MOLECULAR NUTRITION MEETS ENVIRONMENTAL SCIENCE: A REVIEW OF NOVEL BIOACTIVE COMPOUNDS AND THEIR ECOTOXICOLOGICAL IMPACT

Mirela Ahmadi[1], Ioan Pet[1], Lavinia Stef[1], Gabi Dumitrescu[1], Liliana Petculescu-Ciochina[1], Marioara Nicula-Neagu[1], Igori Balta[1], Bogdan Pet[1], Pascalau Raul[2], Dorel Dronca[1]

[1]Department of Biotechnology, Faculty of Bioengineering of Animal Resources, University of Life Science „King Mihai I" from Timisoara, Timisoara – 300645, Calea Aradului 119, Romania
[2]International relations department, Faculty of Agriculture, University of Life Science „King Mihai I" from Timisoara, Timisoara – 300645, Calea Aradului 119, Romania
e-mail: e-mail: ioanpet@usvt.ro; doreldronca@usvt.ro

Abstract

Molecular nutrition has introduced a range of novel bioactive compounds, including synthetic micronutrients, bioactive peptides, and nanoformulations, designed to enhance health and metabolic function. However, their fate in the environment remains largely unexplored. These compounds can enter ecosystems through excretions, agricultural runoff, or industrial processes, with potential impacts on soil and aquatic organisms. This review examines the environmental pathways and ecotoxicological risks associated with emerging nutritional molecules. Analytical techniques such as LC-MS/MS and HPLC for detecting these substances in environmental matrices are discussed. Current regulatory frameworks often overlook these compounds, despite evidence of bioaccumulation or endocrine disruption in non-target species. By linking biotechnology, analytical chemistry, and ecotoxicology, this paper highlights the urgent need for environmental risk assessments in the development of future nutritional products. A sustainable approach to molecular nutrition must consider both human health benefits and ecological safety.

Introduction

Molecular nutrition is an interdisciplinary field at the interface of biochemistry, genomics, and nutritional science, exploring how nutrients and bioactive food components influence cellular processes and gene expression. The rise of precision nutrition and biotechnological advancements has led to the development of novel bioactive compounds, including synthetic micronutrients, functional lipids, bioactive peptides, and nanocarriers for targeted delivery. These innovations aim to improve metabolic health, reduce disease risk, and personalize dietary interventions. However, while their physiological benefits are increasingly documented, their environmental fate and potential ecological risks remain largely under-investigated .

Upon ingestion, many of these compounds—or their active metabolites—are excreted via urine and feces, entering wastewater systems or agricultural environments through manure and sludge application. Industrial production also contributes to environmental release. Current wastewater treatment facilities are often not equipped to remove complex bioactive molecules, allowing their persistence and bioaccumulation in ecosystems. Additionally, nanoformulations designed for enhanced delivery may exhibit unexpected mobility, toxicity, or interactions with other environmental contaminants.

This review explores the ecological implications of novel compounds used in molecular nutrition. It addresses their classification, environmental pathways, detection methods, ecotoxicological effects, and the gaps in current regulations and risk assessment strategies. By bridging molecular nutrition and environmental/ecological science, the paper highlights the need for sustainable innovation that considers both human health and ecological integrity.

Novel chemicals in molecular nutrition

The scope of molecular nutrition has rapidly expanded beyond traditional nutrients to include a wide range of engineered bioactive compounds that exert targeted effects at the cellular and molecular level. These compounds can be classified into several categories (figure 1):

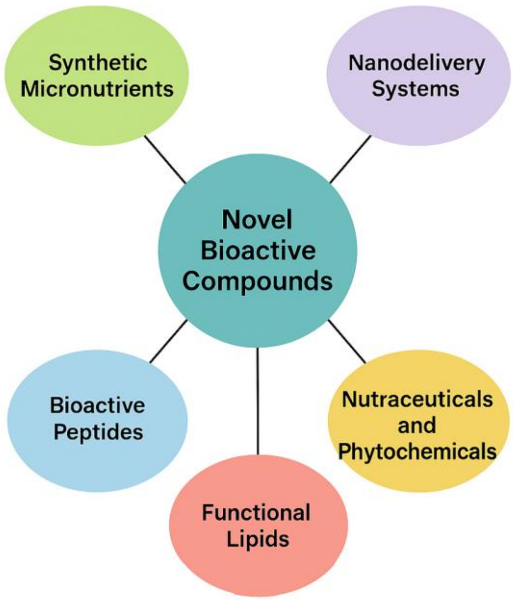

Figure 1. The main classes of novel bioactive compounds involved in molecular nutrition

- Synthetic micronutrients: Modified versions of essential vitamins and minerals with enhanced bioavailability or stability (e.g., methylated B vitamins, chelated minerals).
- Bioactive peptides: Short amino acid sequences derived from protein hydrolysis, exhibiting antihypertensive, antioxidant, and immunomodulatory activities [1].
- Functional lipids: Structured lipids and synthetic omega-3 analogs designed to influence lipid metabolism and inflammation [2].
- Phytochemicals and nutraceuticals: Concentrated plant-derived compounds like curcumin, catechins, and resveratrol, often with anti-inflammatory or antioxidant properties [3-5].
- Nanodelivery systems: Liposomes, nanoemulsions, and polymeric nanoparticles are employed to improve stability, solubility, and targeted release of active compounds [6].

These substances are increasingly present in functional foods, dietary supplements, and fortified animal feeds. While they are generally regarded as safe for human use, their biochemical complexity may result in environmental persistence and unexpected biological activity in non-target organisms (figure 2). For instance, nanoencapsulated compounds may resist degradation or promote co-transport of other environmental pollutants, increasing their ecological footprint [7].

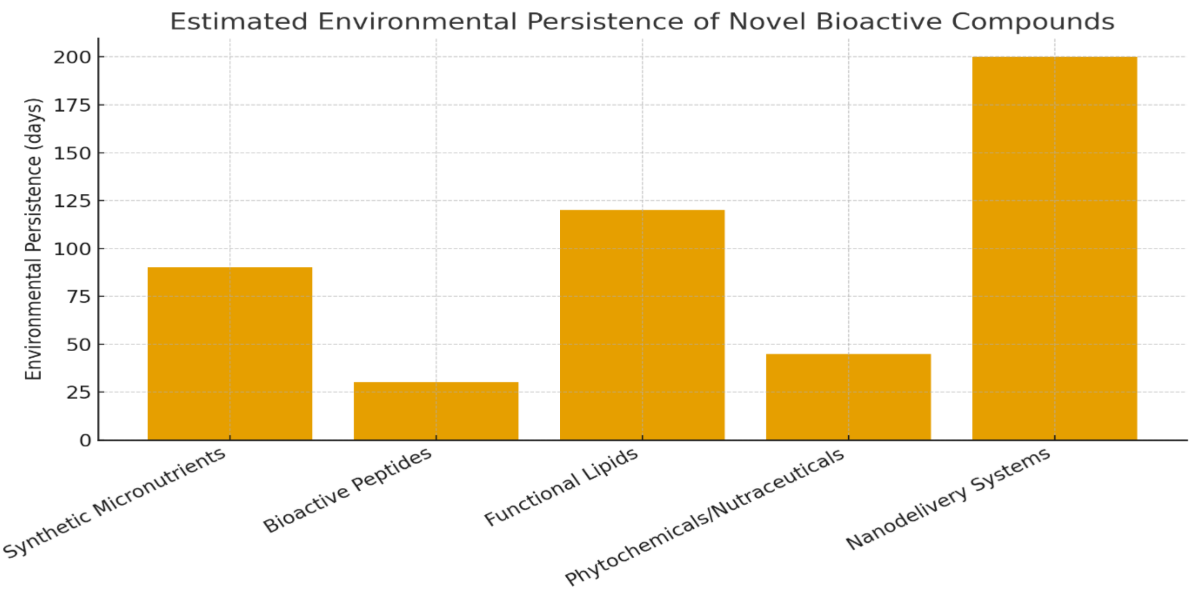

Figure 2. Estimated environmental persistence, bioaccumulation potential, and documented ecotoxicity of different classes of novel bioactive compounds used in molecular nutrition

The continuous development and commercialization of these compounds demand a closer look at their life cycle, particularly post-consumption and disposal. Given the complexity of their structures and the novel formulations involved, it is critical to assess their long-term interactions with environmental matrices, especially aquatic and soil ecosystems.

Environmental pathways and mechanisms

Novel compounds used in molecular nutrition enter the environment through diverse and often overlooked pathways. One primary route is human and animal excretion, where unmetabolized compounds and their transformation products are released into wastewater. Standard sewage treatment plants (STPs) are often not optimized to degrade these complex molecules, allowing them to reach surface waters or accumulate in sludge [8].

Agricultural runoff represents another significant pathway. Nutrient-fortified feeds and veterinary supplements administered to livestock result in manure rich in bioactive residues. When used as fertilizer, these residues can leach into soil and water systems. Furthermore, industrial discharge from nutraceutical manufacturing processes can introduce high concentrations of active compounds directly into aquatic systems.

Nanoformulations pose unique concerns due to their small size and surface reactivity. They can penetrate biological membranes, bind to soil or sediment particles, and persist under environmental conditions that would degrade conventional compounds [9]. Some may facilitate the transport of heavy metals or other contaminants, creating synergistic toxicity effects (figure 2).

Understanding these mechanisms is essential for predicting exposure levels in ecosystems and evaluating the potential for bioaccumulation or ecotoxicological impact.

Analytical techniques for detection

Detecting emerging bioactive compounds in environmental samples requires advanced analytical methods capable of handling complex matrices and low analyte concentrations. The most widely used techniques include:

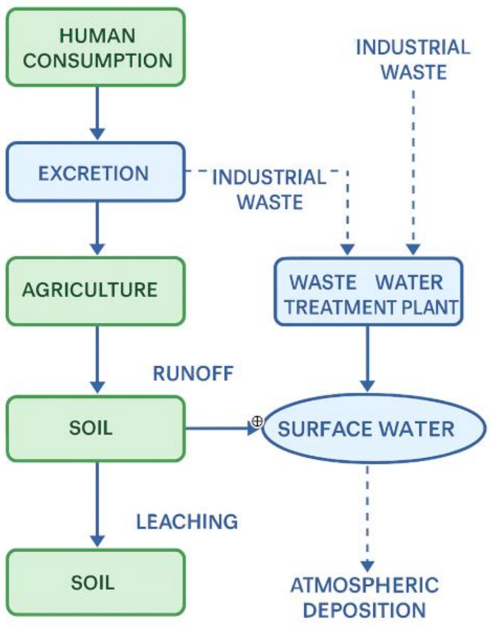

Figure 2. Major pathways through which bioactive nutritional compounds enter and move through

• Solid-phase extraction (SPE): Used for sample pre-concentration and cleanup.

Emerging technologies such as biosensors and nano-enabled detectors offer potential for real-time, in-situ analysis, though they require further validation. A key challenge remains the lack of standardized protocols and reference materials for many novel compounds, limiting the comparability and reproducibility of results across studies.

• Liquid Chromatography coupled with Tandem Mass Spectrometry (LC-MS/MS): Offers high specificity and sensitivity for quantifying trace levels in water, soil, and sludge [10].

• High-Performance Liquid Chromatography (HPLC): Commonly employed for separating structurally similar compounds, especially plant-derived substances.

Ecotoxicological evidence

Initial ecotoxicological studies suggest that novel nutritional compounds can pose risks to various environmental organisms. For instance, bioactive peptides and synthetic antioxidants have been shown to affect the reproductive systems of aquatic invertebrates and fish at sublethal concentrations [11]. Functional lipids and polyunsaturated fatty acids, when accumulated in sediments, may alter microbial community structures and enzyme activities.

Of particular concern are nanoencapsulated compounds, which can exhibit enhanced bioavailability and cellular uptake, leading to oxidative stress, inflammation, or DNA damage in non-target organisms [12]. Studies on Daphnia magna and zebrafish embryos exposed to nanoparticle-based formulations of curcumin or resveratrol have reported impaired development and increased mortality [13].

Additionally, phytochemicals like genistein and catechins have demonstrated estrogenic or endocrine-disrupting effects in aquatic species, raising concerns about their release in significant quantities through wastewater [14].

While short-term toxicity is increasingly documented, data on chronic exposure, mixture effects, and long-term ecosystem-level impacts remain scarce. The interaction of these compounds with existing pollutants—such as heavy metals or pharmaceuticals—could produce synergistic or antagonistic effects, further complicating risk assessments.

Critical gaps and opportunities for advancement

Despite the increasing production and consumption of bioactive nutritional compounds, environmental risk assessments remain limited. Regulatory agencies often do not require ecotoxicological evaluations for compounds considered safe for human use, leading to significant regulatory blind spots.

One major gap lies in toxicological data, particularly concerning chronic exposure and sublethal effects. Many compounds are assessed only for acute toxicity, neglecting their potential to bioaccumulate or interfere with hormonal systems. Furthermore, analytical challenges persist due to the lack of validated detection protocols, reference standards, and environmental occurrence data.

Future research should prioritize:

- Standardized testing frameworks for environmental safety of nutritional compounds
- Life cycle assessments that include environmental endpoints
- Development of biodegradable or eco-safe formulations following green chemistry principles

Interdisciplinary collaboration between nutrition scientists, ecotoxicologists, analytical chemists, and policymakers is essential to close these gaps. The integration of environmental considerations early in the product development pipeline will help ensure that advances in molecular nutrition are sustainable and do not compromise ecosystem health.

Conclusion

Molecular nutrition offers exciting health benefits, but its environmental dimension must not be overlooked. As novel bioactive compounds become more prevalent, understanding their pathways, persistence, and ecotoxicological effects is essential. Improved analytical methods, robust environmental assessments, and interdisciplinary collaboration are urgently needed. By integrating environmental safety into the development of nutritional products, we can ensure that innovation supports both human well-being and ecosystem health. Sustainable nutrition must not end at the body—it must extend to the planet.

References

[1] H. Korhonen, A. Pihlanto, A. International Dairy Journal, 16(9) (2006) 945–960.
[2] P.C. Calder, Journal of Parenteral and Enteral Nutrition, 39(1_suppl) (2015) 18S–32S.

[3] K. Mitra, D. Bhattacharya, J. Banerjee, M. Nag, D. Lahiri, Chapter 13 - Phytochemicals and gut health: modulating microbiota and promoting digestive wellness. In: Sarkar T, Smaoui S, Lai WF, editors. Phytoceuticals in Food for Health and Wellness. Academic Press; 2026. p. 223–34. Available from: https://www.sciencedirect.com/science/article/pii/B9780443264948000203
[4] N. Itrat, B. Israr, J. Shabbir, F. Ameen, A. Ali, Chapter 24 - Phytochemicals in fermented foods: health-promoting transformations and probiotic potential. In: T. Sarkar, S. Smaoui, W.F. Lai, editors. Phytoceuticals in Food for Health and Wellness. Academic Press; 2026. p. 501–13. Available from: https://www.sciencedirect.com/science/article/pii/B9780443264948000288
[5]. X.K.Wong, C. Alasalvar, S. Bo, J. Pan, S.K. Chang, Food Research International. 218 (2025) 116798.
[6] D.J. McClements, Trends in Food Science & Technology, 100 (2020) 114–128.
[7] A.K. Dhakad, R. Kumar, R. Choudhary, S. Singh, S. Khan, P.K. Poonia, Industrial Crops and Products. Sep 1;231 (2025) 121155.
[8] A. Pal, K.Y-H. Gin, A.Y-C. Lin, M. Reinhard, Environment International, 36(5) (2010) 418–435.
[9] H. Abdouss, A. Gholami, M. Pourmadadi, P. Zahedi, M. Abdouss, A. Rahdar. European Journal of Medicinal Chemistry Reports. 12 (2024) 100171.
[10] S.D. Richardson, T.A. Ternes, Anal. Chem., 90(1) (2018) 398-428.
[11] T. Borel, C.M. Sabliov, Annu Rev Food Sci Technol., 5 (2014) 197-213.
[12] M. Kah, R.S. Kookana, A. Gogos, T.D. Bucheli, Nature Nanotechnology, 13(8) (2018) 677–684.
[13] A. Behera, A.K. Nayak, R.K. Mohapatra, A.A. Rabaan (editors), Smart Micro- and Nanomaterials for Pharmaceutical Applications, CRC Press, Taylor & Francis Group, 2025, 39-58, 223-238.
[14] S.C. Cunha, J.O. Fernandes, Food and Chemical Toxicology, 62 (2013) 385–396.