



Eco-friendly technologies in nutraceutical and functional foods: A sustainable approach for health and the environment

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Submission Date: August 14th, 2025; **Acceptance Date:** October 18th, 2025; **Publication Date:** October 20th, 2025

Please cite this article as: Gutte R., Deshmukh V. Eco-Friendly technologies in nutraceutical and functional foods: A sustainable approach for health and the environment. *Dietary Supplements and Nutraceuticals* 2025; 4(10): 59-69. DOI: <https://doi.org/10.31989/dsn.v4i10.1743>

ABSTRACT

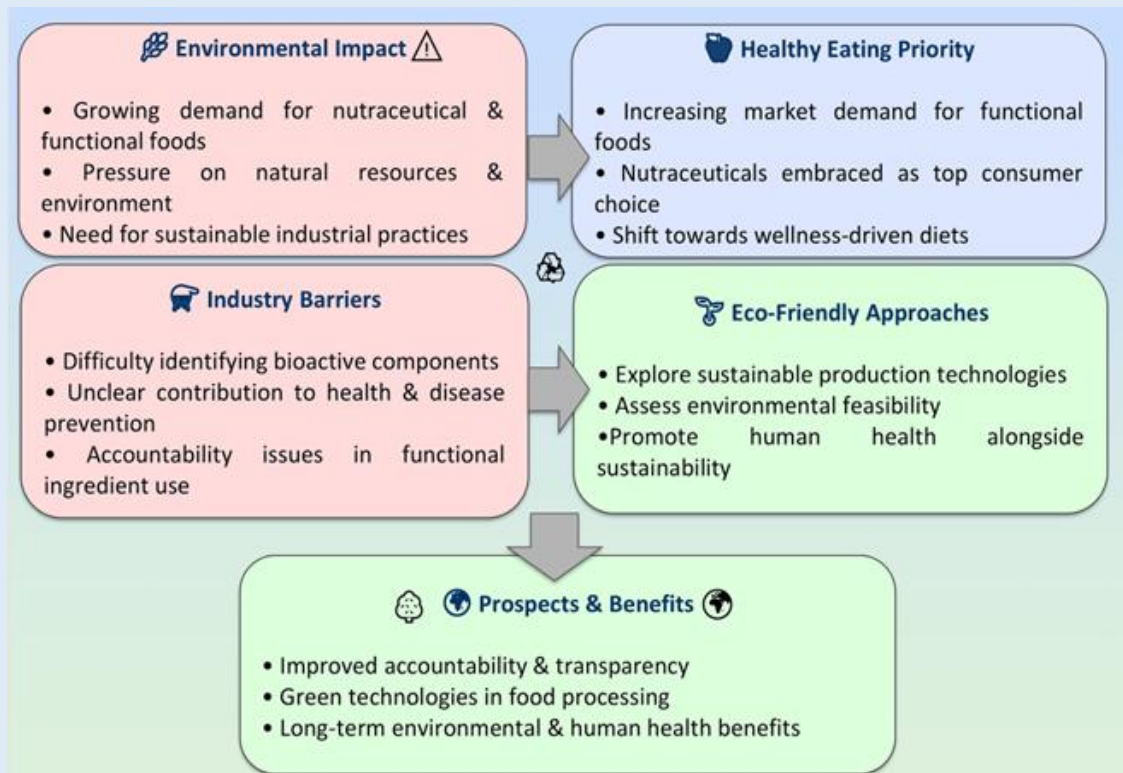
Background: With the growing demand for nutraceutical and functional food products, concerns about environmental impact have also increased. By adopting industrial sustainable practices, we can ensure environmental feasibility while promoting human health. The current market of healthy foods embraces nutraceutical and functional foods because a main concern of consumers is healthy eating. A major hindrance of the food industry is the difficulty of identifying bioactive compounds and explaining their roles in protecting human health and preventing diseases.

This review paper seeks to explore and analyse the various eco-friendly approaches and technologies that can be employed in the production of functional food products with the use of natural nutraceutical ingredients, and will discuss the challenges, benefits, and prospects of these technologies.

In this study, data were collected from regulatory databases, case studies, scientific literature, peer-reviewed journals, etc., related to global sustainability frameworks and Nutraceuticals and functional foods. Focus was given to the key parameters such as green and clean extraction techniques with minimal or no impact on the environment, and adds economic feasibility.

By adopting clean and green technologies like supercritical fluid extraction, pressurized fluid extraction, ultrasound extraction, and eco-friendly processes, the environmental footprint of Nutraceutical and functional food production can be significantly reduced. The finding indicates that the integration of sustainable approaches for the production chain not only supports the conservation of the environment but also adds value to core brands and improves regulatory compliance along with profitability in the long term.

Keywords: Sustainability, Functional foods, Nutraceutical ingredients, Health and diseases, Eco-Friendly Technologies.



Graphical Abstract: Eco-friendly technologies in nutraceutical and functional foods: A sustainable approach for health and the environment

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INTRODUCTION

The world's growing population, linked with rising health consciousness, is increasing the demand for nutraceutical functional foods. Nutraceutical ingredients attract consumers due to their additional health benefits. However, traditional production methods harm the environment by consuming high amounts of energy and water, generating significant waste, and causing degradation. Therefore, there is a necessity to use eco-friendly technologies for the long-term sustainability of this industry.

Nowadays, biotechnology has played an important role in making functional ingredients novel and sustainable with the use of microorganisms, a source of

bioactive compounds and functional formulations. In other words, microorganisms are an innovative tool that can be used for producing the most prominent bioactive and functional molecules. They offer a valuable avenue for developing sustainable products with various health benefits, giving the food science field the potential to create novel ingredients and innovative functional formations [1].

Chiellini C et. al. focused on using microbes as an alternative source of nutritive and functional properties in the field of nutraceuticals and functional food. They studied various papers exploring its use in different food sources in food, feed, nutraceutical, and pharmaceutical sectors. Microalgae is a sustainable source because it can

be grown in small ponds, requiring minimal water. Microalgae are rich in proteins, vitamins, and various essential nutrients [2].

The use of sources such as industrial byproducts is gaining attention for use in new functional foods and sustainable ingredients. However, each ingredient exhibits different properties, and they behave differently when added to other food products altogether, which could affect the health of consumers adversely. It is important to find efficient and suitable formulations that are sustainable and beneficial for human health [3].

Sustainable or ecological foods are foods that imply neutral or beneficial impacts on the environment by minimizing the harmful effects on health, the environment, and communities.

According to the Food and Agriculture Organization of the United Nations (FAO), sustainable food production encompasses the implementation of various agricultural process approach and systems that are environmentally friendly, minimizing load on non-renewable energy, and the best use of natural resources in economically efficient way. It also ensures safety for workers, consumers, and communities, and ensures the future generations can meet their own needs [4].

This paper will highlight different eco-friendly methods and technologies that can be used in creating

nutraceutical functional foods. It will also address the obstacles, advantages, and future possibilities of eco-friendly technologies in nutraceutical functional food production to promote sustainability.

Importance of Nutraceutical and Functional Foods: In 1989, Stefen De Felice first used the term nutraceutical. It originated from two words—nutrition and pharmaceuticals. He illustrated that nutraceutical foods or food ingredients may provide treatment to various diseases [5].

They can be taken in any forms, such as capsules, tablets, powders, pills, or tinctures. Nutraceutical foods might be considered conventional foods in appearance but have different ranges of products like dietary supplements; functional beverages; genetically engineered foods; herbal, protein, minerals or vitamin supplemented products and other manufactured goods. Nutraceuticals are usually food or a part of food identified as refined or extracted food components which can be available as supplementary medicine or alternative medicine [6].

During the 1980s, the term “functional foods” began referring to nutritional foods that enhance quality of life and extend lifespan. Vitamins, minerals, and other essential nutrients fall under the functional food category [7].

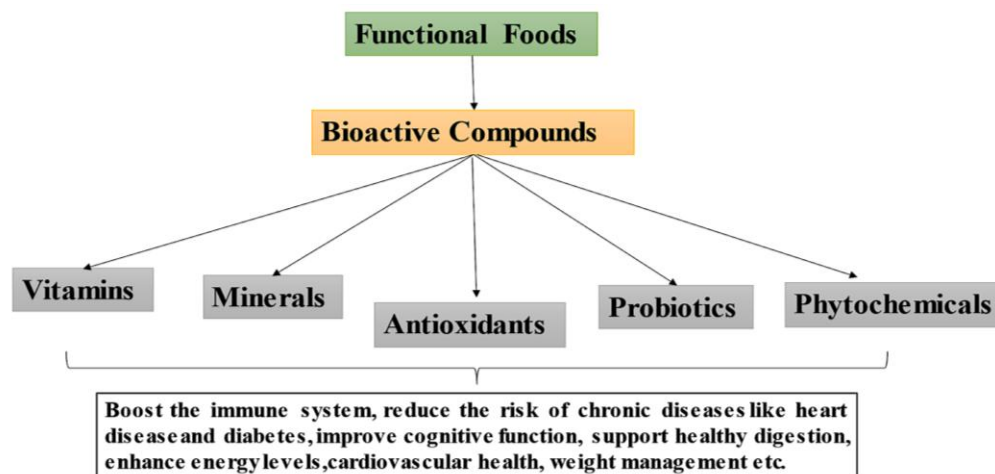


Figure 1. Functional foods and their bioactive compounds.

Studies on the subject underscore the importance of natural nutraceuticals over synthetic ingredients due to their lack of side effects compared to synthetic ingredients. Additionally, the integration of nutraceutical ingredients as a functional food can be beneficial for recovery in various diseases, such as the management of side effects induced by chemotherapy [8].

Eco-Friendly Technologies: Bioactive compounds in nutraceuticals originate from natural origins, such as plants and micro-algae, serving as raw material for food by-products. Various factors, including the extraction technique, the type of raw material, and the organic solvent influence the extraction of these compounds. Traditional extraction methods are associated with significantly high solvent usage, elevated energy consumption, and time-intensive processes. This has sparked interest in innovative technologies known as clean or green technologies, which aim to minimize or eradicate the use of harmful solvents. By adopting these eco-friendly approaches, the natural environment and its resources can be preserved [9].

Microorganism-derived products might have beneficial effects, not only on human health, but also on animal health. They can be successfully implemented in the feed and food industry, cosmetic industry, and nutraceutical and pharmaceutical industries to create valuable components with nutritional and beneficial health features. Microbial processes have led to new developments in research and development, including microalgae, probiotics, and beyond [10].

The byproducts generated in these industries are considered organic waste and can be thrown away. These may include fruit seeds, pulp, skin of the fruit, rinds, etc. So, recycling these byproducts to create bioactive compounds could be beneficial for both health and waste reduction. However, external factors and bioavailability may affect or restrict the use of these compounds [11].

Currently, a wide range of technologies has been

developed to use bench-scale or scale-up phases to check for quality and readiness level. Comprehensive research must be conducted to check how these technologies are affecting the process and final products.

In Ansari et al., a sustainable and cost-effective water-based method was devised to extract oleuropein from olive leaf samples. The work concluded that using deionized water adjusted to pH 3 at 60°C for 4 hours yielded the maximum recovery rate [12].

Recently, there has been a growing concern about the environmental impact, making it a top priority in society. There is an increasing interest in utilizing agricultural and industrial residues regarded as valuable substrates for further application, which can be economically beneficial. Biotechnological advancements present the use of agro-industrial residues like grape and olive pomace, leaves, barks, and roots offer considerable economic potential. Their valorisation within the "waste to wealth" supports resource efficiency. By-products from the olive oil industry serve as an exceptional source of bioactive phenolic compounds [13].

In this context, "Green Chemistry" plays an important role in minimizing or reducing toxic and hazardous substances from industrial processes. It was originally established to help chemists incorporate their efforts to promote sustainability and environmental stewardship in their work [14]. In recent years, there have been advancements in the development of eco-friendly solvents and methods for use in chemical reactions and extractions [15-17].

The utilization of water as a solvent has garnered significant attention in recent times [18]. Water has many benefits, as it is not expensive, it can enable the catalyst recycling to use again and potentially improve reactivity and selectivity, and it can be used in protecting groups by allowing slow reaction conditions [19-21] and in the making of bioactive ingredients rich compounds [22]. Aqueous chemistry, i.e., water-based systems, provides interesting insights into extraction technologies and

biosynthetic pathways for nutraceutical products [23-24].

Green and clean technologies for novel nutraceutical products: The use of green technologies, especially for extracting bioactive compounds, offers numerous benefits, including:

1. Reduced processing time
2. Reduced energy consumption
3. Reduced use of harmful solvents.

By using green solvents in extraction processes, industries in the nutraceutical and nutritional sectors can help in reducing carbon footprints. These sustainable practices efficiently meet the increasing demand of

nutraceuticals for health and wellness using extraction and separation of bioactive products from biomass. Advanced technologies such as supercritical fluid extraction (SCFE), pressurized liquid extraction (PLE), microwave-assisted extraction (MAE), ultrasound extraction (UAE), and pulsed electric fields extraction (PEFE) enable large-scale recovery of products from base material with bare minimum use of energy input and chemical usage [25].

The most important criterion for sustainable foods to meet is having their production and processes be environmentally friendly, by minimizing greenhouse gas emissions, lowering the use of resources, and reducing their carbon footprint in the process.

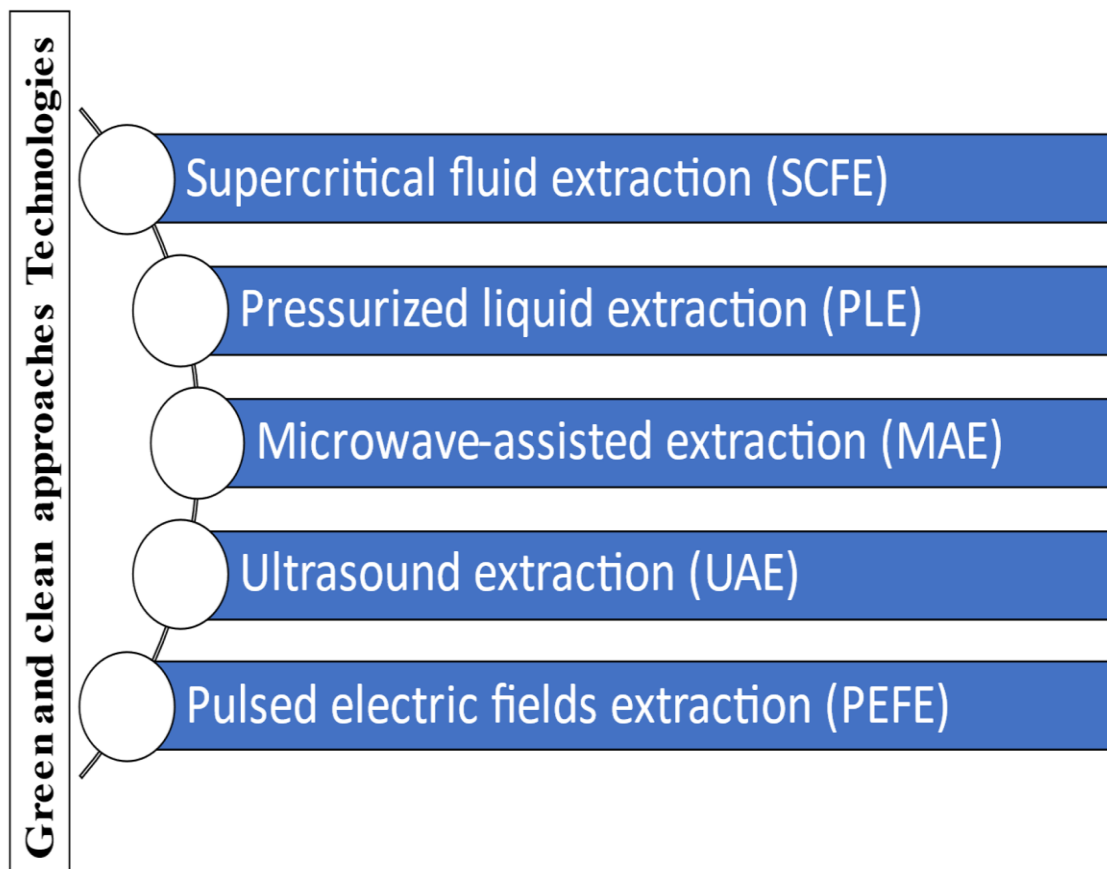


Figure 2. Green and clean technologies.

The table below describes applications and examples of green and clean technologies that give insight into green extraction techniques directed to its

functional uses and illustration of eco-friendly technologies.

Table 1: Operational applications and demonstrations of sustainable technologies.

Sr. No	Green and clean Technologies	Applications	Examples	Reference no.
1	Supercritical Fluid Extraction (SCFE)	Extraction of bioactive compounds using supercritical CO ₂ , a safe method that uses green solvents	Extraction of omega-3 fatty acids from fish oil. Isolation of lycopene from tomatoes for antioxidant supplements. Extraction of caffeine from coffee and tea for decaffeinated products.	[38,39,40]
2	Pressurized Liquid Extraction (PLE)	A rapid extraction of thermally stable bio actives using high temperature and pressure.	Extraction of polyphenols from grapes and berries for antioxidant nutraceuticals. Recovery of carotenoids from carrots and spinach for functional beverages. Extraction of curcuminoids from turmeric for anti-inflammatory supplements.	[41,42,43]
3	Microwave-Assisted Extraction (MAE)	Uses microwave energy to heat solvents and plant tissues for efficient extraction.	Isolation of flavonoids from citrus peels for nutraceutical formulations. Extraction of essential oils from herbs (e.g., rosemary, basil) for natural preservatives. Extraction of saponins from ginseng for adaptogenic supplements.	[44,45,46]
4	Ultrasound-Assisted Extraction (UAE)	Uses ultrasonic waves to create cavitation, improving mass transfer and extraction efficiency.	Extraction of anthocyanins from blueberries and black rice for antioxidant drinks. Recovery of resveratrol from grape skins for anti-aging nutraceuticals. Isolation of chlorophyll from spirulina for natural colorants.	[47,48,49]
5	Pulsed Electric Fields Extraction (PEFE)	Uses short bursts of high voltage to permeabilize cell membranes, enhancing compound release.	Extraction of polyphenols from olive leaves for cardiovascular. health supplements. Recovery of betalains from beetroot for natural coloring and antioxidant activity. Extraction of proteins and peptides from microalgae for functional food formulations	[50,51,52]

Literature review about green and clean technologies:

Olive oil and its byproducts during industrial processes and its health benefits: The author discusses solvent selection steps for olive-byproduct enhancement to increase the quality by agro-waste valorisation processes and specifies green extraction technologies such as eco-friendly bioactive recovery from pomace/waste and wastewater [26].

The author studied the comparative effect of extracts extracted from *Ocimum basilicum* leaves, using organic extract and essential oil. The author reports that

some extracts were obtained by supercritical fluid extraction to obtain essential oils during extraction process and compares biological activities [27].

Optimization of ultrasound-assisted extraction using Box-Behnken design for *Etlingera elatior* inflorescence—an FFHD experimental paper that optimizes UAE parameters to increase phytochemical yields for a potential herbal tea/functional food ingredient by using UAE application and optimization of process to get better yields of herbal tea [28].

In another paper, Maceration and ultrasound comparison is mentioned with different solvents and temperatures for extraction of phenolic components. This paper gives practical comparison of conventional vs new technology for selecting green solvents during the process [29].

Elamin, M. M. (2020) demonstrated solvent extraction of plant bioactive components and spectroscopic IDs gives conventional methods compares against greener solvents choices [30].

The Functional Food Health and Diseases Journal paper reviews green and novel techniques used at lab scale and also summarizes purification techniques for anthocyanins from local resources. They have listed out some extraction of anthocyanins helpful when designing nutraceutical products from local materials [31].

Market Trends and Consumer Demand of Functional Foods in The Nutraceutical Market: The nutraceutical functional food market has been seeing a notable increase in growth lately. Consumers are increasingly focused on their health and are actively searching for food items that provide extra health benefits. The desire for natural and organic ingredients, as well as products without artificial additives and preservatives, is growing. Additionally, there is a rising curiosity in personalized nutrition, with consumers seeking functional foods customized to their individual health requirements and tastes. Consequently, the nutraceutical functional food market is experiencing a rise in product innovation and variety to meet these changing consumer preferences.

Worldwide, roughly 55 million tons by weight of food waste is generated annually, of which 16.5-20 million is from fruit and vegetables. In India alone, around 5.6 million tons of fruits and vegetables are lost annually, representing about 10% of the total post-harvest loss of agricultural commodities [32].

Most fruits and vegetables yield around 25–30% of byproducts like the peel, seed, pomace, and stems. For example, the waste generated from various parts of

produce is comprised of pomace and spoiled fruits, rind/skin/peels, and seeds [33]. These residues are rich in bioactive compounds such as phenolic compounds, flavonoid compounds, tannin derivatives, volatile oils or aromatic oils, plant pigments, organic acids, nutritional vitamins, and dietary fibres. However, the disposal of this substantial waste poses a significant challenge. Despite their valuable bioactive content, these byproducts are often used as animal feed or left unutilized, leading to economic and environmental concerns due to the emission of Climate-warming gases. Additionally, the higher content of nutrients and favourable moisture conditions can promote the proliferation of harmful microorganisms, contributing to unpleasant Odors and the spread of infectious diseases [34].

Consequently, it is important to make use of bioactive compound rich waste by getting them through environmentally friendly and sustainable extraction methods like ultrasound-assisted extraction, supercritical fluid extraction, pulsed electric field, hydrodynamic cavitation, and others. These bioactive compounds can be used as food additives and preservatives by incorporating them into the formulation of functional and nutraceutical foods. Currently, they are employed as natural colour pigments and flavour enhancing agents in food products, given they are recognized as safe by regulatory authorities [35].

Future Challenges and Solutions: The use of sustainable agricultural practices to grow raw material for natural nutraceutical products by organic farming and permaculture [36] is both a challenge and a solution.

It is a big challenge to minimize environmental impact and reduce carbon footprint by implementing energy-efficient manufacturing processes. Packaging materials cause most of the ecological burden due to the use of plastic and non-degradable materials. So, the promotion of recycling to reduce waste is essential. Adopting eco-friendly packaging materials is necessary to reduce the hazardous impact on the earth. The use of

biodegradable and non-toxic materials, such as food-grade or pharma-grade, in packaging and cleaning agents will help minimize pollution. The nutraceutical production units may use solar power and wind power generators, which are excellent sources of renewable energy.

Ethical production practices ensure sustainable sourcing when collaborating with local communities and stakeholders. Biotechnology and Nanotechnology are booming terms in the world, so embracing these innovative technologies to enhance the efficacy, quality, and bioavailability of nutraceutical products is facile.

Some models show the path to the functional food manufacturers for sustainable food production by using a sustainable framework emphasizing environmental impact [37].

There is a necessity for continuous research and development in the field of nutraceuticals to explore green and novel technologies that can further support the sustainability of nutraceutical products.

CONCLUSION

Production processes during food product manufacturing generates a substantial amount of food waste, which may contain valuable bioactive components with nutritional and functional significance. The extraction of these nutritional ingredients helps in reducing environmental impact and enriches functional food development. There are various extraction methods that give immense yield with the help of recent trends in ecofriendly technologies. There is a growing demand for green and clean technologies in which we get highest optimal range of yield with minimal or no use of solvent. Otherwise, we can use solvents that are generally considered safe for the extraction process. It can further improve extraction efficiency by optimizing the techniques in an eco-friendly manner.

However, there are various alternative sources of organic solvents, such as deep eutectic solvents, water, and CO₂. The future aim is to utilize solvent-free, cutting-

edge extraction methods, with a heightened focus on emerging non-thermal extraction technologies, such as pulsed electric fields (PEF), to achieve higher extraction yields and minimize environmental impact. The aim is also to develop products that improve the nutritional quality of food products by incorporating bioactive components.

Processing methods and parameters used during the manufacturing of nutraceutical products will influence the quality and stability of the bioactive components extracted from the raw material.

Moreover, there is a lack of comprehensive studies available specifically on human body interactions with bioactive, so there is a need to conduct qualitative research.

Abbreviations: Food and Agriculture Organization of the United Nations (FAO), supercritical fluid extraction (SCFE), pressurized liquid extraction (PLE), microwave-assisted extraction (MAE), ultrasound extraction (UAE), and pulsed electric fields extraction (PEFE), Carbon dioxide (CO₂), Pulsed electric fields (PEF)

Competing interests: The author has no financial interests or conflicts of interest.

Authors' contributions: All authors conceived the review, performed the literature search and analysis, drafted the manuscript, and approved the final version.

Acknowledgments: There was no external funding supporting this publication.

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