

## Analytical Chemistry Approaches for Evaluating the Quality and Functional Potential of Nutrient-Enriched Foods

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### ABSTRACT

Food enriched with nutrients has become a significant measure to global nutritional problems as well as ensuring consumer health but it requires proper assessment of nutrient content, stability, safety and functionality. Analytical chemistry plays a central role by providing highly sophisticated tools that can solve the chemical intricacy of fortified food matrices. This paper critically reviews contemporary analytical chemistry methods used in the quality and functional evaluation of nutrient-enriched foods and focuses especially on chromatographic, spectroscopic, and biosensing applications. Determination and structural characterization of vitamins, minerals, fatty acids and bioactive compounds can be accurately determined using chromatographic techniques, such as liquid and gas chromatography with sophisticated detectors, and structural changes and

authenticity can be quickly studied using spectroscopic techniques, which do not cause destruction of compositional integrity. Emerging biosensors and analysis platforms with the help of nanotechnology are more sensitive and enable real time tracking of nutrient stability and food quality. In addition to the compositional analysis, the review identifies the importance of analytical chemistry in food safety, analysis of adulteration and determination of nutrient degradation rates in processing and storage. More attention is paid to analytical procedures integrating chemical profiles with bioavailability, bio accessibility, and health-promoting potential with the support of chemometric and data-driven methodologies. This review shows the significance of an interdisciplinary approach in designing nutrient-enriched foods by combining analytical chemistry with food quality and nutrition science. This kind of integration is needed in enhancing regulatory compliance, consumer confidence, and practical workability of enriched food products, which contributes to the overall improvement of population health.

**Keywords:** Analytical chemistry, food with added nutrients, food quality measurement, chromatography, spectroscopy, food biosensors, functional foods, food authenticity and food safety, bioavailability, food functional foods, chemometrics.

## 1. INTRODUCTION

The rapid development of fortified and nutrient-enriched food reflects global response to rising nutritional deficiencies, lifestyle-related diseases, and consumer concerns regarding diet-health relationship. The modern world food systems are increasingly being founded on the enrichment strategies to enrich the nutritional value of the most popular products and to supply them with the required vitamins, minerals, fatty acids, and bioactive compounds without adversely influencing the sensory acceptability. However, effectiveness of this kind of strategies does not only depend on the integration of nutrients but on their stability, bioavailability, safety and functionality under the multifaceted food systems (Ashraf, 2025; Mkambula et al., 2022). Analytical chemistry is at center stage when a solution to such predicaments is required since it offers reliable instruments to describe the composition of food, monitor quality and approximate functional potential. Traditional nutritional labelling does not usually reflect the minor differences in

nutrient integrity or the occurrence of bioactive compounds, which bring about health-promoting benefits. Complex chemical methods, such as chromatography, spectroscopy, and biosensor-based systems, have consequently turned out to be invaluable in a thorough assessment of nutrient-enriched foods. These techniques allow accurate quantification, structural characterization as well as real-time monitoring of both nutrients and functional constituent (Naviglio & Gallo, 2020; Patil et al., 2025). In addition to compositional analysis, other applications of analytical chemistry are in food safety, verification of authenticity, and shelf-life determinations, which are essential because of consumer confidence as well as regulatory requirements. The chemical fingerprints and degradation markers can be used to distinguish between the authentic fortified products and mislabeled or adulterated food. Also, analytic tools are becoming part of the predictive biological activity and health functionality by correlated chemical profiles and bioavailability, and physiological performance (Bharti et al., 2024; Li et al., 2021).

The review combines analytical chemistry methods with food quality and nutritional analysis to bring out their combined use in the assessment of nutrient-added foods. It focuses on the use of modern chemical techniques and their role in comprehending nutrient composition, functional potential, safety, and stability, which ultimately lead to better health outcomes of the consumers.

Foods enriched in nutrients are produced so as to increase the nutritional content of the usual products by adding or increasing the amount of essential nutrients or bioactive compounds. Such foods might contain cereals that have been fortified with vitamins, dairy products that have been fortified with minerals, oils that contain omega-3 supplements as well as food that has been fortified with antioxidants of plant origin. Although the enrichment strategies vary in their formulation and processing, they all are aimed at sealing certain nutritional deficiencies without compromising the quality of the product, as well as its acceptability by consumers (Adinepour et al., 2022; Dziki, 2021; Ursachi et al., 2020). The nutrient-enriched foods should be evaluated in terms of quality and not merely in terms of quantification of the nutrient levels. Interactions of the added nutrients with the food matrix, processing environment, and storage environments affect the

functional performance of added nutrients. As an example, fat-soluble vitamins can be oxidized, whereas micronutrients that are vulnerable to heat damage can be destroyed during heating. Analytical chemistry offers opportunities to identify such alterations and determine the concentration of nutrients along the lifetime of the product (Dima et al., 2020; Xu et al., 2022). The other important factor of the quality assessment is the property of bioavailability that defines the possibility of the proper absorption and use of enriched nutrients by the human body. Releases and absorptions of nutrients depend on chemical form, size of the particles, encapsulation, and interactions between the particles and the matrix. Simulated digestion of nutrients can be followed with the help of analytical methods, which provides information about the functionally effective value of the nutrient, not its nominal content (Nicolescu et al., 2023; Rodrigues et al., 2022). Chemical characteristics of food that are determined in a food quality analysis, e.g. flavor compounds, lipid oxidation products, and volatile profiles, which can be modified during enrichment. Monitoring through analysis will make sure that nutritional enhancement will not affect product acceptability. In this regard, chemistry-induced quality control is a counterbalancing force between nutritional enhancement and food integrity, in general (Clarke et al., 2021; Custodio-Mendoza et al., 2023; Naozuka, 2024). Comprehensively, enriched foods will need a multidimensional quality measurement framework with analytical chemistry as its foundation. Chemical methods can provide a scientifically sound knowledge of enriched food performance by incorporating compositional error, stability examination, and functional assessment (Naozuka, 2024; Petropulos & Balabanova, 2021). Figure 1.1 shows a conceptual framework at the systems level showing how analytical chemistry forms the foundation of the nutrient-enriched foods assessment; beginning with the addition of vitamins, minerals, fatty acids, and bioactive compounds into complex food matrices through the incorporation of these compounds and then evaluating them by applying sophisticated chromatographic, spectroscopic, elemental, and biosensor-based methodologies.

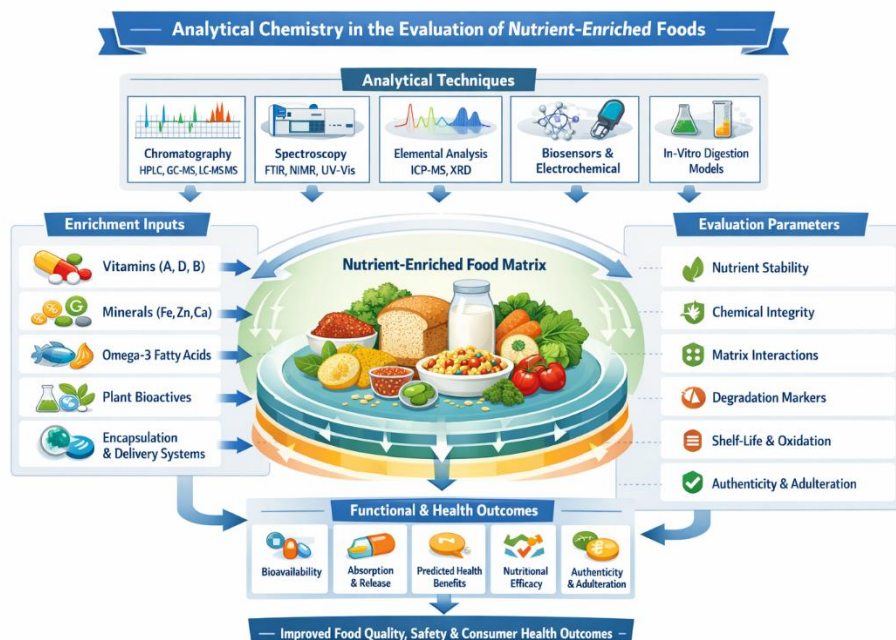


**Figure 1.1** Integrated analytical chemistry scheme depicting the overall assessment of nutrient-enriched foods in composition, stability, bioavailability, safety and functional health outcomes.

## 2. Nutrient and Bioactive Assessment with the Help of Analytical Chemistry Approaches

Food systems that are rich in nutrients are complex, and analytical chemistry provides a wide variety of tools that can be used to tackle the problem. Food matrices are usually a source of proteins, carbohydrates, lipids, and additives that may affect a proper measure of nutrients. In the process of evaluating both macro and micronutrients and bioactive compounds, advanced analytical methods are thus highly required to provide a selective, sensitive, and reproducible analysis (Bharti et al., 2024). One of the most prevalent methods of the nutrient analysis is the chromatographic techniques. High-performance liquid chromatography is highly applicable in the separation of vitamins, amino acids, polyphenols, and antioxidants since it has high resolution and its application can be expanded to various types of detectors (Avrămia et al., 2024). The gas chromatography is most useful in fatty acid profiling and analysis of volatile compounds, which provide information on the quality of lipids and their oxidative stability. In combination with mass spectrometry,

these methods are more sensitive and can be structurally confirmed, and trace amounts of nutrients and degradation products can be detected (Waktola et al., 2020). Spectroscopic techniques are used to supplement chromatographic methods by providing fast and in most cases non-destructive analysis. Ultraviolet and visible spectroscopy are typically used to screen standard nutrient fortification and antioxidant capacity, whereas infrared and Raman spectroscopy can give molecular-scale data on food structure and food composition (Fakhlaei et al., 2024). The nuclear magnetic resonance spectroscopy also represents an extension of the analytic performance as it allows comprehensive metabolomic profiling, which can be used to confirm the quality as well as the authenticity (Balthazar et al., 2021; Maestrello et al., 2022). The combination of various analytical sites makes it possible to have a comprehensive perception of nutrient-enhanced foods. Instead of using one approach, contemporary analytical approaches combine separation, detection, and multivariate data analysis in order to capture the complexity of food systems. This combined methodology reinforces the association between chemical composition and nutritional import, which is the basis of the assessment of functional foods (Balkir et al., 2021). Figure 2.2 compares the applicability of primary analytical techniques of chemistry to determine nutrients and bioactive components in fortified foods. Vitamins, polyphenols, antioxidants, and metabolites have a high affinity to chromatographic techniques, specifically to HPLC and LC-MS/MS, and fatty acids and volatile compounds are best analyzed using GC-MS. The rapid, complementary, and mostly non-destructive screening of structural characterization and metabolomic profiling, as well as authenticity searching, is carried out by spectroscopic techniques (UV-Vis, FTIR, Raman, and NMR). In general, the image underscores the importance of integrated and multi-techniques in the context of the complexity of nutrient-enriched food matrices.

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Suitability of Analytical Chemistry Techniques for Nutrient and Bioactive Compound Assessment

| Target Components                                                                                    | Analytical Techniques                                                             |                                                                                   |                                                                                   |                                                                                   |                                                                                   |                                                                                    |  High<br> Moderate<br> Low |
|------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                      | HPLC                                                                              | GC-MS                                                                             | LC-MS/MS                                                                          | UV-Vis Spectroscopy                                                               | FTIR                                                                              | Raman Spectroscopy                                                                 |                                                                                                                                                                                                                                                                                     |
|  Vitamins           |  |  |  |  |  |  |                                                                                                                                                                                                                                                                                     |
|  Minerals           |  |  |  |  |  |  |                                                                                                                                                                                                                                                                                     |
|  Fatty Acids        |  |  |  |  |  |  |                                                                                                                                                                                                                                                                                     |
|  Amino Acids        |  |  |  |  |  |  |                                                                                                                                                                                                                                                                                     |
|  Polyphenols        |  |  |  |  |  |  |                                                                                                                                                                                                                                                                                     |
|  Antioxidants       |  |  |  |  |  |  |                                                                                                                                                                                                                                                                                     |
|  Volatile Compounds |  |  |  |  |  |  |                                                                                                                                                                                                                                                                                     |
|  Metabolites        |  |  |  |  |  |  |                                                                                                                                                                                                                                                                                     |

Suitability of Major Analytical Chemistry Techniques for Assessment of Nutrient and Bioactive Compounds in Nutrient-Enriched Foods

 High  
 Moderate  
 Low

**Figure 2.2** Suitability map of major analytical chemistry techniques for the assessment of nutrients and bioactive compounds in nutrient-enriched food systems.

### 3. Analytical Chemistry Approaches in Nutrient and Bioactive Assessment

The chemical analysis of food enriched with nutrients needs methodologies that are able to analyse chemically diverse substances in a wide range of concentrations in highly complex matrices. Preparation of samples is a critical step because proteins, lipids, and polysaccharides (among other components) are potential sources of interference with the extraction and detection of the analyte. More sophisticated extraction methods are now being used to enhance selectivity and recovery of the analyte in the form of solid-phase extraction, pressure liquid extraction, and microextraction techniques to reduce solvent consumption (Alahmad et al., 2023; Mosić et al., 2020). The use of high-performance liquid chromatography as an analytical method in the detection of micronutrient and bioactive compounds is still considered the best method as it is versatile and compatible with various detection methods (Donno et al., 2020). The separation of the vitamins, phenolics, and amino acids is generally done by use of reverse-phase and hydrophilic interaction chromatography whilst ion-exchange chromatography is widely applicable to mineral-associated species. Coupling with mass spectrometry allows structural

clarification, isotopic validation, and ultra-trace quantification which is needed to monitor products of nutrient degradation and stability of fortification (Xia et al., 2023; Zhao et al., 2021). Gas chromatography frequently used in conjunction with flame ionization or mass spectrometric detection offers comprehensive data on the quality of lipids using fatty acid methyl ester profiling and oxidative marker analysis. The measurements are of special importance to enriched foods with polyunsaturated fatty acids, in which oxidative stability has direct effects on nutritional efficacy. The high-resolution mass spectrometry continues to improve the identification of compounds and non-targeted screening strategies (Lima-Pereira et al., 2025; Sun et al., 2020). The spectroscopic methods provide complementary analyzing advantages especially in fast screening and fingerprinting. Fourier-transform infrared and Raman spectroscopy can be used to provide coverage of molecular aspects of structural changes in food items, whereas chemometric modelling can be used to discriminate on levels of enrichment and authenticity (Biancolillo et al., 2020). The nuclear magnetic resonance spectroscopy is the best in terms of reproducibility and quantitative accuracy, enabling the results of metabolomic profiling and longitudinal stability research. These methods are used together to promote both analytical strategies that are targeted and holistic (Huang et al., 2022).

#### **4. The new Analytical Instruments and Biosensing Technologies**

Biosensing technologies, as one of the progressive improvements in the analytical assessment of nutrient-enriched food, allow selective, real-time detection of particular chemical species. There are enzyme-based electrochemical biosensors which utilize catalytic redox reactions to measure vitamins and antioxidants at a high sensitivity and ion-selective electrodes are used to measure minerals in fortified matrices. The development of newer materials in transducer such as conductive polymers and nanostructured electrodes has enhanced the stability of the signal and also the detection limits (Pisoschi et al., 2025; Ye et al., 2020). Optical biosensors, in particular fluorescence and surface plasmon resonance platforms, have label free detection, together with kinetic data on nutrient- matrix- interactions. They are progressively used in quality management processes in which quick decisions are needed. Such nanomaterials as gold nanoparticles and graphene derivatives are

integrated to make analytical performance better in terms of signal response and selectivity (Ahmad et al., 2025; Camarca et al., 2021). Portable analytical instruments with biosensors and miniaturized spectroscopic units are transforming the food quality monitoring by making the analysis decentralized. These instruments are used to facilitate ongoing quality evaluation at the production, storage, and distribution level, which is in line with current food supply chain needs (BeĆ et al., 2022). The latest biosensing technology allows selective and instant evaluation of nutrient-enriched foods. Electrochemical and optical biosensors are used to analyze fortified matrices of vitamins, minerals and antioxidants as demonstrated in Figure 4.3 Electrochemical sensors based on enzymes are used in the detection of vitamin and antioxidants (redox reactions), and minerals (ion-selective electrodes). Label-free detection and kinetic techniques of nutrient-matrix interactions can be detected using optical platforms such as fluorescence and surface plasmon resonance systems. Introduction of nanomaterials like gold nanoparticles, conductive polymers, and graphene derivatives are used to improve the sensor sensitivity, selectivity, and signal stability to allow the implementation of portable, on-site quality monitoring all over the food supply chain.

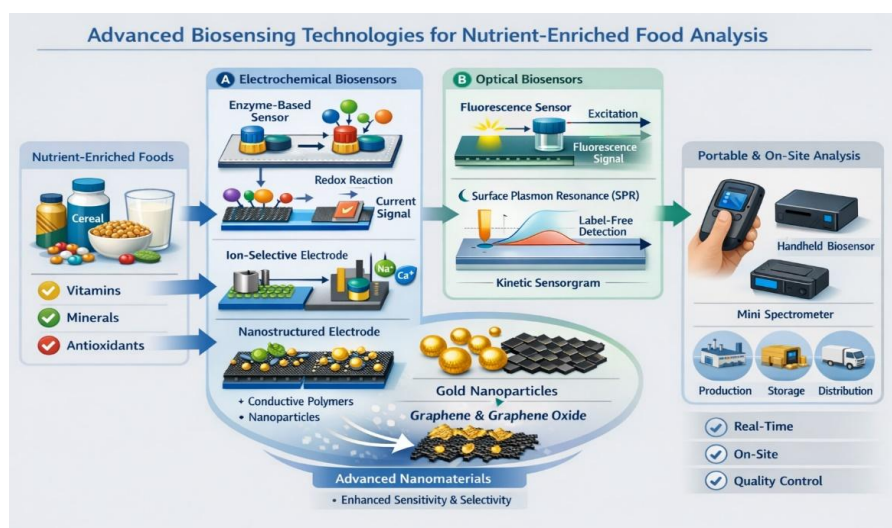


**Figure 4.3** Schematic illustration of the advanced electrochemical and optical biosensing technologies in combination with nanomaterials detection in the analysis of real-time nutrient variation in fortified food matrices.

## 5. Food Safety, Authenticity and Stability of Enriched Foods

The reaction kinetics of environmental and matrix-specific factors determine the chemical stability of fortified nutrients. Sensible monitoring of degradation mechanisms, such as oxidation, hydrolysis and photochemical reactions, gives a quantitative understanding of nutrient degradation mechanisms. Chromatographic data is used to make kinetic models that predict shelf-life and formulation strategies (Lavelli et al., 2021; Lucas-Aguirre et al., 2020). Non-targeted analysis methods with chemometrics are becoming important in the authentication of food fortified with nutrients. Chromatographic profiles and spectroscopic fingerprints, when tested through multivariate statistical tools allow distinguishing authentic products and adulterated products with high confidence. This is a useful method especially in identifying dilution, unauthorized fortification or false health claims (González-Domínguez et al., 2022) (Rodionova et al., 2024).

Further uses of analytical chemistry in food safety evaluation involve the detection of contaminants, toxicants that are produced during the process, and chemicals found during packaging. The sensitive analytical platforms are used to meet regulatory limits and risk assessment frameworks required to govern fortified food (Khatri et al., 2025).

## 6. Anticipating the Potential of Function and Health Promotion

Chemical composition alone is not sufficient to determine functional performance of nutrient-enriched foods, but rather nutrient bio accessibility and bioavailability are additional factors that influence functional performance of these foods. These processes can be studied mechanistically with the help of analytical chemistry which monitors chemical changes in simulated digestion and absorption. The quantitative data obtained through chromatographic and spectroscopic analyses of digesta fractions give information on the nutrient release and matrix interactions (Dima et al., 2020). Integration of compositional, structural and functional datasets is made possible by the use of chemometric and machine learning applications. These data-oriented solutions enable to predict a biological activity, as well as to develop evidence-based nutritional claims. The chemistry-based models can help to refine nutrition strategies through the correlation of analytical signatures with

functionality (García-Pérez et al., 2024; Picard et al., 2021).

## 7. FUTURE DIRECTIONS

The next step in analytical evaluation of nutrient-enriched foods ought to focus on the creation of combined, high-throughput, and sustainable analytical platforms, which can support the complexity of food matrices that are growing. More effort should be focused on green methods of analytical chemistry that minimize the use of solvents, the use of energy, and the time of sample preparation without loss of the accuracy of an analytical procedure. Combining sophisticated spectroscopy, biosensing, and artificial intelligence is likely to improve prediction modeling of nutrient stability and bioavailability and functional performance. The combination of metabolomics and nutritional and physiological information, based on multi-omics approaches, will enhance the knowledge of diet-health interactions. Moreover, harmonization and standardization of data analysis procedures in different laboratories are still crucial in ensuring comparability of data and acceptability by the regulatory authorities. Integration of mobile and live analysis tools in the distribution and production systems of food will facilitate active quality control and disclosure. All these developments together will lead to the ability to pursue more precise nutrition, develop more informed food design, and increase the scientific accuracy of health-related claims.

## 8. CONCLUSION

Analytical chemistry has offered a solid and essential platform on which the quality, safety, and functional possibilities of nutrient-enriched foods are judged. With a high level of chromatography, spectroscopy and biosensing, it can be ensured to characterize the nutrient composition in food systems, ascertain stability, authenticity and also bioavailability. Combining chemical analysis with food quality test and nutrition science will enhance the scientific foundation of developing functional foods and compliance. The chemistry based analytical methodologies would still remain at the center of product integrity and health efficacy as the consumers are increasingly making evidence-based nutritional product demands. Increasing the interdisciplinary teamwork and methodological creativity will also contribute to the enhancing of the contribution of analytical chemistry to the

achievement of better health outcomes in society.

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