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Review Article

Contemporary Developments in Nutraceuticals: A Comprehensive Review

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ABSTRACT

Located at the intersection of nutraceutical, nutrition and pharmaceuticals, they are gaining widespread recognition for their role in promoting health, prevent chronic diseases and complement therapeutic strategies. In the current healthcare landscape, the demand for nutraceuticals is accelerated due to preventive health, lifestyle related disorders, and increased awareness about global shift towards natural and plant-based remedies. Recent trends have been found in industry, such as the integration of personal nutrition, the rise of plant based and clean label products, innovation in delivery systems such as ayurveda with modern wedges. And here we discussed the recent developments on nutraceuticals, including nanotechnology, personal nutrition, biotechnology advancement, fermented innovation, marine sources, herbal nutritional, bioactive food components.

INTRODUCTION

Nutraceuticals are made from bioactive compounds obtained from food sources that provide more health benefits that basic nutritional value. Designed by dr. Stephen difflis in 1989, the word "nutraceutical" is a combination of "nutrition" and "pharmaceutical" that highlights their role to promote health, prevent chronic diseases, and support the physical functions of the body. In recent years, nutraceuticals have merged as a crucial component of preventive healthcare and received significant attention to both medical and professional domains.

With increasing global load of non -prevalent diseases such as diabetes, obesity, cardiovascular disorders and certain types of cancer, lifestyle changes and increasing interest in non-pharmacological intervention.

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Fig.1 Concept Of Nutraceuticals

Nutraceuticals, including dietary supplements, functional foods, herbal products and probiotics, are more commonly used to complement traditional therapy and improve the quality of life. Their appeal is in the possibility of long-term well-being without their natural origin, considered safety and significant side effects. And here we discussed the recent developments on nutraceuticals, including nanotechnology, biotechnology advancement, fermented innovation, marine sources, herbal nutrition, bioactive food components. [1,2,3,4,5,6,7]

2. Recent trends and developments in nutraceuticals:

2.1 Nanotechnology in nutraceuticals: Numerous dangerous diseases, such as cancer, hypertension, osteoporosis, diabetes, obesity, infectious diseases, hyperlipidaemia, and pain, inflammation is become more common as the worlds population grows. Nutraceuticals have a low bioavailability, meaning they are routinely eliminated from the from the body without providing any therapeutic benefit. This is main cause for concern in this subject. Nanotechnology can be used to increase the oral bioavailability, permeability, and therefore the bioavailability of nutritional and health supplements. [4]

Nanomaterials have extraordinary qualities because of their tiny size. A high surface area to volume ratio, and increased efficiency because of increased uptake by endocytosis and additional biological transport processes. Nanotechnology has also contributed to important advances in food science by improving nutrient delivery systems. These nanomaterials can prevent the digestion of nutrients in the mouth and stomach. One of the ways to ensure efficient delivery of nutrients is encapsulation, so selection of nanomaterials as encapsulants to fabricate edible nanoparticles must be carefully done with full consideration of their individual physicochemical and structure properties as well as the molecular interactions with those of co-existing molecules in the nanoparticles. Some works have described the encapsulation of therapeutic bioactive substances such as nucleic acids, peptides, and proteins with hydrophilic nature. [5]

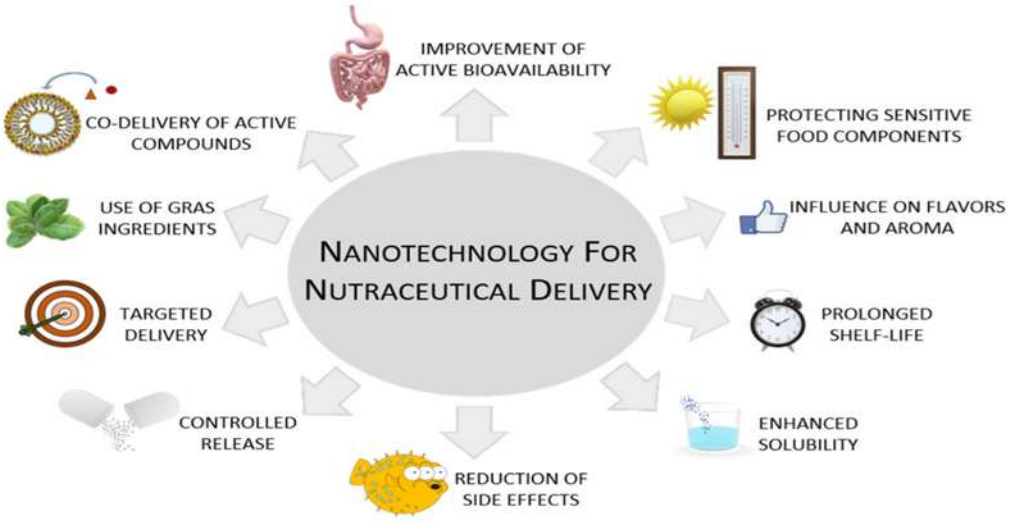

Fig.2 Nano nutraceuticals: The new frontier of supplementary food.

Numerous uses of nanotechnology in nutraceuticals are being investigated, such as:

Vitamin and mineral nanoencapsulation: This improves the stability and absorption of vital elements.

Phytochemical and antioxidant delivery: Increasing the positive effects of substances like carotenoids, resveratrol, and curcumin.

The creation of functional foods: Enhancing the health advantages of fortified foods and beverages. Enhancing nutrient absorption in animal feeds is one way to improve feed quality. [8,9,10,11]

2.2 Personalized nutrition through nutrigenomics: Nutrigenomics, the study of how food influences our genes and how individual genetic differences affect how we respond to nutrition, is arguably the most groundbreaking advancement in this discipline. Personalized dietary advice based on genetic profiles are replacing the "one-size-fits-all" approach to nutrition tanks to this new knowledge. Genetic testing might soon be a standard component of dietary counselling. Imagine going to a nutritionist who suggests functional foods or nutraceuticals based on your genetic predisposition after analysing your DNA sample. You may be given recommendations for foods high in anti-inflammatory chemicals if your genes indicate a propensity for inflammation. Your diet may focus on specifically prepared calcium-enhanced functional foods if you have genetic markers linked to poor calcium absorption. [8]

How individual nutrition is achieved through nutrigenomics:

a) Genetic testing: To find differences in a person's genes related to food metabolism, absorption, and dietary responses, a DNA sample is taken (often using a check swab) and examined.

b) Genetic profile analysis: Following interpretation of the genetic profile, information on a person's metabolic predisposition, nutrient absorption efficiency, and sensitivities to foods or dietary components is revealed.

c) Tailored dietary advice: Based on the genetic findings, individualized dietary advice is given. This may include suggestions for food selection, portion sizes, macronutrient ratios (proteins, fats, and carbs), particular

micronutrient requirements, and may be supplementation. [9]

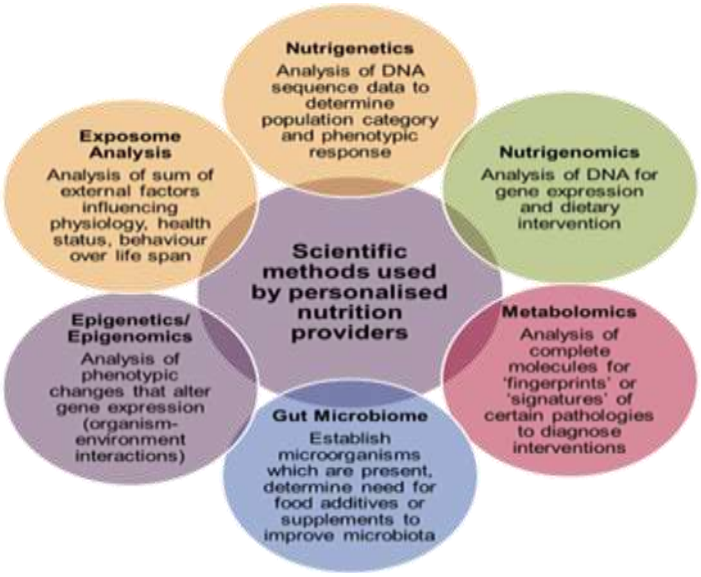

Fig.3 Scientific methods used by personalised nutrition provides.

Advantages of nutrigenomics-based individualised nutrition:

Improved nutrition efficiency: Diets that maximize nutrient usage can be developed by understanding how genetic variations affect nutrient absorption.

Targeted weight management: Based on a person's genetic predisposition, nutrigenomics can identify their metabolic type and help build more effective weight management technique.

Preventing nutrient deficiencies: By identifying those who are genetically susceptible to deficiencies in particular nutrients (such as vitamin D or B12), these deficiencies can be avoided through proactive dietary changes or supplementation.

Enhanced performance and fitness: Nutrigenomics information about how the body uses proteins, lipids, and carbs for energy and performance might help athletes and fitness enthusiasts minimize the risk of injury.

Reduced risk of chronic diseases: Dietary interventions can be personalised to proactively lower an individuals inherited risk of diseases including diabetes, heart disease, and obesity. Problems and items to consider although promising, the science of nutrigenomics for personalised nutrition is still in its early stages and confronts various challenges. [12,13,14,15]

2.3 Biotechnology advancements: Biotechnology's transformative role in nutraceuticals: Biotechnology is critical for boosting the nutritional value of meals. Biofortification, which involves increasing the nutritional value of crops through conventional breeding, genetic modification, or agronomic methods, is gaining popularity. Golden rice, treated with beta-carotene to combat vitamin A deficiency, is one early example. Crops with enhanced protein profiles, more essential fatty acids, or more antioxidants content may be created in the future. In India, where micronutrient deficiencies remain a public health issue, biofortified crops such as iron-rich pearl millet and zinc-enriched where are being created and

distributed. These approaches align with national nutrition missions and have the potential to alleviate malnutrition at the population level.

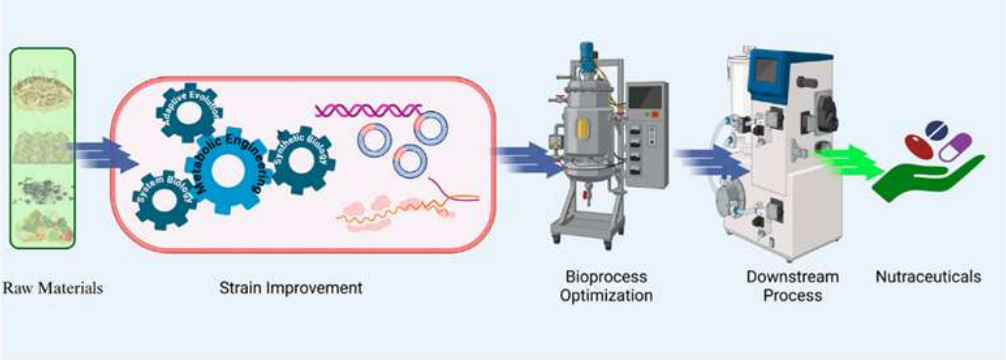

Fig.4 Microbial bioprocessing for nutraceutical production

Here are some key advancements:

Enhanced manufacturing of nutraceuticals: Genetic engineering modifies crops to produce critical nutrients and bioactive chemicals. For example, golden rice has been developed to produce higher levels of beta-carotene, a precursor to vitamin A.

Improved phytosterol content in rapeseed and soyabean oil can lower cholesterol levels.

Transgenic plants are being modified to produce more omega-3 fatty acids. Microorganisms are being exploited as “bio-factories” to manufacture nutraceuticals such as probiotics, peptides, polyunsaturated fatty acids (PUFAs), polyphenols, and vitamins. Advantages include consistency and scalability over traditional plant and animal sources.

Reduce production expenses.

Optimal use of simple carbon.

Improved bioavailability:

Nutraceuticals commonly face challenges with low water solubility and stability, limiting their absorption and effectiveness in the body. Biotechnology uses nano-delivery methods such as liposomes, nanoparticles, nano emulsions, and nanogels to encapsulate nutraceuticals, enhancing absorption and distribution in the body.

Absorption enhancement technologies: Strategies for enhancing the permeability of nutraceuticals across cell membranes. Excipient foods: food matrices that enhance the food matrices that enhance the biological activity of nutraceuticals.

Sustainability and ethical practice: The nutraceutical sector is increasingly focusing on sustainable and ethical principles, such as responsible raw material sourcing, environmentally friendly production techniques, and transparent supply chains.

Challenges and future outlook: Despite these advances, obstacles remain, particularly in terms of regulatory monitoring, ensuring scientific evidence backs up health claims, and resolving ethical issues about data privacy and access to personalised nutrition services. However, the future of biotechnology in nutraceuticals offers enormous promise. Advancements in genomics, bioinformatics, and technology will result in more effective tailored nutrition techniques and

sustainable production method, paving the path for a healthier and more sustainable future. [16,17,18,19]

2.4 Fermentation innovation in nutraceuticals: Nutraceuticals and functional foods are undergoing a dramatic transition in the rapidly changing world of health and wellness, thanks to advances in fermentation technology. Fermenters, which were previously utilized in food manufacturing, are now at the vanguard of transforming these industries. Let's look at how this ancient method is making current progress. The role of technology modern fermenters is outfitted with advanced technology, allowing for exact control of the fermentation process. This precision ensures that the ultimate product is of consistently high quality and safe. Smart fermenters combine sensors and automation to monitor and alter fermentation conditions in real-time, leading to optimal results. Fermentation advances revolutionize nutraceuticals. A classic food preservation method is gaining popularity in the nutraceuticals industry due to its ability to produce long -lasting, unique, and extremely useful products. [14]

Fermentation process: A brief overview fermentation is a naturally occurring metabolic process that converts glucose to acids, gasses, or alcohol. This process, carried out by microorganisms such as bacteria, yeast, and Molds, improves the nutritional profile and bioavailability of numerous meals. Fermentation has long played an important role in the production of staples such as yogurt, sauerkraut, and kimchi. Today, its applications go far beyond traditional cuisine.

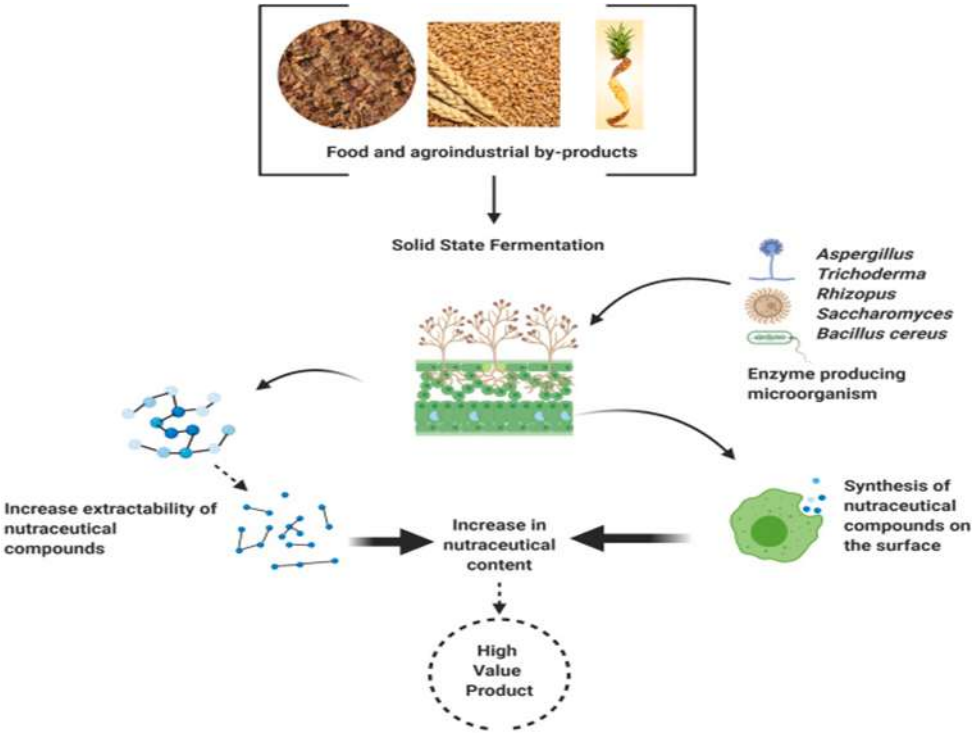

Fig.5 Solid state fermentation process.

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Today, its applications go far beyond traditional cuisine.

Innovation in functional foods: Fermentation is greatly helping functional foods, which are intended to have a good impact on health in addition to basic nutrients.

Innovation includes:

Fortified fermented products: Companies are now supplementing fermented meals with extra nutrients or bioactive ingredients. This combination not only preserves the food organically, but it also provides health advantages.

Customized fermentations: Advances in biotechnology enable fermentation processes to be tailored to specific health results, such as anti-inflammatory properties or improved cognitive function.

Sustainable and natural solutions: Fermentation is an essentially sustainable process. It often uses less energy and produces fewer byproducts than traditional food processing procedures. This is consistent with the increased +customer demand for natural and environmentally friendly products.

Key points include fermentation reduces the need for artificial preservatives, matching with clean label tendencies. Trash reduction: Fermentation may convert food byproducts and trash into valuable ingredients, helping to promote to promote a circular economy.

Key areas of innovation: Fermentation improves the bioavailability and absorption of essential nutrients such as minerals (iron, calcium, magnesium, zinc) and vitamins (B vitamins, K2) by reducing anti-nutritional factors like phytates and boosting enzyme activity. For example, fermented spirulina showed increased antioxidants activity and protein fragmentation, according to MDPI.

Functional foods and bioactive compounds: Beyond conventional fermented foods, new uses in functional meals are emerging that target specific health advantages. This includes employing fermentation to create.

Probiotics and prebiotics: Fermentation increases the levels of beneficial probiotics and prebiotics, which promote gut health and immunological function.

Bioactive peptides: According to scrivener publishing, fermentation can convert proteins into bioactive peptides that have antioxidants, anti-inflammatory, and antibiotic characteristics.

Vegan and plant-based alternatives: Fermentation is critical in developing plant-based alternatives to dairy, meat, and protein, mimicking their nutritional and taste characteristics.

Sustainable and clean label solutions: Fermentation, a natural and resource-efficient process, meets the growing need for natural, environmentally friendly products. It also decreases the need for artificial preservatives, promotes waste valorisation, and contributes to the circular economy.

Technological advancements: Modern fermentation processes leverage advanced technologies such as:

Precision fermentation: Using genetically modified microbes to create specific chemicals with high purity and tailored functions.

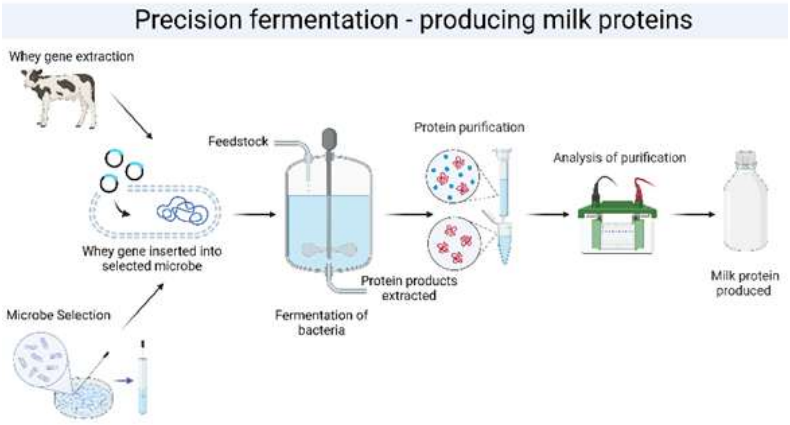

Fig.6 Precision fermentation

Bioreactor innovations: Advanced bioreactor designs incorporate real-time monitoring and control systems to optimize fermentation parameters, increase efficiency, and eliminate contamination hazards.

AI and machine learning: Optimizing fermentation operations and anticipating results with more accuracy and efficiency.

Market trends: According to global newswire, the global fermented ingredients market is expected to reach $59.9 billion by 2029, growing at a 9.7% CAGR.

Fermented foods are becoming more popular due to increased consumer awareness of their health advantages and demand for natural, organic items.

Key market drivers include expanding demand for fermented foods and beverages, increased health consciousness, and technological developments in fermentation processes. [20,21,22,23,24,25,26]

2.5 Recent developments in marine sources in nutraceuticals: The subject of marine nutraceuticals is rapidly expanding, driven by rising scientifically understanding and technical breakthroughs. This field focuses on using the great biodiversity of marine species to collect and use bioactive chemicals with varied health-promoting qualities.

Hrere are some recent key developments:

Marine microbes: Researchers are looking at the ability of marine microorganisms such as bacteria, fungus, and microalgae to develop novel bioactive chemicals for nutraceutical uses. These organisms, which have adapted to severe maritime habitats, may produce chemicals with novel medicinal characteristics.

Sustainable sourcing: The growing awareness of environmental effect has changed the focus to sustainable sourcing strategies, such as researching underutilized marine creatures and discovering methods to use processing byproducts as nutraceutical sources.

Diverse applications: Researchers are actively identifying and characterised new marine-derived compounds, as well as investigating their potential applications in areas such as oral health, where marine bioactive compounds have anti-inflammatory, antimicrobial, and antitumor properties that can be used to treat a variety of oral diseases.

Exploring marine peptides and polysaccharides: Marine peptides and polysaccharides are still

being studied for their potential health advantages, which include decreasing inflammation, regulating immunological responses, and potentially showing anti-cancer properties.

Harnessing algal potential: Macroalgae and microalgae are known for their high concentrations of functional components such as polyunsaturated fatty acids (PUFAs), polysaccharides, carotenoids, and chlorophyll pigments, which have applications in both the food and pharmaceutical industry.

Advancements in processing and extraction technologies:

Novel delivery and application technologies: New delivery systems and application technologies are being developed for both known and novel marine components, with the goal of increasing consumption and incorporating them into a wider range of functional foods and beverages.

Addressing extraction challenges: Research and development are addressing issues in extracting marine components, such as improving procedures for various marine matrices and assuring product stability and shelf life.

Nanotechnology for enhanced bioavailability: Nanotechnology is being investigated to protect marine bioactive chemicals from degradation while increasing their bioavailability and effectiveness in nutraceutical applications.

Fig. 7 Marine sources for nutraceuticals

Focus on specific areas:

Oral health: Significant research is being conducted on the use of marine-derived substances to prevent and treat oral disorders such as dental caries, gingivitis, periodontitis, and oral cancer.

Sustainable aquaculture: Aquaculture is essential for the sustainable production of seafood as well as marine-derived compounds for nutraceuticals and pharmaceuticals.

In conclusion, the marine nutraceutical industry is expanding rapidly, thanks to scientific study into marine biodiversity, the discovery of novel bioactive compounds, and technical improvements targeted at optimizing the extraction, processing, and delivery of these beneficial chemicals. The emphasis on sustainability, as well as overcoming existing extraction and product development issues, promises to broaden the impact of the years ahead. [27,28,29,30,31,32,33]

2.6 Recent developments in herbal nutraceuticals: The field of herbal nutraceuticals is witnessing a surge in innovation, driven by several key factors:

Growing consumer demand: verified market research identifies a growing demand for preventive healthcare solutions and natural goods that promote overall wellness among health-conscious consumers. The aging populations health concerns, such as joint pain and cognitive loss, are driving demand for herbal nutraceuticals that address these issues.

Innovative delivery systems:

Nano-delivery systems: Nanotechnology is demonstrating remarkable efficacy in overcoming the limits of traditional herbal medication delivery, such as poor solubility and limited bioavailability. According to the national institute of health (NIH), nanocarriers like as liposomes, nanoparticles, and nano emulsions improve the absorption, stability, and targeted delivery of herbal constituents.

Encapsulation technologies: Microencapsulation technique are utilized to protect herbal ingredients from degradation and hide disagreeable flavours, so improving consumers sensory experiences. [19]

Diverse formats: Herbal supplements are now accessible in more formats than just capsules and tablets, including as powders, liquids, and even functional meals and beverages.

Increasing scientific validation and research: Clinical trials and research are being conducted to strengthen scientific evidence supporting the efficacy and safety claims of herbal nutraceuticals. New formulations and delivery methods are being explored to maximize the health benefits of these compounds.

Potential benefits of specific herbal ingredients: Herbal nutraceuticals such as ginger, turmeric, aloe vera, and garlic are gaining popularity for their potential health benefits, Such as anti-inflammatory properties. The herbal nutraceuticals market is expanding due to rising consumer demand for natural products, increased awareness of preventive healthcare, and advancements in extraction and formulation technologies.

Technological advancements in extraction and formulation: New extraction methods such as enzyme assisted extraction (EAE), pulsed electric field extraction (PEF), supercritical fluid extraction (SFE), ultrasound-assisted extraction (UAE), and microwave-assisted extraction (MAE) are becoming more popular.

These cutting-edge techniques seek to improve the quality and bioavailability of herbal extracts while reducing extraction times, solvent use, and extraction yields. UAE recovers phenolic compounds from avocado peels, while MAE extracts polyphenols from corn tassels.

Innovative encapsulation methods, such as spray drying, spray chilling, and fluidized bed coating,

protect sensitive bioactive compounds and improve their stability and bioavailability. [20,21,23]

Fig.8 Herbal nutraceutical process

Market growth and consumer trends: The herbal nutraceuticals market is expected to grow from US $72.66 billion in 2024 to US$140.28 billion by 2034, with a CAGR of 6.80% between 2025 and 2034. Herbal nutraceuticals are becoming more popular among consumers due to concerns about chemical-based treatments and a preference for natural cures with fewer negative effects. Consumers are increasingly turning to herbal nutraceuticals to manage chronic conditions, increase immunity, and improve general well-being.

Geriatric population growth and chronic disease prevalence have a significant impact on the market. Online platforms are expanding the reach of herbal nutraceuticals by providing a diverse range of products at competitive costs. [34,35,36,37,38,39,40,41]

2.7 Encapsulation techniques in nutraceuticals: Encapsulation is critical in the nutraceutical sector, addressing issues such as component instability, limited bioavailability, unwanted sensory characteristics (flavour/ Odor), and the necessity for targeted or controlled release. Encapsulation entails encapsulating bioactive molecules (the core material) under a protective layer (the wall material).

Nanotechnology -based delivery methods: Nanocarriers such as nanogels, nano emulsions, nanoparticles (lipidic, polymeric, or protein based), noisome, liposomes, and nanocrystals are being used more frequently to improve nutraceutical encapsulation, stability, bioavailability, cellular internalization, and targeted delivery.

Focus on biopolymer-based systems: Biodegradable polymers such as chitosan, alginate, lignin, zein, casein, and other polysaccharides are commonly employed to create non-toxic, non-irritating, and readily available nanocarriers.

Targeted and controlled release: Encapsulation techniques are being enhanced to enable regulated and site-specific release of nutraceuticals, hence enhancing efficacy and reducing degradation in the gastrointestinal tract.

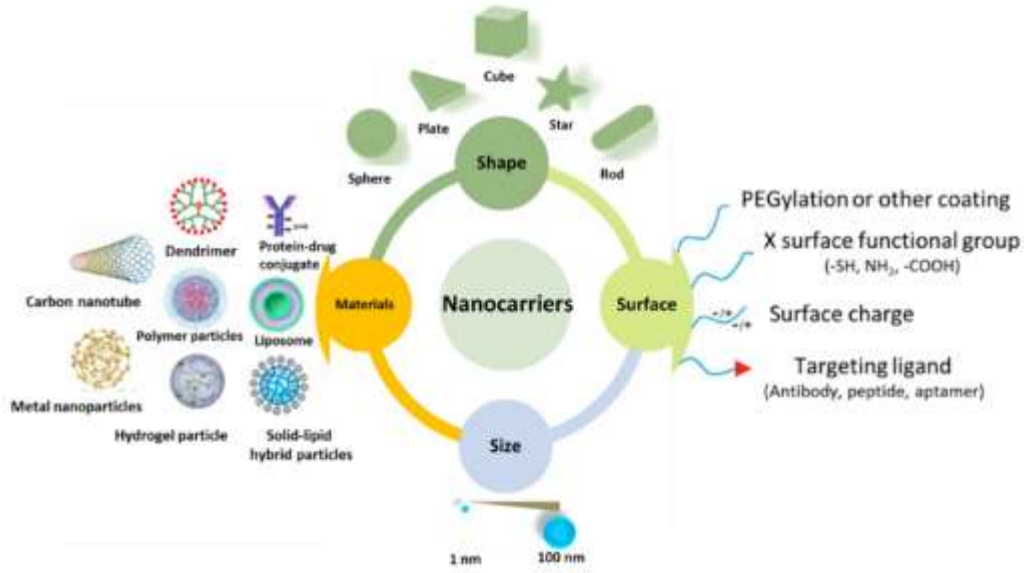

Fig.9 Encapsulation of nutraceutical active ingredients using electrospinning process.

Targeted and controlled release: Encapsulation techniques are being enhanced to enable regulated and site-specific release of nutraceuticals, hence enhancing efficacy and reducing degradation in the gastrointestinal tract.

Improved encapsulation efficiency: Research is focusing on optimizing parameters like wall material selection and concentration, process condition (temperature, pH), and interaction between the core and wall material to enhance encapsulation efficiency and prevent degradation.

Addressing challenges with conventional techniques: Efforts are ongoing to overcome limitations of traditional methods like spray drying (heat sensitivity), freeze drying (porous coating), extrusion (thermal instability), and coacervation (scalability issues).

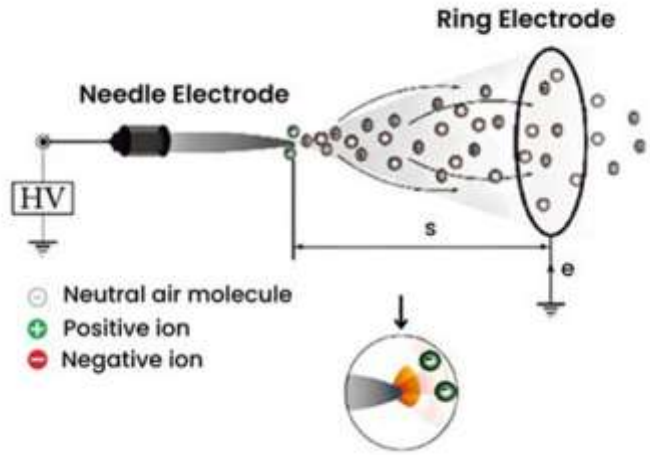

Fig.10 Electro hydrodynamic drying

Emergence of electrohydrodynamic (EHD) encapsulation: EHD techniques like electrospinning and electro spraying are gaining attention for encapsulating thermolabile bioactive, producing smaller and more stable particles with high encapsulation efficiency compared to some conventional methods.

Focus on functional lipids: New encapsulation strategies are being developed to improve the bio-accessibility and oxidative stability of functional lipids like omega-3 fatty acids, which are prone to oxidation. [42,43,44,45,46,47,48,49,50]

CONCLUSION:

Nutraceuticals are made from bioactive compounds obtained from food sources that provide more health benefits that basic nutritional value. In recent years, nutraceuticals have merged as a crucial component of preventive healthcare and received significant attention to both medical and professional domains. With increasing global load of non -prevalent diseases such as diabetes, obesity, cardiovascular disorders and certain types of cancer, lifestyle changes and increasing interest in non-pharmacological intervention.

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