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Antioxidant effects of *Spirulina platensis* and its role in neurological disorders: A review

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Abstract
Spirulina (Arthrospira platensis) is a filamentous cyanobacterium that has ever attracted concern because of its nutritional value and its possible therapeutic effects. It is interesting to note that its neuroprotective and antioxidant nature have been studied to great detail. The current evidence that is used to consolidate in this review focuses on the phycocyanin, phenolic acids and essential fatty acids bioactive compounds present in *Spirulina* adding to its antioxidative properties. The mechanistic effect of *Spirulina* is that efficacy of the endogenous antioxidants enzyme systems (such as superoxide dismutase, catalase, and glutathione peroxidase) is promoted and the oxidative stress is reduced. In *vitro* and in *vitro* experiments have been carried out in neuroprotective settings to establish the efficiency of *Spirulina* in minimizing neuronal cell injury, enhancing cognitive abilities, and neuroinflammatory reactions. The effects can be largely seen in neurodegenerative diseases models like Alzheimer and Parkinson. Although the findings were encouraging in the preclinical outcomes, there is the need to conduct more clinical trials to confirm the same results in humans. The review highlights the possibility of *Spirulina* being utilized as a natural supplement in the treatment of neurological disorders of oxidative stress nature.

Keywords: Spirulina platensis, antioxidant activity, neuroprotection, neurodegenerative diseases

Introduction

Spirulina (Arthrospira platensis*)* is a filamentous cyanobacterium that has received important concerns because of its widespread use in nutritional, pharmaceutical and industrial fields as shown in fig. 1. The taxonomic classification of this microorganism has been constantly revised throughout history and historically, it was called under different names, including *Spirulina* and *Arthrospira* and more recently, *Limnospira* (Sinetova *et al.*, 2024) [27, 28]. The organism is nevertheless an open book and grown frequently under the name *Arthrospira platensis*, at least in the business world. It can grow alkaline and with high salinity, and thus is a suitable candidate to be produced on large scale in controlled systems, including open raceway ponds and photobioreactors (ElFar *et al*, 2022) [6]. Certainly, it is used in various fields in the food industry and the sphere of therapeutic treatment because of its high protein content, richness in the composition of useful vitamins, essential fatty acids, and bioactive compounds (Gentscheva *et al*, 2023) [7]. The recent publications by Ram *et al.* (2022) [20] and Sharma *et al.* (2022a) [27] have emphasized the use of soil microbes which are beneficial; *Pseudomonas* spp. *Rhizobium* spp in enhancing plant resilience of arid legumes such moth bean and ajwain. These microb are great in terms of governing their nutrient intake as well as biochemical and enzyme stability under biotic stress, which manifests some form of oxidative stress within the plant system. The plant and microalgae have conserved oxidative stress reduction mechanisms especially by enzyme regulation. As an example, *Vigna aconitifolia* has showed high adaptation in enzyme capacity and high seed viability in areas of bacterial stress due to *Xanthomonas axonopodis*, which prove that this plant is biochemically resilient (Sharma *et al*, 2022b) [26]. This resilience to adapt to stress occurs through prolonged activity of the major antioxidant enzymes, so that the plant can survive the biotic perturbation. Related mechanism seen in *Spirulina (Arthrospira platensis)* a cyanobacterium that has been well studied in an animal and has shown antioxidant and neuroprotective effects. This chapter below gives a summary of its taxonomy, its cultivation and general biological features alongside the significance of the organism as a nutritionally and sustainably healthy source.

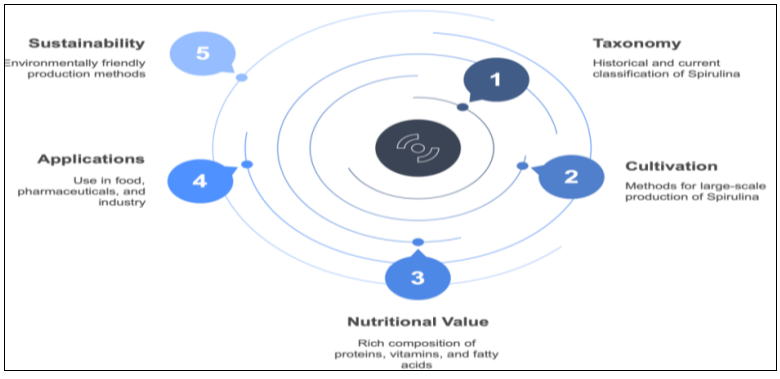

Fig 1: Spirulina's Multifaceted Significance

In neurodegenerative disorders like Alzheimer, Parkinson and Huntington disease, oxidative stress is very important in pathogenesis. That has fuelled the growing scientific efforts to seek information on natural compound search with natural antioxidant and neuroprotective effects. Of these, *Spirulina*, a cyanobacterium that is abundant in bioactive molecules, has become a potential candidate owing to its capacity to eliminate oxidative damage and inflammation of the neuronal tissue (Abd Elkader *et al*, 2024) [1]. The studies have also revealed that neuroprotection of *Spirulina* is mainly ca used by its wide range of compositions such as phycocyanin, phenolic acids, and essential fatty acids as shown in fig. 2, aid in the modulation of the oxidative stress pathways thereby decreasing the neuroinflammation (Rodrigues *et al*, 2024) [22]. With aging populations the burden of neurodegenerative diseases is increasing exponentially and the search of therapeutics that can serve as a preventive and as adjuvant treatment, the use of algal-based treatment, especially that derived by *Spirulina* is appealing and sustainable (Paranthaman & Palraj, 2024) [17]. The part highlights the importance of researching on *Spirulina* and other natural compounds in respect to their potential in fighting oxidative strain and in averting the advancement of neurological conditions.

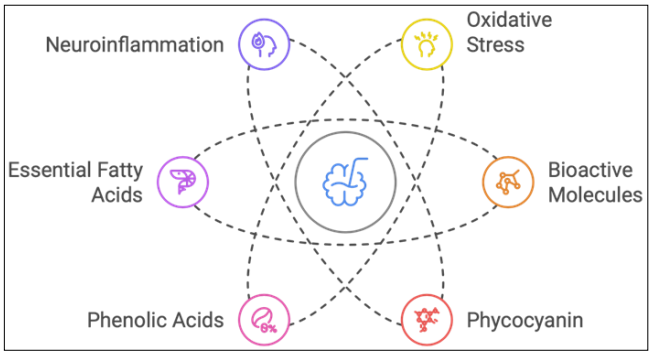

Fig 2: Spirulina's Role in Neuroprotection

Phytochemical Composition of *Spirulina*

1.1 Primary Bioactive Compounds

Teble 1 show well-known dense and diversified phytochemical profile supported the extensive bioactivities of *Spirulina* spp., especially *Spirulina platensi*s. *Spirulina* contains the richest phycobiliprotein (especially phycocyanin), phenolic compound, polysaccharides, polyunsaturated fatty acid (PUFAs), vitamins, and minerals of which play an essential role in its bioefficacy and pharmacological properties (Bortolini *et al.*, 2022) [5].

Phycocyanin is among the highly found and explored bioactive constituent that boasts of a potent antioxidant, anti-inflammatory, and an immunomodulatory effect. It is an antioxidant that has been attributed to anticancerous properties to different oxidative stress-related disorders (Kavisri *et al.*, 2023) [10]. It has also been observed that *Spirulina* has abundant phenolic acids and flavonoids such as gallic acid, chlorogenic acid and quercetin that increases the antioxidant and antimicrobial properties (Ben Mya *et al.*, 2025) [4, 40]. *Spirulina* contains essential fatty acids, which account for the majority of lipid profile of the same, including linoleic, gamma-linolenic acid (GLA), playing a crucial role in maintaining the cellular integrity and controlling inflammatory pathways. In addition, *Spirulina* biomass contains large various of polysaccharides, which have prebiotic, antiviral, and immunostimulatory effects, which can be used in the nutraceutical and pharmaceutical industries (Kavisri *et al.*, 2023) [10]. These compounds can be affected by regional and environmental factors by their concentration and composition. As an example, a comparational analysis of the Algerian and Egyptian harvested *Spirulina* showed massive differences regarding the protein, lipid, and phenolic components, where the origin and cultivation conditions may be essential in defining the nutritional and functional value of *Spirulina* (Ben Mya *et al.*, 2025) [4]. To summarize, the health-promoting properties of *Spirulina* are provided by its main bioactive components especially phycocyanin, polyphenols, essential fatty acids, and some polysaccharides. Emerging finds and continuous research unbloom even more area of application of these compounds as well as extraction methods to get the best out of these compounds in the food, cosmetic and pharmaceutical sectors.

The colossal bioactivities of *Spirulina* spp. especially *Spirulina platensi*s that is supported by renowned dense and diversified phytochemical profile. *Spirulina* abounds in phycobiliprotein (especially phycocyanin), phenolic compound, polysaccharide, polyunsaturated fatty acid (PUFAs), vitamins and minerals whose contribution is essential in its bioefficacy and pharmacology profile (Bortolini *et al.*, 2022) [5].

Another cyanobacterium referred to as the *Spirulina* (or also *Limnospira platensis*) is a screw-like and filamentous micro-organism which has been known to have a very high phytochemical content and high nutritive value. Phycocyanin is a major signature pigment-protein complex and is one of the most excellent bioactive compounds. Phycocyanin is another constituent of the *Spirulina* which effectively not only contributes towards the typical blue-green color that characterizes it but is also powerfully endowed to exhibit antioxidant, anti-inflammatory and also immunomodulatory activities. It plays a major role in assistance of neutral state of the reactive oxygen species and oxidative stress amelioration of biological systems (Sabat *et al.*, 2025; Spinola *et al.*, 2024) [23, 31].

The other important category of compounds in *Spirulina* is phenolic compounds (phenolic acids, and flavonoids), which also plays an important role in antioxidant potential. The effect of these substances is to protect the cells against destruction and is associated with antimicrobial, anti-inflammatory, and endocardial protection effects (Marjanovic *et al.*, 2024) [14]. The polysaccharides also provide biological activities of species *Spirulina* making it of interest. These complex carbohydrates are prebiotic, immunostimulatory and antiviral stimulating the microbial environment in the intestine and the overall immune in the body (Sabat *et al.*, 2025) [23]. The other key ingredient is essential fatty acids particularly 9.63 omega-6/d6 linolenic acid (GLA). GLA plays an essential role in obtaining a healthy flow of the cell membranes, which is beneficial to cardiovascular as well as skin (Spinola *et al.*, 2024) [31].

Table 1: Major Bioactive Compounds of *Spirulina* platensis and Their Pharmacological Activities

Bioactive Compound	Category	Biological Activities	Key Findings / Remarks	References
Phycocyanin	Phycobiliprotein	Antioxidant, anti-inflammatory, immunomodulatory, anticancer	Major pigment-protein complex responsible for blue-green color and strong antioxidant effects	Bortolini *et al.*, 2022[5]; Kavisri *et al.*, 2023[10]; Sabat *et al.*, 2025[23]; Spinola *et al.*, 2024[31]
Phenolic compounds	Phenolic acids, flavonoids	Antioxidant, antimicrobial, anti-inflammatory, endocardial protection	Includes gallic acid, chlorogenic acid, quercetin; enhances cell protection against oxidative damage	Ben Mya *et al.*, 2025[4]; Marjanovic *et al.*, 2024[14]; Sabat *et al.*, 2025[23]
Polysaccharides	Complex carbohydrates	Prebiotic, antiviral, immunostimulatory	Stimulates gut microbiota and immune system; applicable in nutraceutical and pharmaceutical industries	Kavisri *et al.*, 2023[10]; Sabat *et al.*, 2025[23]
Polyunsaturated Fatty Acids	Lipids (PUFAs)	Anti-inflammatory, membrane fluidity, cardiovascular and skin health	Includes linoleic and gamma-linolenic acid (GLA); supports cellular function and systemic anti-inflammatory action	Spinola *et al.*, 2024[31]; Ben Mya *et al.*, 2025[4]
Vitamins and Minerals	Micronutrients	Antioxidant support, enzymatic cofactor roles, immune support	Enhances Spirulina's nutraceutical value and contributes to overall health benefits	Bortolini *et al.*, 2022[5]
Geographical Variability	Environmental influence	Affects bioactive compound content (protein, lipids, phenolics)	Regional cultivation conditions (e.g., Algerian vs. Egyptian Spirulina) influence nutritional and functional value	Ben Mya *et al.*, 2025[4]

Nutritional Profile

More than these specific active compounds, *Spirulina* is known to be an exceptionally high protein source as it represents up to 80 percent of its weight in the dry form. *Spirulina* is rich in proteins consisting of complete and all essential amino acids rendering it to be an excellent source of proteins derived out of a plant (Marjanovic *et al.*, 2024) [14]. Ram *et al.* (2021) [19] also reported 20.23 % protein content in Ajwain seeds. *Spirulina* also contains abundant minerals and vitamins such as the B-complex vitamins (especially B12 in a form that the body can use), and vitamin E, iron, calcium, magnesium and potassium. These nutrients help several biological activities, ranging between metabolic operations to immune resistance (Spinola *et al.*, 2024) [31]. Moreover, *Spirulina* has numerous pigments, including chlorophyll and carotenoids (e.g., 8-carotene, zeaxanthin) that, besides their strong coloring character, improves its antioxidant and detoxifying effect (Marjanovic *et al.*, 2024) [14].

Antioxidant

Spirulina platensis has been widely recognized for its robust antioxidant capacity, which is primarily attributed to its rich composition of bioactive compounds such as phycocyanin, carotenoids, phenolic acids, and polysaccharides. These compounds work through multiple mechanisms to combat oxidative stress, a major contributor to cellular aging and various chronic diseases as shown in fig. 3.

One of the primary antioxidant actions of *Spirulina* is its ability to directly scavenge reactive oxygen species (ROS), including superoxide anions, hydroxyl radicals, and hydrogen peroxide. This free radical scavenging activity has been confirmed in both in *vitro* and in *vitro* studies. For instance, Han *et al.* (2021) [9] demonstrated that *Spirulina* extracts significantly reduced ROS levels in oxidative stress models, attributing this effect largely to phycocyanin and other antioxidant pigments. Similarly, Sarkar *et al.* (2021) [24] showed that a sulfite reductase enzyme (TL15) derived from *Arthrospira platensis* displayed strong radical scavenging activity in a zebrafish model exposed to oxidative stress, supporting the potential of *Spirulina* at a molecular and organismal level.

In addition to direct ROS neutralization, *Spirulina* enhances the activity of key antioxidant enzymes that play vital roles in endogenous defense systems. Studies have reported increased levels of superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) following *Spirulina* administration. Kumar *et al.* (2022) [11] observed that rats supplemented with *Spirulina platensis* showed significant upregulation of these enzymes in liver tissues, suggesting improved cellular resistance to oxidative damage.

Moreover, *Spirulina* has been shown to modulate biochemical markers associated with oxidative stress. In particular, it has demonstrated a significant ability to reduce levels of malondialdehyde (MDA), a lipid peroxidation byproduct and a widely used marker for oxidative damage. Reduced MDA levels following *Spirulina* supplementation indicate a decrease in membrane lipid degradation and an overall reduction in oxidative stress (Kumar *et al.*, 2022) [11]. These effects are further supported by reductions in total lipid peroxidation levels in various tissues, highlighting the systemic antioxidant efficacy of *Spirulina*.

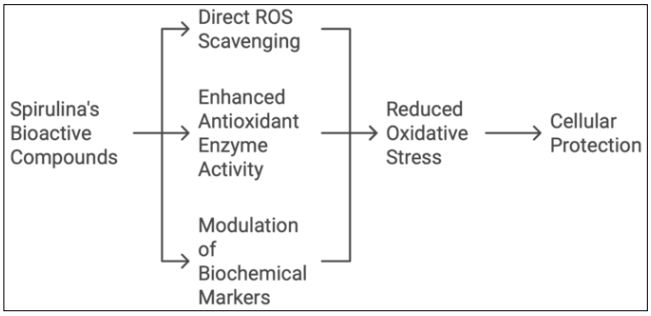

Fig 3: Antioxidant Mechanisms of Spirulina

Neuroprotective Effects of *Spirulina*

Spirulina platensis has attracted much interest over its neuroprotective properties, and both in *vitro* and in *vitro*

evidence demonstrates the same. Among the bioactive compounds it is rich in, phycocyanin, polysaccharides, and essential fatty acids, are especially significant to alleviate neurotoxicity and neuroinflammation, which are two major pathogenic features of neurodegenerative conditions as shown in fig. 4.

It has been demonstrated that in *vitro Spirulina* has the ability to defend neurological cells against neurotoxicity caused by neurotoxicants. Mallamaci *et al.* (2023) [13] have been able to show that *Spirulina* extracts introduced resplendent safety against cytotoxicity caused by heavy metals in SH-SY5Y human neuroblastoma cells. In particular, cadmium, mercury and lead exposure also caused a significant cell death and oxidative stress, which was significantly attenuated in the presence of *Spirulina*, evidencing its antioxidative and membrane-stabilizing action. This can be related to its capability to overcome iron-induced neurotoxicity which is related to the progression of diseases such as Parkinson as well as similar security mechanisms can be the cause behind this.

The neuroprotective potential of *Spirulina* is also strengthened with in *vitro* experiments. Parkinsonian animal models have proven that the neurobehavioral enhancement and the balancing of neurochemistry will be attained in *Spirulina* supplementation. According to Asuku *et al.* (2024) [3], the use of marine green *Spirulina* in neurodegenerative animal models was associated with declines in pro-inflammatory cytokines as well as oxidative stress markers, and related to augmented antioxidant enzyme activities within brains tissues. The results indicate the two mechanisms of action, i.e., anti-inflammatory and antioxidative ones.

Besides, Ramos *et al.* (2023) [21] emphasized the general therapeutic possibilities of cyanobacteria, including *Spirulina*, in the reduction of neurodegenerative disease progression. They explained that compounds obtained in *Spirulina* can regulate cellular signaling pathways that are linked to inflammation, abnormal mitochondrial processes, and the survival of nerve cells, which are major targets in the management of diseases like Alzheimer and Parkinson.

Spirulina platensis has recently been described as a potential neuroprotective agent especially in the management of neurodegenerative diseases like Alzheimer disease (AD). It has a complex neuroprotective effect on many bioactive compounds (e.g., phycocyanin, polysaccharides, and polyunsaturated fatty acids) which lead to the antioxidant, anti-inflammatory, anti-apoptotic, and neurotrophic pathways of the mechanism of neuroprotection.

Amelioration of cognitive deficits relating to Alzheimer disease is one of the important neuroprotective effects of *Spirulina*. According to Abdelmoniem *et al.* (2024) [2], *Spirulina* was found to enhance memory and learning behavior in the animal models of Alzheimer disease. They could be connected to the improvement of the antioxidant status in brain tissue, a decrease in markers of oxidative stress and an increase in activity of endogenous antioxidant enzymes. This kind of redox balance modulation plays a pivotal role in reducing neuronal damage that normally occurs in Alzheimer pathology.

In addition to its antioxidant functions, *Spirulina* diet is highly anti-inflammatory. Neuroinflammation causes most neurodegenerative diseases, and the research implicates that *Spirulina* can lower brain pro-inflammatory cytokines, including TNF- A and IL-6 (Rodrigues *et al.*, 2024) [22]. This down regulation of inflammation aids in maintaining of the neuronal integrity and averts further degeneration.

The second process that brought about the neuroprotective profile of *Spirulina* is that it averts apoptosis or programmed cell death. As it has been noted by Abd Elkader *et al.* (2024) [1], the pro-apoptotic markers which include caspase-3 were reduced and the cell survival signals which were induced by the bioactive compounds of *Spirulina* also reduced the neuronal death in the diseased models.

In addition to this, *Spirulina* has also been found to influence neurotrophic factors that are actually the proteins that generate the simulated growth, survival and advances of neurons. That the level of brain-derived neurotropic factor (BDNF), as in studies of experimental animal subjects, can be regulated suggests that even *Spirulina* might have a place in enhancing synaptic plasticity and cognitive flexibility (Abdelmoniem *et al.*, 2024) [2].

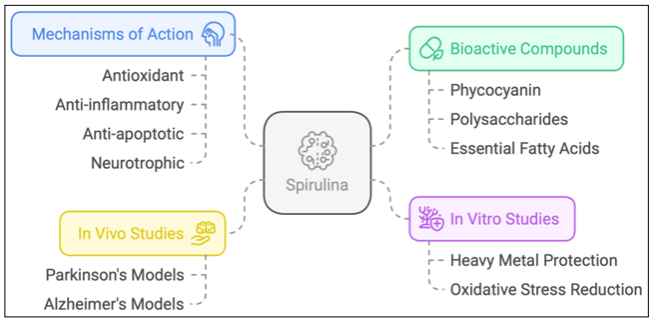

Fig 4: Neuroprotective Effects of Spirulina

Clinical Implications and Potential Therapeutic Applications

The resulting evidence of increasing scientific studies highlights the clinical possibilities of the neuroprotective dietary nutraceutical *Spirulina platensis*. Phycocyanin, polyphenols, essential fatty acids, vitamins, and mineral substances are the significant bioactive components of *Arsenicum album* that are responsible in antioxidative, anti-inflammatory, and neurotrophic activities. These qualities render *Spirulina* as a promising option of prevention and adjunctive approaches against neurodegenerative disorders as shown in fig. 5.

The efficacy of the *Spirulina* supplementation in brain health is studied in several experimental and clinical studies. In a scoping review, Sorrenti *et al.* (2021) [30] noted the low-quality but preclinical and limited clinical evidence of supporting *Spirulina* in the reduction of oxidative stress and enhancement of cognitive ability. Their analysis of clinical trials showed that there were positive effects in matters of attention, memory, and mental fatigue especially in the elder populations and in people subjected to oxidative stress. These results point at a possible benefit of *Spirulina* in the prevention of ageing cognitive and neurodegenerative deterioration.

Moreover, Kumar *et al.* (2025) [12] edited a systematic evaluation of the positive impact of *Spirulina* on the brain health. Their results reiterate the neuroprotective effects of *Spirulina* that can inhibit neuroinflammatory markers and improve the defense of endogenous antioxidants, which is an environment favoring neuroprotection. Although most existing evidence is formed on animal models, preliminary human research exhibits favorable toleration and lack of any

severe adverse effects when supplementing on a long-term basis, emerging to be safe.

The two reviews affirm that further research by means of rigorous, big in size, and extensive in length clinical trials are required in order to ascertain with certainty, the therapeutic value of *Spirulina* in the management of neurodegenerative diseases. Moreover, standardized formulation, dose patterns, and recommendations to particular patients are the aspects that still need their investigation.

Spirulina platensis is attracting growing attention as an adjuvant therapy in neurodegenerative diseases because of its high content of neuroactive compounds of antioxidant, anti-inflammatory, and neuroprotective nature. These bioactivities correlate well with the pathogenesis of neurodegenerative disorders like Alzheimer disease, Parkinson disease, and amyotrophic lateral sclerosis, which results due to oxidative stress, chronic inflammation, and apoptosis of neurones.

Rahman *et al.* (2021) [18] state that a growing number of natural products, such as *Spirulina*, are becoming increasingly popular in therapy research because of their multi-targeting and positive safety characteristics. Most uniquely, *Spirulina* has been found to be promising in regulating various biochemical pathways that have been found to contribute to neurodegeneration. Its phycocyanin concentration is found to be strong reactive oxygen species (ROS) scavenger and its polysaccharides and polyphenols are involved in the suppression of inflammatory molecules including TNF-alpha and IL-1 beta-like TNF-alpha and IL-1beta. These mechanisms imply that *Spirulina* may be used in therapeutic setting as an adjuvant of standard treatments or as a preventing entry in the diet.

Parameswari and Lakshmi (2022) [16] also help promote *Spirulina*, or rather microalgae in general, as a therapeutic tool in neurology. They emphasize that it attenuates the important neurodegenerative mechanisms such as mitochondrial failure, apoptosis, and synaptic abasement. The review highlights the prospects of *Spirulina* based formulations in exerting neuroprotective effect devoid of the known adverse side effects that is often displayed in the use of synthetic drugs. In addition, ensuring *Spirulina* into numerous delivery platforms such as capsules, functional foods, or nutraceuticals also makes the compound more versatile, as a therapeutic compound.

Nonetheless, although evidence of the therapeutic qualities of *Spirulina* is robust using preclinical research, translation to clinical practice is still circumscribed. Rahman *et al.* (2021) [18] support the fact that before its successful implementation into practice, rigorous human trials and standardization of bioactive compound profiling are necessary to prove its usefulness in clinical practice. The issues like the bioavailability, the dosing, and long-term safety have to be solved.

Although *Spirulina platensis* has started gaining much appreciation in the research world as an effective natural compound in health and neuroprotection, there exist a few key limitations that need to be resolved before translation to clinic mode can be fully affected. Among them, issues of bioavailability, standardization of dosage, and long-term safety profile of *Spirulina*-based interventions deserve to be mentioned in the first place.

The greatest limitation to maximizing the therapeutic effect of *Spirulina* is the bioavailability barrier. Most of the bioactive substances present in *Spirulina* (phycocyanin, and other antioxidants, among them) are degraded along the digestive tract or have low absorption rates, as ElFar *et al.* (2022) [6] mention. As a result, new delivery methods - including microencapsulation, nanoparticle systems, lipid-based formulations- are under investigation to improve stability and specific delivery. The idea of these superior delivery platforms is to raise systemic absorption and extended biological activity of the products in reducing the therapeutic effect.

Issues with standardized dosing are yet another huge problem. Since *Spirulina* is grown under very changing environmental conditions its phytochemical composition may vary widely depending on the batch and the source. According to Gogna *et al.* (2023) [8], variation in clinical outcomes is caused by the lack of regulatory standards on composition and purity, and it is also difficult to provide effective and safe doses. When there are no definite recommendations on the dosage, practitioners and patients may have problems with reproducible *Spirulina* use as a therapy.

Besides, long term effects and toxicological aspects are underexplored. At the same time, it is found that, despite the general perception of *Spirulina* as risk free and generally tolerable, Gogna *et al.* (2023) [8] warn about the increase or prolonged usage of the food supplement and the possible dangers in the event of the use thereof being contaminated with heavy metals or microcystins since risk free production thereof cannot be guaranteed because of the lack of regulation of that process. More research is required to evaluate cumulative effect, possible interactions with other medicines, and safety about susceptible individuals, including children, gestationary demographics, or those with established diseases.

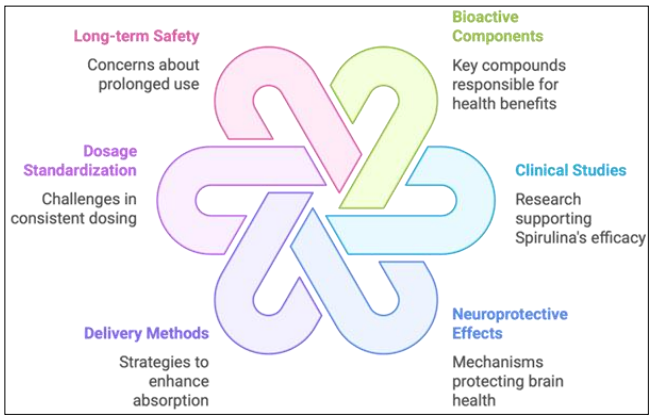

Fig 5: Exploring Spirulina's Therapeutic Potential

Future Research Directions

Although significant preclinical evidence exists of the therapeutic and neuroprotective effect of *Spirulina platensis*, coupling those findings into a clinical setting requires systematic and broad, human-based studies. Due to the limitations of data currently in circulation, most of the data is based on in *vitro* models and animal studies, with even this data only being informative and not entirely indicative of not only efficacy but also safety in human populations. Such a gap highlights the necessity of well-conceived clinical studies that confirm the effect of *Spirulina* in practical use in medicine as shown in fig. 6.

Mehta *et al.* (2025) [15] state that modernization of drug development is an issue that can always be assured not only by acquiring effective preclinical data but also by incorporating New Approach Methodologies (NAMs) that can always facilitate the translation of laboratory findings into human subjects. Such NAMs are in silico modeling and organ-on-chip models, which can be applied in combination with human trials, to enhance the knowledge of *Spirulina* mechanism of action, pharmacodynamics and interaction in complex biological systems. Such methodological approaches can make clinical experimental designing more effective so that researchers can anticipate results to make the design more anticipated instead of making doses regimens.

In addition, compounds having good preclinical profiles may still have considerable difficulties in clinical translation due to lack of standard protocols and findings based on a randomized controlled trial (RCT) as Solon *et al.* (2025) [29] emphasize in their discussion on the natural products. In the case of *Spirulina*, the scope of future trials should subject endpoints (discussed as cognitive performance, biomarkers of oxidative stress, inflammation, or quality of life indicators) to clear definition. Elderly people and risk groups with neurodegenerative diseases should be paid serious attention.

Although, the long-term safety examination and studies on the interaction with pharmaceuticals are vital in setting the position of *Spirulina* in treatment programs. In an effort towards this, multi-centre studies, consistent formulation, and an identical dosing range will be essential in ensuring that the outcomes can be generalized and put into clinical practice.

Therapeutic potential of *Spirulina (Arthrospira platensis)* has been established, additional studies are needed to determine its molecular mechanisms of action and the process of its delivery optimization related to clinical application. The bioactivity of *Spirulina* is pegged more on the convoluted pharmacology of a set of bioactive compounds, which include phycocyanin, polyphenols, and essential fatty acids, although a great number of the intracellular sign update posts they contribute towards are still not very well understood. The use of mechanistic research is imperative in the study of the mechanism of action of *Spirulina* and its role in oxidative stress and autophagy, inflammation, apoptosis, and mitochondrial dynamics, among others (Shah *et al.*, 2024) [25]. As an example, phycocyanin has been demonstrated to regulate nuclear factor erythroid 2-related factor 2 (Nrf2) signaling that govern cellular antioxidant networks of vital importance. Nevertheless, further studies on its high-resolution coverage of activity in different tissues and disease models are necessary such as; neurodegeneration, metabolic syndrome, and immune regulation.

Formulation development is the other important research field besides mechanistic exploration. Limited oral bioavailability and losses of les-sensitives prevalent in gastrointestinal tract have held traditional oral administration of *Spirulina*. According to ElFar *et al.* (2022) [6], the novel delivery systems (e.g. microencapsulation, nanoemulsions, lipid-based carriers) to secure a better stability of *Spirulina* with active constituents' absorption and target delivery is important to implement. Such technologies are able not only to preserve bioactives during the allure of harsh gastric conditions but also allow targeted release and tissue specific delivery and direct it to the given tissue missed by traditional protein drugs by far enhancing its therapeutic effect. A combination of the mechanistic understanding and refined formulations may aid in speeding the process through which *Spirulina* becomes a clinically-proven nutraceutical or additional therapeutic agent. In future, priority should be given to combining molecular biology, pharmacokinetics and delivery science to help maximise the potential of *Spirulina* as precision medicine.

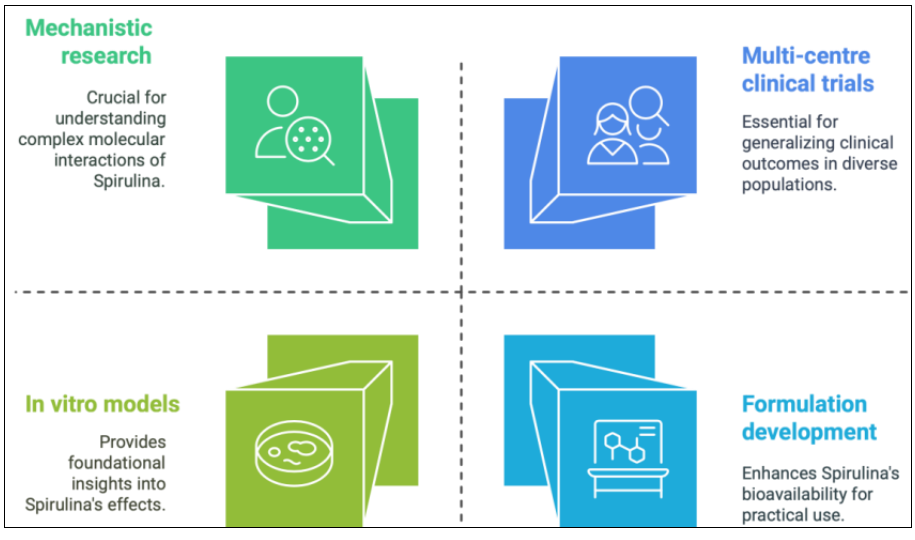

Fig 6: Future Research Directions for Spirulina

Conclusion

There is a lot of preclinical / experimental evidence that supports the fact that *Spirulina* (*Arthrospira platensis*) has a great antioxidant and neuroprotective ability. Its high content of bioactive compounds (phycocyanin, phenolics and essential fatty acids), allows it to effectively perform the role of antioxidants, scavenge reactive oxygen species, augment the endogenous antioxidant enzymes, like SOD, CAT and Gpsx, and regulate the vital indices of oxidative stress. This has been credited with its protective effects with neurodegenerative pathophysiological models where *Spirulina* showed the ability to limit inflammation, inhibit

apoptosis of neurons and augment neuronal network ability through regulation of neurotrophic factors. In light of such beneficial quality, *Spirulina* is a great prospect in terms of natural therapy which can be utilized in the domain of dietary supplementation and alternative interventional strategies that can be implemented in cases of neurological disorders. However, its clinical translation is weak and poorly stretched with several issues such as variable formulations, insufficient human evidence, and bioavailability. Further research, particularly, the ones entailing well-designed clinical trials, mechanistic studies and delivery system engineering are likely to reveal the entire therapeutic potential of *Spirulina*, which will ensure uniform efficacy and safety of the substance towards chosen population groups. Additional studies of the inter-disciplinary could be critical in the process of developing the full potential of it as an agent of functional neuroprotection.

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