnesium, phosphorus, and calcium show similar trends in how they are retained. Their losses are mostly caused by them being dissolved rather than destroyed (Murphy et al., 1975; Rickman et al., 2007).

In this study, it was aimed to understand how nutrients are retained when different foods are processed under different conditions. We obtained a total of 261 retention factor values for 16 nutrients (vitamins and minerals) from 30 food types and 57 processing methods using the Australian Food Composition Database (AFCD, 2023). PCA, ISOMAP, UMAP, and HCA were used to find patterns, relationships, and how things group together based on nutrients, food categories, and processing treatments. This integrative framework was designed to elucidate linear and nonlinear relationships among variables and reveal shared degradation or stabilization patterns across nutrient classes.

MATERIALS AND METHODS

Data collection

The data used in this study is publicly available in the Australian Food Composition Database (AFCD, 2023). The data contains retention factor (RF) values for 16 food nutrients (vitamins and minerals) obtained from 30 food types and 57 processing types or food conditions. The data includes a total of 261 RF values for different foods and processing methods. No missing values were observed in the data, and no filtering procedures were applied. The one-hot encoding procedure was applied to the food processing methods in order to prepare the data for further analysis.

Principal component analysis (PCA) and Isometric mapping (ISOMAP)

PCA was used to determine linear correlations between the variables and to evaluate the independent variables. After standardizing and breaking down the data into principal components (PCs), the first two PCs were used to generate a biplot (Jolliffe & Cadima, 2016). PCA was performed on retention factor data, with the first two principal components explaining 61.9% (PC1) and 13.0% (PC2) of the total variance, accounting for 74.9% of the overall variability in nutrient retention patterns. The first two principal components (PC1 and PC2) from the PCA results were selected and used to plot the two-dimensional biplots. ISOMAP is a non-linear dimensionality reduction technique that is used to generate a low-dimensional representation of high-dimensional data by preserving the local geometric structure of the original data. Unlike traditional dimensionality reduction techniques such as PCA, ISOMAP is able to discover non-linear relationships between data points, allowing it to produce more accurate and robust embeddings (Tenenbaum et al., 2000). The number of neighbors to consider for each point was set to 5 and the metric that used when calculating distance between instances as Euclidean. PCA and ISOMAP analyses were performed with Python 3 (version 3.12.3).

Uniform manifold approximation and projection (UMAP) and Hierarchical cluster analysis (HCA)

UMAP is one of the unsupervised machine learning methods and is a non-linear dimension reduction technique. First, UMAP constructs a weighted k-nearest neighbor graph in the original feature space to approximate the local geometry of the underlying manifold. Then, distances between neighboring points are converted into probabilistic edge weights using locally adaptive scaling. This results in a fuzzy simplicial complex that encodes the strength of connectivity between data points. The topological structure of the data is captured by this representation, which emphasizes local relationships while allowing overlap between neighborhoods (McInnes et al., 2018; Becht et al., 2019). The size of local neighborhood was set to 3, the metric that used to compute distances as Manhattan, and the minimum distance between embedded points as 0.536 for UMAP. HCA was performed to group together the independent variables, and the outcome was represented as a dendrogram. The distance between two clusters was determined using the "Ward" algorithm described by Ward (1963). The Euclidean metric was used to determine the distance between two points (Alfakih, 2018). UMAP and HCA analyses were performed with Python 3 (version 3.12.3). All parameters for ISOMAP, UMAP, and HCA were calculated based on the best local structure retained described by Van Der Maaten (2009).

RESULTS AND DISCUSSION

Cases with high RF values

The foods, food processes, and nutrients with the highest average RFs are shown in Table 1. RF shows the amount of a nutrient that is kept after food is processed or cooked. Values close to 1 show that not many nutrients are lost. Tomatoes showed the greatest overall retention among foods (0.967), followed by fats or oils (0.966), oats (0.948), cereal products (0.948), and fish (0.942). Tomatoes, for example, contain heat-stable nutrients like lycopene and carotenoids. These nutrients can actually increase in bioavailability after being heated because the cell walls soften and the matrix breaks down (Dewanto et al., 2002; Shi & Maguer, 2000). In a similar manner, fats and oils frequently function as protective matrices, thereby diminishing oxidative degradation of lipophilic vitamins (e.g., tocopherols) during the process of heating (Choe & Min, 2007). The relatively high nutrient retention in cereals, oats, and fish aligns with prior research suggesting that moderate heating and controlled moisture conditions preserve the stability of minerals and vitamins in these foods (Bognár, 1998; Murphy et al., 1975).

Table 1. Top 5 highest retention factor values for food, food process, and nutrient in average

Category	Description	Retention factor
Food	Tomato	0.967
	Fat or oil	0.966
	Oats	0.948
	Cereal	0.948
	Fish	0.942
Food process	Reheated	0.977
	Instant	0.975
	Toasted	0.959
	Heated 10 min.	0.946
	With fat	0.944
Nutrient	Zinc (Zn)	0.983
	Iron (Fe)	0.961
	Calcium (Ca)	0.959
	Phosphorus (P)	0.921
	Magnesium (Mg)	0.919

In terms of processing techniques, reheating (0.977) and instant preparation (0.975) were linked to the highest overall RFs, indicating minimal nutrient breakdown during brief, low-temperature thermal processes. The negligible losses during reheating and expeditious preparation could be attributed to diminished water activity and abbreviated exposure times relative to boiling or stewing, which are recognized to induce enhanced leaching of water-soluble vitamins (Miglio et al., 2008). The demonstration of relatively high retention was also accomplished by toasting (0.959) and heating for 10 min (0.946), while the retention of nutrients at an average factor of 0.944 was demonstrated by foods processed with fat. This finding aligns with the protective role of lipids in reducing thermal oxidation and leaching losses (Bognár, 2002; Choe & Min, 2007).

Among the nutrients, zinc (Zn) exhibited the highest mean RF (0.983), followed by iron (Fe) (0.961), calcium (Ca) (0.959), phosphorus (P) (0.921), and magnesium (Mg) (0.919). The stability of minerals during processing is indicated by these results, as they are not destroyed by heat, though they may undergo leaching or redistribution between food components (Bognár, 1998; Murphy et al., 1975). The structural integrity of food matrices where these minerals are bound was preserved by most applied processing conditions, as indicated by the particularly high retention of Zn and Fe. On the other hand, the moderately lower but still significant preservation of P and Mg indicates slight losses through dissolution or dripping losses during moist-heat treatments.

Table 2 shows the five lowest average nutrient retention factors (RFs) across food categories, processing methods, and nutrients. Lower RF values indicate greater nutrient loss due to processing or handling. Legumes had the lowest average RF (0.752) among foods, followed by ham (0.792), beef (0.800), veal (0.809), and lamb (0.811). Legumes are known for their low retention of nutrients, which is largely due to their typical preparation methods. These methods often involve soaking and boiling for extended periods, which causes the leaching of water-soluble nutrients, especially B vitamins and minerals (Muroki et al., 2023; Rehman & Shah, 2005). Meat products, including ham, beef, veal, and lamb, demonstrated diminished mean RF, presumably attributable to thermal degradation and drip losses during the culinary process. These processes can lead to significant nutrient loss, particularly of thermolabile vitamins and minerals, which are prone to migration into the cooking liquid or fat during prolonged and high-temperature heating (Bognár, 1998; Murphy et al., 1975). Furthermore, during the curing and heat treatment of meats like ham, there's a possibility of oxidative degradation of essential vitamins, such as vitamin B1 and folate, due to the exposure to heat (Estévez, 2011).

Table 2. Top 5 lowest retention factor values for food, food process, and nutrient in average

Category	Description	Retention factor
Food	Legumes	0.752
	Ham	0.792
	Beef	0.800
	Veal	0.809
	Lamb	0.811
Food process	Boiled (2-2.5 h.)	0.695
	Raw	0.740
	Boiled (45-75 min.)	0.745
	Without drippings	0.761
	Boiled (15-20 min.)	0.782
Nutrient	Folic acid	0.746
	Vitamin B1	0.747
	Vitamin B6	0.786
	Vitamin C	0.788
	Iodine (I)	0.848

In terms of food processing, boiling for an extended period of time (2–2.5 h) resulted in the lowest mean RF (0.695). This was followed by the following methods, in order: raw (0.740); boiling for 45–75 min (0.745); boiling without drippings (0.761); and boiling for 15–20 min (0.782). These results demonstrate that moist heat treatments, particularly long boiling times, cause substantial water-soluble nutrient loss through leaching into the cooking medium (Miglio et al., 2008; Murphy et al., 1975). Even shorter boiling times (15–20 min) were associated with notable reductions in vitamin stability, indicating its sensitivity to aqueous processing conditions. The low retention value observed for "raw" foods likely reflects the inclusion of food items that are typically consumed uncooked but undergo preprocessing steps, such as soaking or peeling. These steps may lead to enzymatic or oxidative losses of sensitive vitamins (Lešková et al., 2006). Furthermore, the "without drippings" condition suggests that nutrients are lost when cooking fluids containing significant amounts of dissolved or emulsified vitamins and minerals are separated and discarded (Bognár, 2002). When individual nutrients were considered, the lowest mean RF was exhibited by folic acid (0.746) and vitamin B1 (0.747), followed by vitamin B6 (0.786), vitamin C (0.788), and iodine (0.848). These nutrients are known for being unstable when they are heated or cooked in water. Folic acid and vitamin B1 are particularly unstable. They break down quickly at high temperatures or when they are exposed to oxygen and light for a long time (Gregory, 2001; Horzum, et. al. 2025; Lešková et al., 2006). The low retention of vitamin C and B6 under boiling and reheating conditions can be explained by their considerable susceptibility to oxidation and thermal degradation (Bognár, 1998; Miglio et al., 2008). Iodine is more stable under dry-heat conditions but prone to volatilization and leaching in water. This leads to moderate losses during boiling or stewing (Teas et al., 2004).

Cases with low RF values

The foods exhibiting the lowest nutrient RF values in the dataset are enumerated in Table 3, along with the nutrients most impacted. Similarly, Table 4 summarizes the nutrients with the lowest RF values and the foods in which these losses were observed. These data show important connections between nutrients and food. These connections show how things like the composition, structure, or processing of food can make it easier for nutrients to be lost or degraded. The lowest RF value (0.20) was recorded for fruits with respect to vitamin C, which aligns with its well-documented instability due to sensitivity to oxidation, heat, and light exposure (Lešková et al., 2006; Miglio et al., 2008). Even simple processes like cutting, blending, or heating for a short time can destroy a lot of vitamin C, especially in foods with a lot of moisture like fruits and potatoes. In line with this, potatoes exhibited a minimal RF (0.25) for vitamin C, validating the extensive degradation of this nutrient during boiling or extended heating due to its leaching into water and oxidative reactions (Bognár, 1998; Murphy et al., 1975). Legumes exhibited an RF of 0.25 for folic acid, signifying considerable losses during thermal processing. Folic acid and related folate compounds exhibit high water solubility and are susceptible to degradation by heat and oxidation (Gregory, 2001; Lešková et al., 2006). Prolonged boiling, a common method of preparing legumes, promotes chemical degradation and the leaching of folates into the cooking medium (Rehman & Shah, 2005). Similarly, sausages showed an RF of 0.30 for folic acid, possibly due to oxidative degradation during curing, smoking, or frying—processes that enhance the loss of heat-labile vitamins in meat products (Estévez, 2011).

Table 3. Foods with the lowest retention factors and corresponding nutrients

Food	Retention factor	Corresponding nutrient
Fruits	0.20	Vitamin C
Legumes	0.25	Folic acid
Potatoes	0.25	Vitamin C
Pasta	0.25	Iodine (I)
Lamb	0.30	Vitamin B1
Sausage	0.30	Folic acid
Milk	0.30	Vitamin B12
Beef	0.35	Vitamin B6
Organ meats	0.40	Iodine (I)
Liver	0.40	Iodine (I)

Among foods derived from animals, milk displayed a low RF (0.30) for vitamin B12, which is consistent with the recognized sensitivity of cobalamin to light exposure and extended heat treatment such as pasteurization or boiling (Watanabe, 2007). The RF for vitamin B6 was 0.35, which is in line with earlier findings. These findings suggest that pyridoxine is quite unstable when exposed to moist heat during cooking. This instability can be attributed to heat degradation and leaching into the drippings (Bognár, 1998; Murphy et al., 1975). Lamb exhibited an RF of 0.30 for vitamin B1, which is one of the most heat-labile vitamins found in meats. Vitamin B1 degradation has been shown to increase with temperature and duration of heating, and its loss can be further enhanced by the presence of sulfite or nitrite curing agents (Gregory, 2001; Lešková et al., 2006). As shown in Table 4, the RF values for vitamin B3 (0.45) and vitamin B2 (0.55) in liver samples indicated that these nutrients were moderately to minimally stable. This stability was influenced by exposure to heat and oxidation, which led to their degradation. Though vitamin B2 is relatively more stable than other B vitamins, it is particularly sensitive to light. Vitamin B3 can be lost through leaching during aqueous cooking (Gregory, 2001; Lešková et al., 2006). Both organ meats and liver exhibited low RFs (0.40) for iodine. Although iodine is a mineral that is not destroyed by heat, it is volatile at elevated temperatures and soluble in water, which can cause substantial losses during boiling, frying, or baking (Teas et al., 2004). Depending on tissue type and fat content, organ meats may also show high variability in iodine retention, as these factors influence mineral partitioning during cooking. In a similar way, pasta showed an RF of 0.25 for iodine, which indicates that a notable amount of iodine is released into boiling water during the cooking process. This is a well-known route for iodine loss in starchy foods (Meinhardt et al., 2019).

Table 4. Food nutrients with the lowest retention factors and corresponding foods

Food nutrients	Retention factor	Corresponding food
Vitamin C	0.20	Fruits
Folic acid	0.25	Legumes
Iodine (I)	0.25	Pasta
Vitamin B12	0.30	Milk
Sodium (Na)	0.30	Pasta
Vitamin B1	0.30	Lamb
Vitamin B6	0.35	Beef
Vitamin B3	0.45	Liver
Beta carotene	0.50	Fruits
Vitamin B2	0.55	Liver

Table 5 shows the food processes associated with the lowest observed RFs, along with the corresponding foods and nutrients. The findings demonstrate that certain processing techniques, particularly those involving heat, water, and prolonged storage, result in significant nutrient loss. Citrus fruits and dried fruits had the lowest RF values (0.20) for vitamin C, showing how easily ascorbic acid breaks down when it's exposed to heat or oxygen. The lability of vitamin C in potatoes was also demonstrated by the browned and stored samples, which exhibited an RF of 0.25. The loss of vitamin C during browning reactions (Maillard-type processes) and prolonged storage is well-documented and is often attributed to enzymatic oxidation and exposure to oxygen and light (Zerdin et al., 2003).

Vitamin C is water-soluble, thermolabile, sensitive to oxygen and enzymatic oxidation, especially during dehydration or drying processes (Lee & Kader, 2000; Rickman et al., 2007). Similarly, the decline of vitamin C content in citrus fruits and related products is further accelerated by storage and exposure to light (Favell, 1998). Extended boiling of legumes (RF =

0.25) for 2–2.5 h and frying processes were associated with substantial folic acid loss. Folates are highly unstable when exposed to heat and can leach into the cooking water (McKillop et al., 2002). These findings highlight the importance of cooking methods and duration in maintaining the nutritional quality of legume-based dishes, as boiling and frying result in chemical degradation and water-soluble vitamin loss. The cooking of sausages led to an RF of 0.30 for folic acid. This result shows that the compound is unstable in high-fat, protein-rich mixtures when it is exposed to heat. These results are consistent with previous studies indicating that up to 50% of folate can be lost during the cooking of meat products, depending on temperature and moisture levels (McKillop et al., 2002). The observed retention patterns can be mechanistically explained by specific physicochemical interactions between nutrients, processing conditions, and food matrices. The substantial loss of water-soluble vitamins (vitamin C, folate, and B-complex vitamins) during moist-heat treatments arises from the combined effects of thermal degradation and diffusion-driven leaching. Elevated temperatures accelerate degradation kinetics, while high water activity facilitates the migration of labile vitamins from disrupted cellular structures into the cooking medium, particularly in porous, starch-rich matrices such as legumes and pasta (Lešková et al., 2006; Miglio et al., 2008; Rickman et al., 2007). Similarly, several thermal processes applied to pasta, including boiling, draining, and baking, showed low RF values (0.25) for iodine. The volatility of iodine salts and their susceptibility to leaching during aqueous and high-temperature treatments may result in significant reductions in iodine content in processed cereal-based foods (Thomson, 2009). This finding is consistent with earlier observations that heat processing and water exposure significantly reduce iodine retention (Zimmermann et al., 2003).

Table 5. Food processes with the lowest retention factors and corresponding foods and nutrients

Food process	Retention factor	Corresponding food	Corresponding nutrient
Citrus	0.20	Fruits	Vitamin C
Dried	0.20	Fruits	Vitamin C
Boiled (2-2.5 h.)	0.25	Legumes	Folic acid
Boiled	0.25	Pasta	Iodine (I)
Browned	0.25	Potatoes	Vitamin C
Fried	0.25	Legumes	Folic acid
Drained	0.25	Pasta	Iodine (I)
Baked	0.25	Pasta	Iodine (I)
Stored	0.25	Potatoes	Vitamin C
Cooked	0.30	Sausage	Folic acid

Relationships between foods, food processes, and nutrients

Figure 1 presents the frequency distributions of nutrient RFs for sixteen food nutrients, illustrating the variability and stability of each nutrient during food processing. The observed average RFs ranged from 0.746 for folic acid to 0.983 for Zn, indicating a broad spectrum of nutrient stability under different processing conditions. Minerals such as Zn (0.983), Fe (0.961), Ca (0.959), P (0.921), and Mg (0.919) exhibited the highest RFs, confirming their thermal and oxidative stability. These findings are similar to other studies that showed minerals are mostly not affected by most cooking and storage processes, except when minerals leach into cooking water or when drippings are removed (Bognár, 1998; Murphy et al., 1975). The narrow distribution and right-skewed histograms for these nutrients indicate consistently high retention across foods and processing methods.

Among the vitamins, vitamin B2 (0.911), vitamin B3 (0.876), and alpha tocopherol (0.883) showed relatively high stability, consistent with earlier observations that these compounds are less sensitive to moderate heat and oxygen exposure (Erdman Jr et al., 2012; György & Pearson, 2013). Water-soluble vitamins, on the other hand, showed broader and left-shifted distributions, suggesting significant variations in retention based on the process and food matrix. The lowest RFs were observed for folic acid (0.746), vitamin B1 (0.747), vitamin B6 (0.787), and vitamin C (0.788), confirming that these compounds are among the most labile nutrients. Their degradation is primarily driven by heat, oxidation, and leaching losses during boiling and other aqueous processes (Lee & Kader, 2000; McKillop et al., 2002; Miglio et al., 2008). The wide dispersion of their RF values also suggests strong dependence on processing time, temperature, and pH (Figure 1).

Iodine (0.848) showed moderate retention, leaning toward lower values. This is consistent with its volatility and tendency to evaporate or leach out (Zimmermann, 2009; Zimmermann et al., 2003). Similarly, vitamin B12 (0.859) is partially sensitive to heating, especially in animal-derived foods, where prolonged cooking can destroy it (Watanabe, 2007). Beta-carotene (0.867) showed intermediate stability, reflecting its susceptibility to oxidation during drying, frying, and exposure to light, yet it is more resilient than vitamin C (Rodriguez-Amaya, 2001). Sodium (0.905) followed a similar pattern to minerals, though retention may decrease slightly in drained or washed foods (Figure 1).

Figure 2 illustrates the Pearson correlation coefficients among the RFs of 16 nutrients across all foods and processing conditions. Overall, the results revealed predominantly positive correlations, indicating that nutrients often exhibit parallel retention behavior under similar processing conditions. The strongest correlations were observed among mineral elements, particularly between Na and iodine (0.973), Mg and P (0.904), and Na and Mg (0.863). These high coefficients imply that mineral retention is governed by similar physicochemical principles, mainly the extent of solubility and migration into cooking water. Since minerals are not destroyed by heat, but rather lost through dissolution or drainage, foods processed under conditions that minimize leaching (e.g., dry heat or limited water cooking) tend to preserve multiple minerals simultaneously (Bognár, 2002; Rickman et al., 2007). Ca and Fe retention showed moderate positive correlations with other minerals (0.5–0.6 range), reflecting variability due to food matrix effects and binding forms. In contrast, vitamin C displayed weak or even negative correlations with several nutrients, notably with beta carotene (−0.302) and vitamin B6 (0.274). This indicates that vitamin C retention behaves distinctly, being more susceptible to oxidative and thermal degradation (Lee & Kader, 2000; Miglio et al., 2008). Its unique instability compared to minerals and fat-soluble vitamins underscores the need for gentler cooking and minimal exposure to oxygen.

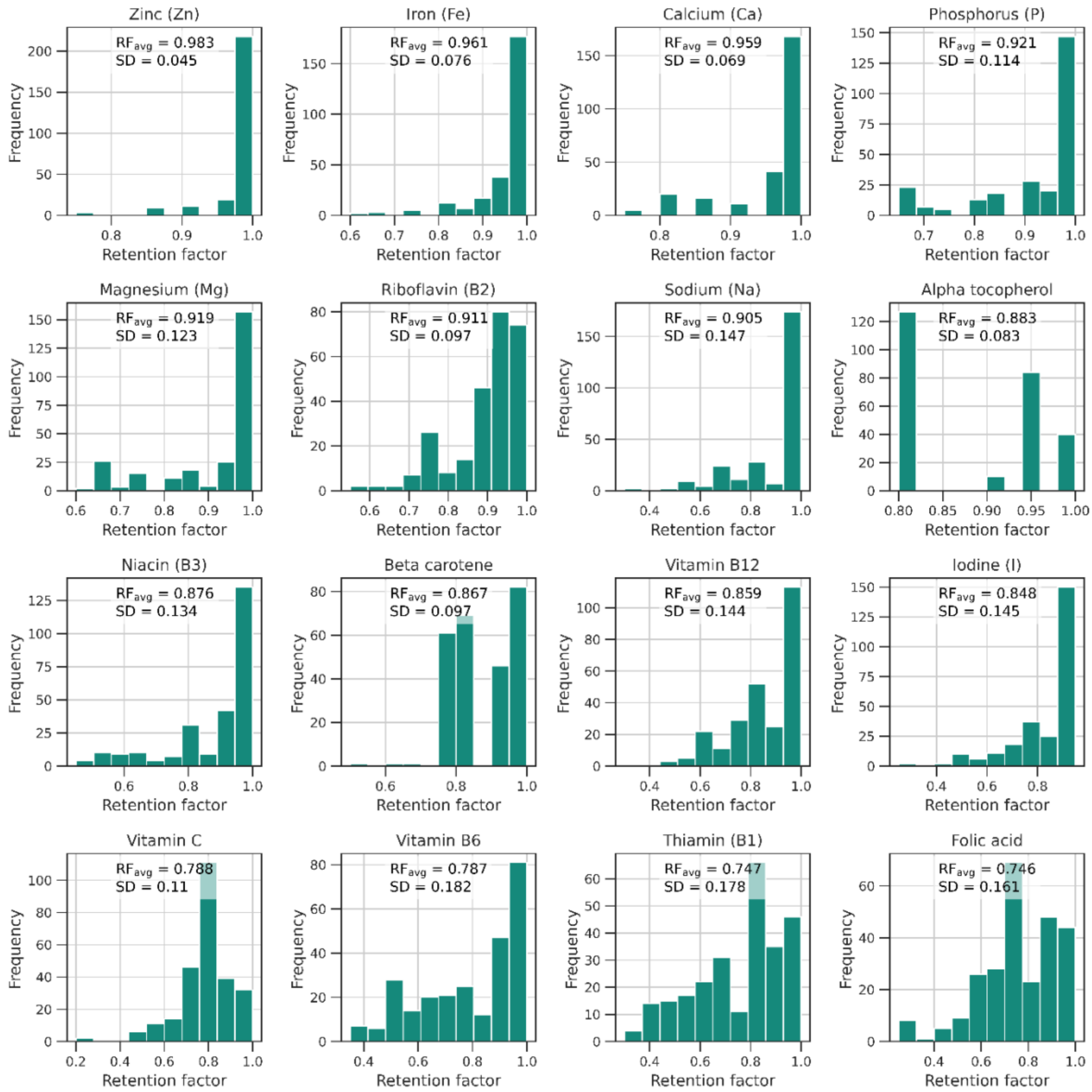


Figure 1. Histogram plots for the nutrients. SD = Standard deviation

Strong correlations were found among B-complex vitamins, suggesting that these labile, water-soluble vitamins tend to co-degrade under harsh conditions such as boiling or prolonged heating. For example, vitamin B1 was strongly correlated with vitamin B6 (0.795), vitamin B12 was strongly correlated with vitamin B6 (0.724), and vitamin B2 was strongly correlated with vitamin B3 (0.811). Similarly, folic acid showed positive correlations with vitamins B3 (0.692) and B1 (0.555). Moderate positive correlations were found among fat-soluble nutrients such as alpha tocopherol (vitamin E) and beta-carotene (0.454), as well as between these nutrients and several minerals (0.4–0.5 range).

The protective role of lipids likely accounts for these relationships, with the ability to reduce oxidative losses and stabilize both fat-soluble vitamins and metal ions during thermal treatment (Erdman Jr et al., 2012; Rodriguez-Amaya, 2001). Minerals exhibited high intercorrelations, reflecting shared loss mechanisms through leaching. The water-soluble vitamins (B-group, C, folate) exhibited a moderately correlated pattern, influenced by heat and water exposure. Lipid-soluble vitamins and carotenoids were moderately interrelated, impacted by fat interactions and oxidation processes. These findings align with previous reports on nutrient retention behavior during thermal processing. These reports emphasize the primary determinants of matrix effects, water activity, and processing temperature (Bognár, 1998; Lee & Kader, 2000; Rickman et al., 2007). Understanding these correlations provides valuable insight into optimizing nutrient preservation strategies to maintain the overall micronutrient density of processed foods.

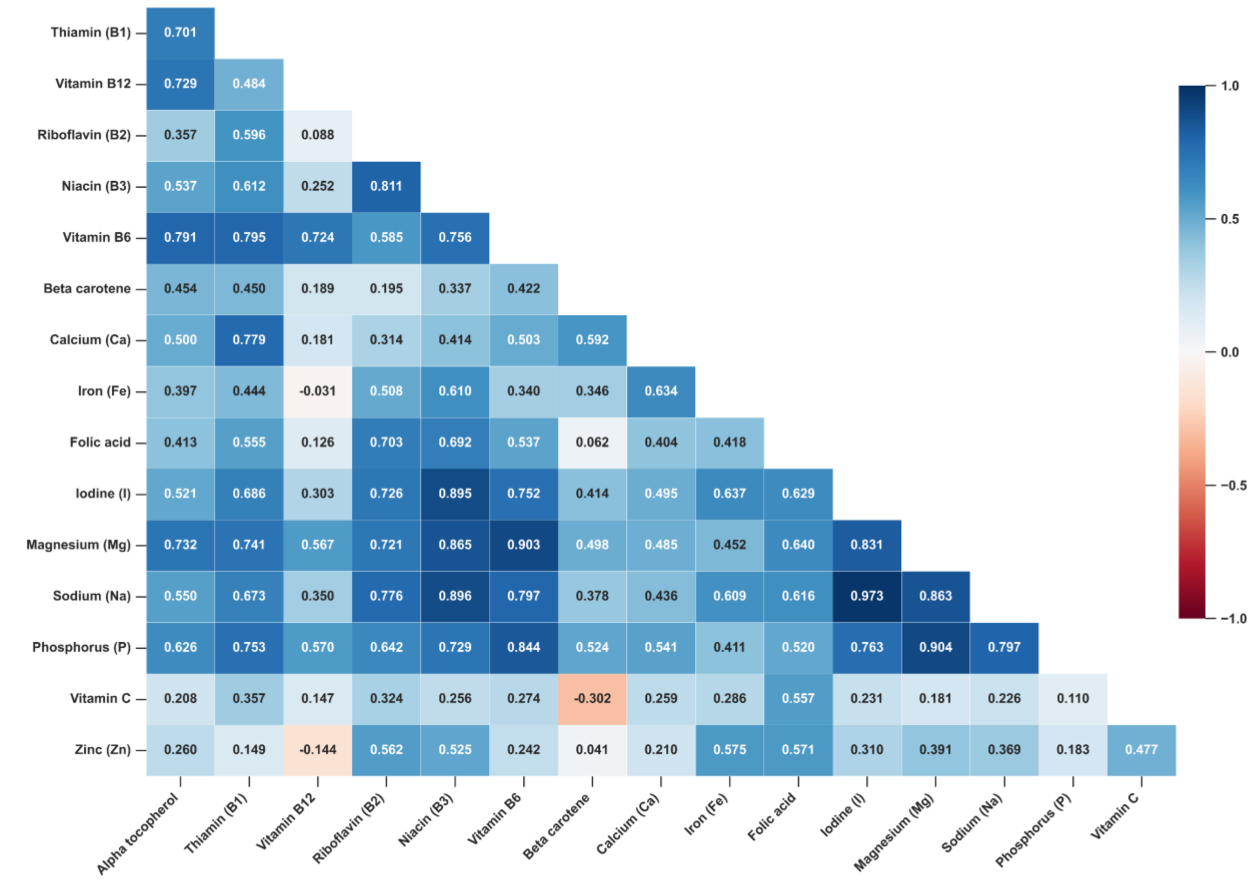


Figure 2. Correlation results for the nutrients.

Figures 3A and 3B show the PCA and ISOMAP of RFs across various food groups, respectively. The first two principal components (PC1 and PC2) explained 61.9% and 13.0% of the total variance, respectively, accounting for approximately 74.9% of the overall variation in nutrient retention among foods (Figure 3A). This high cumulative variance indicates that a limited number of latent factors can effectively summarize the complex relationships between nutrients and food matrices during processing. Foods that were closer together in the PCA space exhibited similar retention behavior across multiple nutrients. In contrast, foods that were farther apart differed substantially in their nutrient stability patterns. Foods such as beef, lamb, veal, pork, ham, bacon, liver, chicken, turkey, and organ meats clustered closely in the negative region of PC1. This suggests that these foods have comparable retention profiles dominated by protein-rich matrices with moderate losses of heat-sensitive vitamins and minerals. These meats are similar due to their shared composition of muscle proteins and connective tissue. These components influence the diffusion and binding of water-soluble nutrients during cooking (Bognár, 1998; Murphy et al., 1975). Furthermore, their dense tissue structure limits leaching losses, which explains the moderate retention of minerals such as iron (Fe) and zinc (Zn) (Erdman Jr et al., 2012; Rickman et al., 2007). In contrast, milk and cheese formed a distinct group in the lower-right quadrant of Figure 3A and 3B, characterized by high fat and Ca contents but low retention of heat-labile vitamins. The stability of fat-soluble vitamins (A, D, E, and K) may be enhanced by the high lipid fraction, but water-soluble vitamins such as folate and B12 can be reduced by the thermal processing of dairy products (e.g., pasteurization, curd formation) (György & Pearson, 2013; Ribaya-Mercado & Blumberg, 2004). Their distinct position suggests that matrix composition and processing type, rather than raw nutrient concentration, play critical roles in shaping retention profiles.

Legumes were found to be far apart along the positive PC2 axis, indicating a unique nutrient retention pattern characterized by high folate content and significant thermal losses. The high moisture absorption of legumes during soaking and boiling promotes nutrient leaching, particularly of folate and B-complex vitamins (Bognár, 1998; McKillop et al., 2002). Their proximity to other plant foods highlights the disproportionate effect of cooking medium and duration on water-soluble vitamin retention in legumes. Pasta, which is located near legumes but has a lower PC2 loading, exhibited similarly low RFs for iodine and Na (Table 4). This pattern reflects losses due to leaching into the cooking water because starch-based foods lack the complex matrices necessary to retain soluble elements (Murphy et al., 1975). Plant-derived foods, such as fruits, vegetables, nuts, cereals, and tubers (e.g., potatoes, sweet potatoes, rice, and oats), clustered toward the right side of PC1. This grouping reflects a higher retention of fat-soluble nutrients, such as β-carotene and vitamin E, as well as a variable stability of water-soluble vitamins, especially vitamin C and folate. This varies depending on the intensity of processing (Miglio et al., 2008; Rickman et al., 2007). The proximity of fruits and rice indicates that both groups experience similar degradation of labile compounds when exposed to heat. Meanwhile, cereals and nuts cluster together due to their shared lipid and mineral content, which contributes to the improved retention of nonpolar micronutrients (Erdman Jr et al., 2012; Rodriguez-Amaya, 2001). Seafood, shellfish, and fish were grouped together in the middle-right region, indicating similar nutrient profiles. Fat and oil are isolated in the far-right, positive PC1 region, reflecting their unique composition, which is dominated by lipophilic nutrients and the complete absence of water-soluble vitamins or minerals. This distinct placement confirms that fat-rich foods retain nearly all fat-soluble vitamins while remaining unaffected by leaching processes (Erdman Jr et al., 2012; Rodriguez-Amaya, 2001).

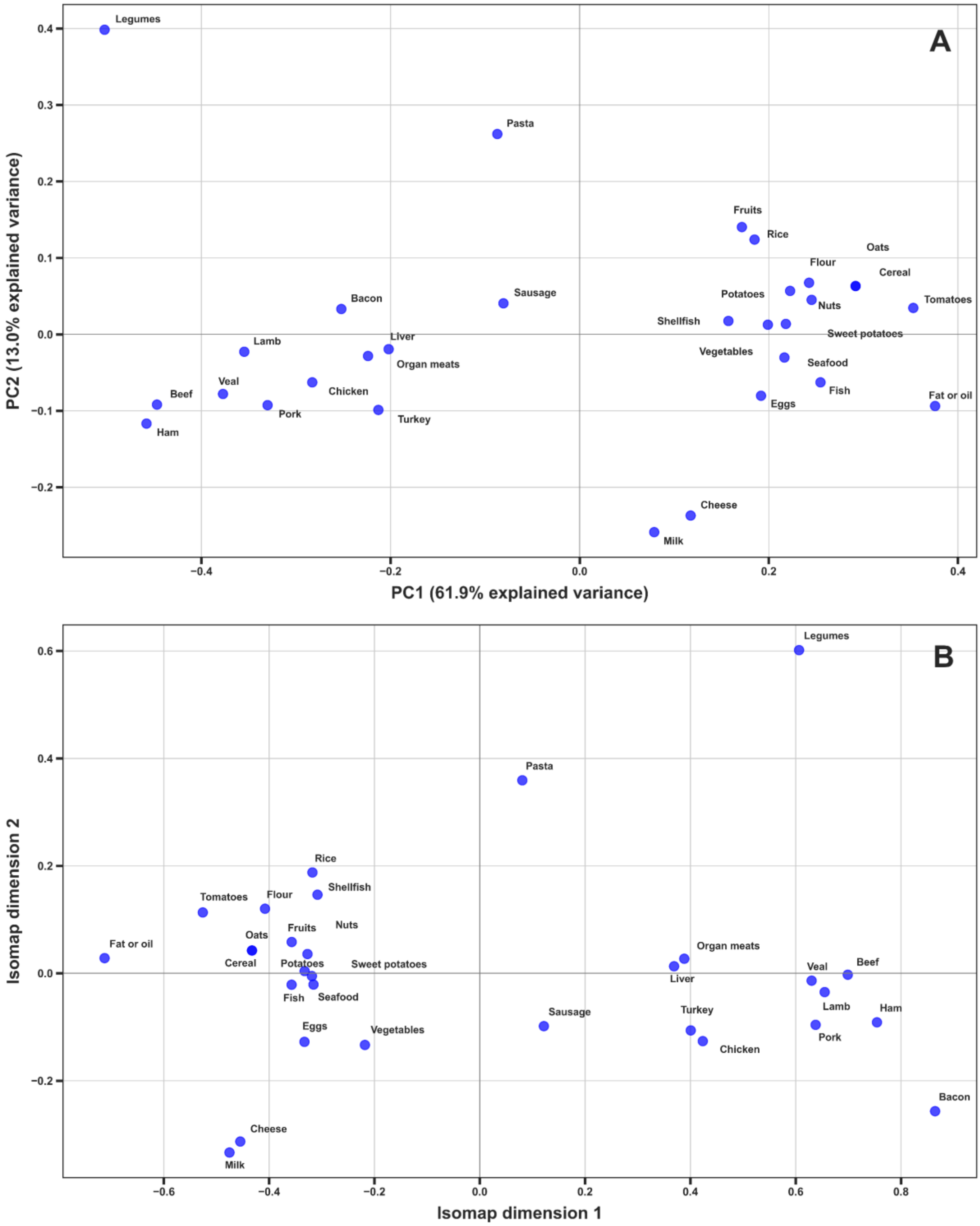
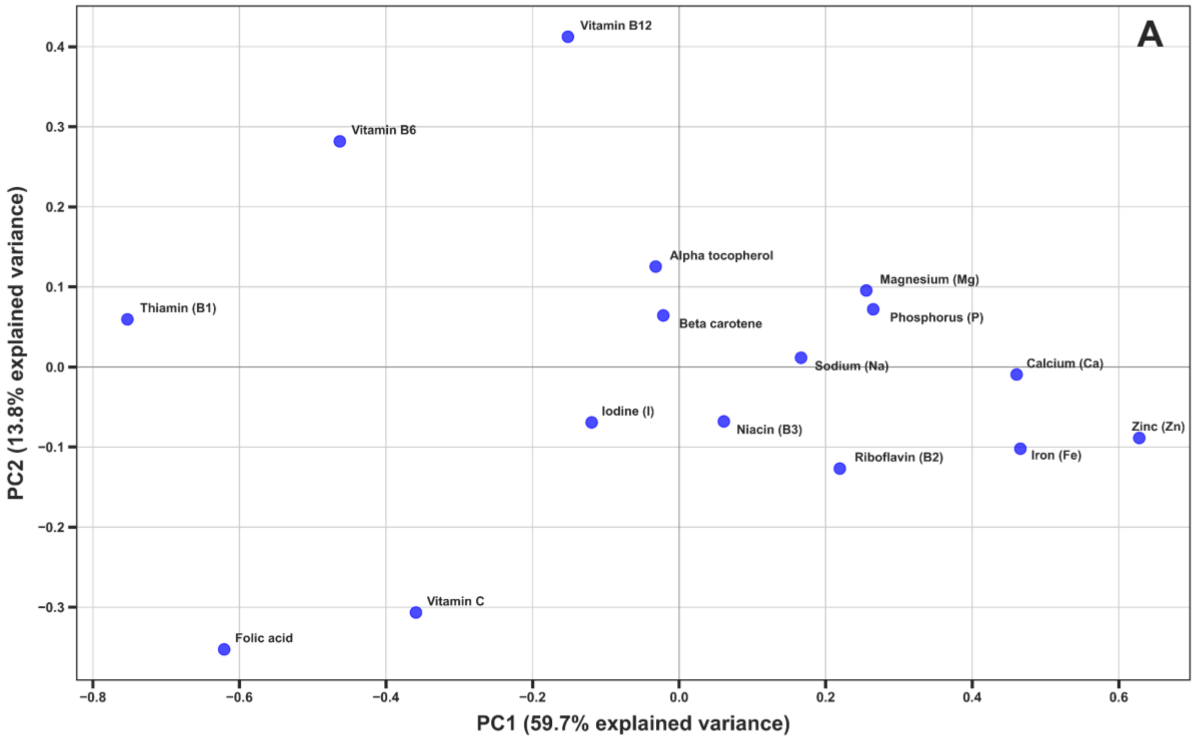


Figure 3. Biplots of PCA (A) and Isometric mapping (B) illustrating the overall variation among the foods

The variations among nutrients are shown in Figure 4. Vitamin B1, vitamin B2, vitamin B3, and vitamin B6 grouped together in both PCA and UMAP. These water-soluble B-vitamins are structurally related and often co-occur in cereals, legumes, and meats. Their clustering reflects both their hydrophilic nature and their susceptibility to leaching during boiling or steaming (Dewanto, Wu, & Liu, 2002; Ziegler & Filer, 1996). Figure 4A shows that Ca, Mg, P, and Zn are located closely together, which is consistent with their role as structural minerals in bones and grains. They are less influenced by heat and more influenced by processing steps that remove the outer layers of grains or leach minerals into the cooking water. Vitamin C and folic acid are positioned close together, reflecting their sensitivity to oxidation and thermal degradation (Figure 4A and 4B). They are both rapidly lost during prolonged heating or storage, which explains why they are separated from more stable fat-soluble vitamins (Rickman et al., 2007). In contrast, fat-soluble vitamins and carotenoids (alpha tocopherol, beta carotene) were positioned further apart from the water-soluble group. Their clustering reflects lipid solubility and antioxidant properties, which confer greater stability during boiling but increased vulnerability to oxidative degradation during frying or prolonged storage (Murador et al., 2014).

The HCA grouped the 30 food categories into 7 distinct clusters (C1–C7), reflecting similarities in nutrient composition, food matrix, and processing-related nutrient retention (Figure 5A). Foods with similar biochemical properties and processing methods were grouped together, while those with different matrices or processing pathways were positioned farther apart. This clustering emphasizes the relationship between food composition, processing, and nutrient stability, which is consistent with previous food science and nutrition findings (Murador et al., 2014; Rickman et al., 2007). Legumes and pasta are similar in that they are both starch- and protein-rich and are commonly exposed to boiling or prolonged hydration. These processes cause water-soluble vitamins (e.g., vitamin B1, folate, and vitamin C) to leach into the cooking water. Minerals remain relatively stable, but they may also leach depending on the amount of water used (Dewanto, Wu, & Liu, 2002; Ziegler & Filer, 1996). The presence of phytates in legumes and grains further influences mineral retention and bioavailability.

The C2 cluster (Figure 5A) includes tomatoes, vegetables, potatoes, cereals, oats, rice, fruits, sweet potatoes, flour, and nuts. These foods have a high sensitivity to the loss of water-soluble vitamins (e.g., vitamin C, folate, and B vitamins) during moist-heat cooking and oxidative degradation (Rickman et al., 2007). Tomatoes and orange-fleshed vegetables have carotenoids that exhibit enhanced bioaccessibility after heating and oxidative losses under prolonged or high-temperature cooking (Murador et al., 2014). Cereals and flours are grouped together due to their similar grain chemistry and processing methods, while nuts are grouped with plant foods despite their high lipid content.



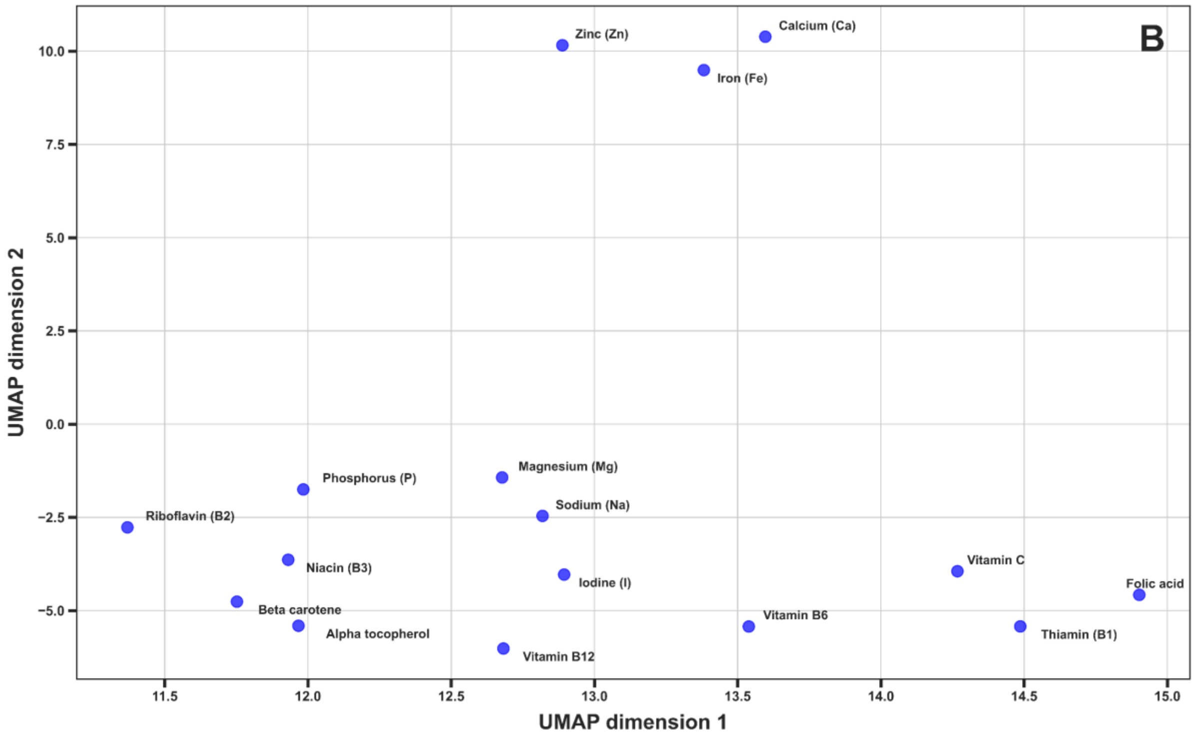


Figure 4. Biplots of PCA (A) and UMAP (B) illustrating the overall variation among the nutrients.

Marine foods are grouped together in Cluster 3 due to their protein-lipid matrices and characteristic mineral profiles, particularly iodine (Figure 5A). Moist-heat cooking methods, such as steaming and poaching, tend to preserve fat-soluble vitamins, but iodine can be lost due to its volatility (Zimmermann, 2009). Their distinct nutrient composition differentiates them from terrestrial animal foods. Dairy products and eggs cluster together due to their high calcium-to-phosphorus (Ca:P) ratio and protein-rich matrices. Heat treatments such as pasteurization cause only modest losses of vitamin B2 and vitamin B12, which explains their cohesive grouping (Ball, 2005). Eggs and dairy share similar properties, such as lipid-soluble vitamins (A and E) and protein denaturation behavior, which explains their similarity in C4 cluster (Figure 5A). The C5 cluster included liver and other organ meats, as well as chicken, turkey, beef, veal, lamb, and ham. These foods are rich in heme iron and B vitamins, which are susceptible to drip loss and thermal denaturation during cooking (Hurrell & Egli, 2010).

Organ meats, which have a particularly high folate and B12 content, aligned with muscle meats because they undergo similar degradation pathways under moist and dry heat. Pork and bacon formed a distinct cluster (C5 and C6) due to the processes of curing, smoking, and frying, which increase sodium content and promote the oxidation of fat-soluble vitamins (Murador et al., 2014). These processing-specific effects cause their nutrient retention profiles to diverge from those of fresh meats. Fats and oils formed a distinct cluster, reflecting their lipid-dominant composition and minimal water-soluble vitamin and mineral content. The stability of their nutrients is primarily governed by the oxidative degradation of tocopherols and carotenoids during heating and storage (Rickman et al., 2007).

The HCA grouped the 16 vitamins and minerals into 5 distinct clusters (C1–C5), reflecting similarities in their biochemical properties, solubility, and stability under food processing conditions (Figure 5B). Nutrients with similar chemical structures or degradation pathways were positioned close together, while those with different physicochemical behaviors were positioned farther apart. This clustering pattern is consistent with previous research on the stability and retention of nutrients in food (Rickman et al., 2007; Ziegler & Filer, 1996). Figure 5B shows that the C1 cluster reflects the extreme sensitivity of both nutrients to heat, oxygen, and water leaching. Vitamin C is well known for rapidly degrading during boiling, steaming, and storage (Rickman et al., 2007). Similarly, folic acid is highly unstable under thermal and oxidative conditions, and significant losses have been reported during cooking and processing (McKillop et al., 2002). Their shared instability explains their close association in the dendrogram. Vitamin B1 and vitamin B6 formed C2 cluster and are water-soluble B vitamins that are moderately sensitive to moist-heat cooking. Vitamin B1 is particularly vulnerable to leaching and prolonged heating, while vitamin B6 undergoes degradation during thermal processing and storage (Ziegler & Filer, 1996). Their clustering reflects their hydrophilic nature and similar degradation kinetics under common cooking methods. Zn, Ca, and Fe clustered together (C3) due to their structural roles in food matrices and relative stability under heat. Mineral nutrients are not destroyed by cooking, but they can be lost when water used for cooking is washed away. Their grouping is explained by their co-occurrence in cereals, legumes, and meats, as well as their similar retention behavior.

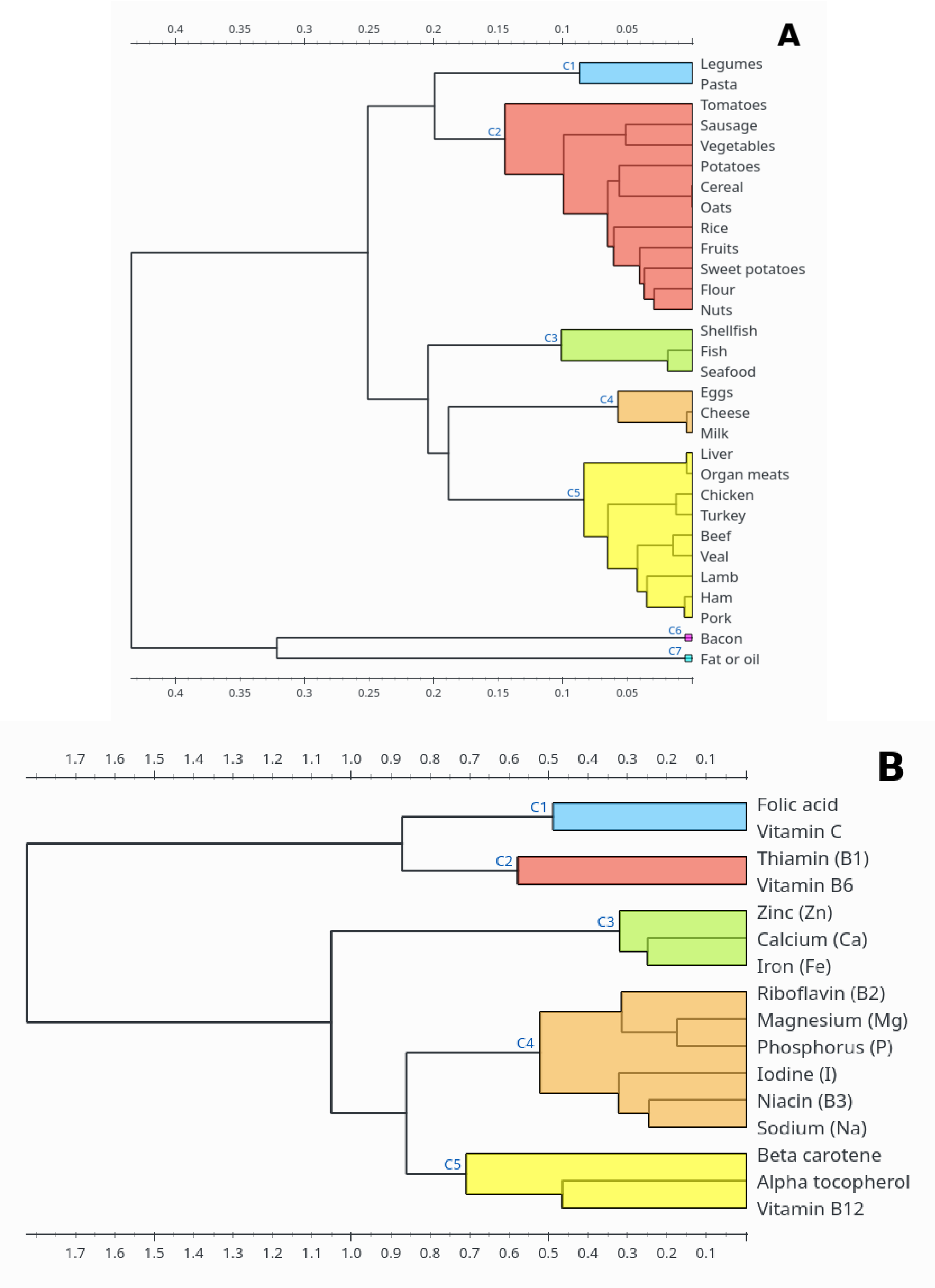


Figure 5. Dendrograms of cluster analysis based on foods (A) and nutrients (B).

A diverse cluster (C4) formed that included vitamin B2, Mg, P, I, vitamin B3, and Na. These nutrients are generally more stable under heat, but they differ in volatility and solubility (Figure 5B). Vitamin B2 and vitamin B3 are relatively heat-stable B vitamins (Ball, 2005), while minerals such as Mg, P, and (Na are stable but subject to leaching. Iodine is unique in that it is highly volatile, experiencing significant losses during boiling and baking (Zimmermann, 2009). Despite their differing chemical properties, their clustering suggests overlapping retention patterns. Beta carotene, alpha tocopherol, and vitamin B12 clustered together combines fat-soluble vitamins (carotenoids and tocopherols) with vitamin B12, which is structurally distinct but shares sensitivity to oxidative and thermal degradation (Figure 5B). Carotenoids and tocopherols are prone to oxidation during frying and storage (Murador et al., 2014), while vitamin B12 degrades under prolonged heating (Ball, 2005). Their grouping highlights the influence of processing-induced oxidative stress on nutrient stability. The clustering patterns shown in this study provide a predictive framework for nutrient stability, supporting targeted interventions to maximize nutrient retention in food systems.

CONCLUSION

This study used multivariate analyses, including PCA, ISOMAP, UMAP, and HCA, to evaluate nutrient retention factors (RFs) across diverse foods and processing methods. The findings revealed significant variability in nutrient stability, which is influenced by the interaction between the physicochemical properties of nutrients, the composition of the food matrix, and the intensity of processing. Among the evaluated methods, boiling, prolonged thermal treatment, and high-moisture processing were consistently associated with the lowest RFs, particularly for water-soluble vitamins, due to thermal degradation and leaching into cooking media. In contrast, short-duration, low-moisture methods such as reheating, instant preparation, and mild thermal treatments showed significantly higher RFs, indicating their effectiveness in preserving labile micronutrients. Minerals such as Zn, Fe, Ca, P, and Mg exhibited the highest mean RFs (>0.90), confirming their resilience to heat and oxidation. In contrast, water-soluble vitamins, particularly folic acid, vitamin B1, vitamin B6, and vitamin C, showed the lowest retention values (<0.80), indicating their susceptibility to thermal and oxidative degradation. - The strong positive correlations observed among minerals and B-complex vitamins suggest that they are governed by similar physicochemical mechanisms. Dimensionality reduction and clustering analyses revealed distinct grouping patterns among food categories and nutrients, highlighting matrix-specific effects. Meat and dairy products formed clusters characterized by moderate vitamin loss and stable minerals. In contrast, legumes and pasta exhibited high water-soluble vitamin loss due to leaching. From an industrial perspective, these findings recommend minimizing high-moisture and long-duration thermal processes when nutrient preservation is a priority, particularly for vitamin-rich foods. Adopting alternative strategies such as reduced cooking times, limited water contact, controlled reheating, and instant or minimally processed formulations can substantially improve micronutrient retention. Overall, the results highlight the importance of choosing cooking and processing methods that balance food safety with nutritional preservation. The multivariate framework used here is a robust approach for identifying nutrients sensitive to processing and can guide the optimization of food preparation strategies to improve micronutrient retention in various food systems.

Compliance with Ethical Standards

Peer Review

This article has been reviewed by independent experts in the field using a rigorous double-blind peer review process.

Conflict of Interest

The author declares that there is no conflict of interest.

Author Contribution

The author solely conceived, designed, and conducted the study, analyzed the data, and wrote the manuscript.

Data Availability

All data are included in the article is publicly available at https://www.foodstandards.gov.au/science-data/food-nutrient-databases/afcd/australian-food-composition-database-download-excel-files

REFERENCES

Alfakih, A. Y. (2018). *Euclidean distance matrices and their applications in rigidity theory*. Springer International Publishing. https://doi.org/10.1007/978-3-319-97846-8

Australian Food Composition Database. (2023). *The food file contains background information relating to each food*. https://www.foodstandards.gov.au/science-data/food-nutrient-databases/afcd/australian-food-composition-database-download-excel-files

Ball, G. F. M. (2005). *Vitamins In foods: Analysis, bioavailability, and stability* (1st ed.). CRC Press. https://doi.org/10.1201/9781420026979

Becht, E., McInnes, L., Healy, J., Dutertre, C. A., Kwok, I. W., Ng, L. G., Ginhoux, F., & Newell, E. W. (2019). Dimensionality reduction for visualizing single-cell data using UMAP. *Nature biotechnology*, 37(1), 38-44.

Bognár, A. (1998). Comparative study of frying to other cooking techniques influence on the nutritive value. *Grasas y Aceites*, *49*(3–4), 250–260. https://doi.org/10.3989/gya.1998.v49.i3-4.746

Bognár, A. (2002). *Tables on weight yield of food and retention factors of food constituents for the calculation of nutrient composition of cooked foods (dishes)*. Berichte der Bundesforschungsanstalt für Ernährung.

Choe, E., & Min, D. B. (2007). Chemistry of deep-fat frying oils. *Journal of Food Science*, *72*(5). https://doi.org/10.1111/j.1750-3841.2007.00352.x

Dewanto, V., Wu, X., Adom, K. K., & Liu, R. H. (2002). Thermal processing enhances the nutritional value of tomatoes by increasing total antioxidant activity. *Journal of Agricultural and Food Chemistry*, *50*(10), 3010–3014. https://doi.org/10.1021/jf0115589

Dewanto, V., Wu, X., & Liu, R. H. (2002). Processed Sweet Corn Has Higher Antioxidant Activity. *Journal of Agricultural and Food Chemistry*, *50*(17), 4959–4964. https://doi.org/10.1021/jf0255937

Erdman Jr, J. W., Macdonald, I. A., & Zeisel, S. H. (2012). *Present knowledge in nutrition*. John Wiley & Sons.

Erdman, J. W., Jr., Smith, J. W., Kuchan, M. J., Mohn, E. S., Johnson, E. J., Rubakhin, S. S., Wang, L., Sweedler, J. V., & Neuringer, M. (2015). Lutein and Brain Function. *Foods*, 4(4), 547-564. https://doi.org/10.3390/foods4040547

Estévez, M. (2011). Protein carbonyls in meat systems: A review. *Meat Science*, *89*(3), 259–279. https://doi.org/10.1016/j.meatsci.2011.04.025

Favell, D. J. (1998). A comparison of the vitamin C content of fresh and frozen vegetables. *Food Chemistry*, *62*(1), 59–64. https://doi.org/10.1016/S0308-8146(97)00165-9

Gregory, J. F. (2001). Case study: Folate bioavailability. *Journal of Nutrition*, *131*(4), 1376S-1382S. https://doi.org/10.1093/jn/131.4.1376S

György, P., & Pearson, W. N. (2013). *The vitamins: Chemistry, physiology, pathology, methods*. Elsevier.

Horzum, Ö., Karaman, H. T., & Dumanoğlu, H. (2025). Physicochemical and functional quality characteristics of fresh, dried, and chip forms of 'fuji'apple: insights into variable relationships. *International Journal of Agriculture Environment and Food Sciences*, 9(2), 599-607. https://doi.org/10.31015/2025.2.33

Hurrell, R., & Egli, I. (2010). Iron bioavailability and dietary reference values. *American Journal of Clinical Nutrition*, *91*(5), 1461S-1467S. https://doi.org/10.3945/ajcn.2010.28674F

Jolliffe, I. T., & Cadima, J. (2016). Principal component analysis: A review and recent developments. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *374*(2065), 20150202. https://doi.org/10.1098/rsta.2015.0202

Lee, S. K., & Kader, A. A. (2000). Preharvest and postharvest factors influencing vitamin C content of horticultural crops. *Postharvest Biology and Technology*, *20*(3), 207–220. https://doi.org/10.1016/S0925-5214(00)00133-2

Lešková, E., Kubíková, J., Kováčiková, E., Košická, M., Porubská, J., & Holčíková, K. (2006). Vitamin losses: Retention during heat treatment and continual changes expressed by mathematical models. *Journal of Food Composition and Analysis*, *19*(4), 252–276. https://doi.org/10.1016/j.jfca.2005.04.014

McInnes, L., Healy, J., & Melville, J. (2018). Umap: Uniform manifold approximation and projection for dimension reduction. arXiv preprint arXiv:1802.03426.

McKillop, D. J., Pentieva, K., Daly, D., McPartlin, J. M., Hughes, J., Strain, J. J., Scott, J. M., & McNulty, H. (2002). The effect of different cooking methods on folate retention in various foods that are amongst the major contributors to folate intake in the UK diet. *British Journal of Nutrition*, *88*(6), 681–688. https://doi.org/10.1079/BJN2002733

Meinhardt, A.-K., Müller, A., Burcza, A., & Greiner, R. (2019). Influence of cooking on the iodine content in potatoes, pasta and rice using iodized salt. *Food Chemistry*, *301*, 125293. https://doi.org/10.1016/j.foodchem.2019.125293

Miglio, C., Chiavaro, E., Visconti, A., Fogliano, V., & Pellegrini, N. (2008). Effects of different cooking methods on nutritional and physicochemical characteristics of selected vegetables. *Journal of Agricultural and Food Chemistry*, *56*(1), 139–147. https://doi.org/10.1021/jf072304b

Murador, D. C., Da Cunha, D. T., & De Rosso, V. V. (2014). Effects of cooking techniques on vegetable pigments: A meta-analytic approach to carotenoid and anthocyanin levels. *Food Research International*, *65*, 177–183. https://doi.org/10.1016/j.foodres.2014.06.015

Muroki, M. W., Waswa, L. M., Fungo, R., Kabwama, A., & Mahungu, S. M. (2023). Cooking properties and nutrient retention of biofortified common bean (phaseolus vulgaris) varieties: The case of Burundi. *Frontiers in Sustainable Food Systems*, *7*, 1062978. https://doi.org/10.3389/fsufs.2023.1062978

Murphy, E. W., Criner, P. E., & Gray, B. C. (1975). Comparisons of methods for calculating retentions of nutrients in cooked foods. *Journal of Agricultural and Food Chemistry*, *23*(6), 1153–1157. https://doi.org/10.1021/jf60202a021

Rehman, Z., & Shah, W. H. (2005). Thermal heat processing effects on antinutrients, protein and starch digestibility of food legumes. *Food Chemistry*, *91*(2), 327–331. https://doi.org/10.1016/j.foodchem.2004.06.019

Ribaya-Mercado, J. D., & Blumberg, J. B. (2004). Lutein and zeaxanthin and their potential roles in disease prevention. *Journal of the American College of Nutrition*, *23*(sup6), 567S-587S. https://doi.org/10.1080/07315724.2004.10719427

Rickman, J. C., Barrett, D. M., & Bruhn, C. M. (2007). Nutritional comparison of fresh, frozen and canned fruits and vegetables. Part 1. Vitamins C and B and phenolic compounds. *Journal of the Science of Food and Agriculture*, *87*(6), 930–944. https://doi.org/10.1002/jsfa.2825

Rodriguez-Amaya, D. B. (2001). *A guide to carotenoid analysis in foods* (Vol. 71). ILSI press Washington, DC, USA:

Shi, J., & Maguer, M. L. (2000). Lycopene in tomatoes: Chemical and physical properties affected by food processing. *Critical Reviews in Food Science and Nutrition*, *40*(1), 1–42. https://doi.org/10.1080/10408690091189275

Teas, J., Pino, S., Critchley, A., & Braverman, L. E. (2004). Variability of iodine content in common commercially available edible seaweeds. *Thyroid*, *14*(10), 836–841. https://doi.org/10.1089/thy.2004.14.836

Tenenbaum, J. B., Silva, V. D., & Langford, J. C. (2000). A Global Geometric Framework for Nonlinear Dimensionality Reduction. *Science*, *290*(5500), 2319–2323. https://doi.org/10.1126/science.290.5500.2319

Thomson, B. M. (2009). Stability of added iodine in processed cereal foods. *Food Additives & Contaminants, Part A*, *26*(1), 25–31. https://doi.org/10.1080/02652030802258842

United States Department of Agriculture Agricultural Research Service. (2007). *Table of nutrient retention factors, release 6*. Nutrient Data Laboratory. https://www.ars.usda.gov/northeast-area/beltsville-md-bhnrc/beltsville-human-nutrition-research-center/methods-and-application-of-food-composition-laboratory/mafcl-site-pages/nutrient-retention-factors/

Van Der Maaten, L. (2009). Learning a parametric embedding by preserving local structure. In Artificial intelligence and statistics (pp. 384-391). PMLR.

Ward, J. H. (1963). Hierarchical grouping to optimize an objective function. *Journal of the American Statistical Association*, *58*(301), 236–244. https://doi.org/10.1080/01621459.1963.10500845

Watanabe, F. (2007). Vitamin B_{12} sources and bioavailability. *Experimental Biology and Medicine*, *232*(10), 1266–1274. https://doi.org/10.3181/0703-MR-67

Zerdin, K., Rooney, M. L., & Vermuë, J. (2003). The vitamin C content of orange juice packed in an oxygen scavenger material. *Food Chemistry*, *82*(3), 387–395. https://doi.org/10.1016/S0308-8146(02)00559-9

Ziegler, E., & Filer, L. (Eds.). (1996). *Present knowledge of nutrition* (Issue Ed. 7). International Life Sciences Institute (ILSI Press); CABI Databases.

Zimmermann, M. B. (2009). Iodine deficiency. *Endocrine Reviews*, *30*(4), 376–408. https://doi.org/10.1210/er.2009-0011

Zimmermann, M. B., Zeder, C., Chaouki, N., Saad, A., Torresani, T., & Hurrell, R. F. (2003). Dual fortification of salt with iodine and microencapsulated iron: A randomized, double-blind, controlled trial in moroccan schoolchildren. *American Journal of Clinical Nutrition*, *77*(2), 425–432. https://doi.org/10.1093/ajcn/77.2.425