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DATA-DRIVEN MODELING OF NUTRITIONAL QUALITY AND DIGESTIBILITY OF ALGAL PROTEINS FOR BIOMEDICAL INFORMATICS APPLICATIONS

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ABSTRACT

The quest for sustainable protein sources and personalized treatment has pushed algal protein nutritional research. Proteins from microalgae and macroalgae are intriguing alternatives to conventional protein sources due to their high protein content, essential amino acids, bioactive substances and environmental sustainability. Traditional nutritional evaluation emphasizes nutrient composition; current biomedical informatics emphasizes digestibility, absorption, and physiological response. This review introduces a data-driven paradigm for modelling the nutritional quality and digestibility of algal proteins through machine learning, biomedical analytics, and computational intelligence. The project covers nutritional profile, digestibility assessment, predictive healthcare, and algal protein-based personalized nutrition. Neural networks, support vector machines, and deep learning are used to predict nutrient bioavailability and health consequences. Biomedical informatics added to nutritional science can enhance precision nutrition, illness prevention, and intelligent dietary recommendation systems. Also discussed are data quality, interpretability, and healthcare privacy issues and potential opportunities in AI-driven nutritional healthcare systems.

***Keywords*:** Algal Proteins, Nutritional Quality, Digestibility Analysis, Biomedical Informatics, Machine Learning

Introduction

Algal proteins are popular as sustainable, nutrient-rich protein substitutes. Micro and macroalgae provide high-quality proteins, vital amino acids, vitamins, minerals, antioxidants, and bioactive substances for human health and nutrition. Global population increase; food insecurity, environmental degradation, and healthcare concerns have pushed the hunt for sustainable diets. Algal proteins are promising because to their high productivity, minimal land consumption, and environmentally benign farming.

The traditional approach to nutrition research focuses primarily on the bio- chemical makeup of dietary products. However, current health care systems are increasingly focusing on nutrient digestibility, bioavailability, metabolic response and personalized planning of diets. Biomedical informatics is the integration of artificial intelligence, healthcare analytics and nutritional science to improve health monitoring and decision making. Researchers can easily assess the nutritional quality and digestibility of algal proteins using machine learning and data-driven modelling (Theodore Armand *et al.*, 2024).

The nutritional value of proteins is heavily influenced by their digestibility. Even the most nutritious protein sources may not deliver adequate physiological advantages if nutrient absorption is limited (Marze, 2017). Cell wall composition, processing methods, enzyme activity, gut flora, and individual metabolic circumstances all have an impact on algal protein digestibility. Computational techniques can assist in identifying correlations between these characteristics and support predic- tive nutritional analysis (Pascari *et al.,* 2022).

Advances in artificial intelligence, deep learning, wearable healthcare devices, and biomedical data analytics have changed nutritional healthcare systems. AI-powered nutritional models may analyze food composition, clinical datasets, and patient-specific health indicators to provide personalized dietary advice and disease preventive techniques (Bleakley and Hayes, 2017). Thus, the integration of biomedical informatics with algal protein analysis offers a potential avenue for precision nutrition and smart healthcare systems

This review explores data-driven ways to assessing the nutritional value and digestibility of algal proteins. The study also discusses machine learning techniques, biomedical applications, healthcare analytics, mathematical modelling, and future research directions in intelligent nutritional healthcare systems.

Overview of Algal Proteins

Algae are photosynthetic organisms that are broadly divided into microalgae and macroalgae. Microalgae, including Spirulina, Chlorella, and Dunaliella, are known for their high protein content and nutritional value. Macroalgae, or sea-weeds, are rich in proteins, minerals, dietary fibers, and bioactive substances.

Algal proteins contain critical amino acids that are required for tissue development, immunological function, and metabolic regulation. When compared to traditional animal protein sources, algal proteins are more sustainable and environmentally benign, with lower greenhouse gas emissions and land utilization. Algal proteins also contain antioxidants, polyunsaturated fatty acids, and pigments, all of which help to improve human health.

Table 1 presents a comparison of common algal protein sources.

The nutritional value of algal proteins varies depending on growing conditions, harvesting methods, extraction processes, and environmental factors.

Table 1: Comparison of common algal protein sources Algal Source Protein Content Major Nutrients Application

Spirulina	60–70%	Iron, Vitamins	Dietary Supplements
Chlorella	50–60%	Chlorophyll, Protein	Functional Foods
Dunaliella	40–50%	Beta-Carotene	Nutraceuticals
Seaweed	20–40%	Fiber, Minerals	Food Industry

Thus, improved computer models are required to assess nutrient variability and optimize nutritional quality.

Nutritional Quality Assessment

Nutritional quality assessment assesses food products' ability to offer necessary nutrients and support physiological processes. Traditional nutritional analysis uses laboratory procedures to analyze proteins, carbs, lipids, vitamins, and minerals. However, contemporary biomedical informatics expands nutritional analysis to include digestibility, bioavailability, metabolic efficiency, and personalized dietary response.

Algal proteins' nutritional quality is determined by their amino acid con- tent, protein digestibility, mineral availability, antioxidant characteristics, and bioactive substances. Algal proteins contain critical amino acids including lysine, leucine, and valine, which help with muscle growth and metabolic activity. Furthermore, algae contain bioactive peptides with antibacterial, antioxidant, and anti-inflammatory properties.

Machine learning techniques can analyze big nutritional datasets and un- cover links between food patterns and human health consequences. Data-driven healthcare systems can predict vitamin deficiencies, metabolic diseases, and personalized nutritional needs based on patient-specific data (Theodore Armand *et al.*, 2024).

Digestibility Modeling and Biomedical Analysis

Digestibility modelling seeks to understand how nutrients are broken down, ab- sorbed, and utilized in the human body. Protein digestibility is especially relevant in determining the nutritional value of algal proteins since cell wall architecture and biochemical makeup might affect nutrient absorption.

Several factors influence algal protein digestibility, including enzyme activity, food processing methods, gut microbiota makeup, age, metabolism, and health status. Traditional digestibility analysis techniques are labor-intensive and time-consuming. Therefore, computational intelligence and biomedical informatics technologies are increasingly applied to improve digestibility assessment (Demarco *et al.*, 2022).

Mathematical modeling can estimate nutrient absorption efficiency using predictive equations. Digestibility percentage can be calculated as:

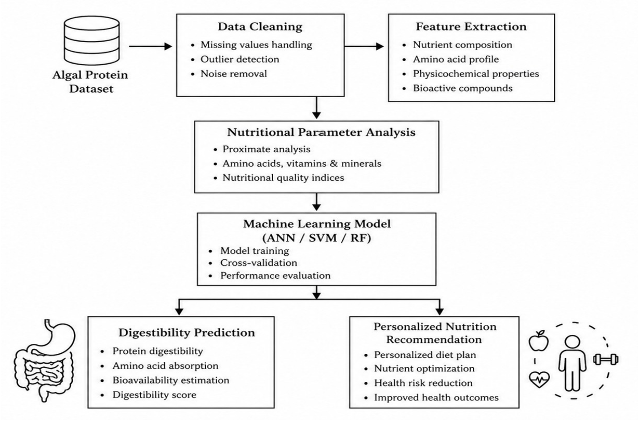

Fig. 1: Framework for nutritional quality prediction of algal proteins

$$D = \frac{N_a}{N_t} \times 100$$

where:

D – represents digestibility percentage,

N_a – represents absorbed nutrient amount,

N_t – represents total nutrient intake.

Machine learning algorithms including Support Vector Machines (SVM), Random Forests, Decision Trees, and Artificial Neural Networks (ANN) are commonly used in digestibility prediction systems. These algorithms can examine complex nutritional and biological information to reveal hidden patterns related to food absorption and metabolic response.

Gut microbiome data is also crucial for digestibility modelling. The interactions of gut microbes and algal nutrients have a substantial impact on metabolic efficiency and overall health consequences (Duncanson *et al.,* 2024). Biomedical informatics systems can handle microbiome-related datasets to facilitate personalized nutrition applications (Kussmann *et al.,* 2023).

Machine Learning Approaches to Nutritional Prediction

Machine learning approaches have emerged as highly useful tools for nutritional healthcare analytics. These algorithms can analyze massive amounts of biological and dietary data to detect nutritional patterns and predict health effects.

Supervised learning methods, including Decision Trees, Naïve Bayes, Support Vector Machines, and Neural Networks, are commonly employed for nutritional prediction. Deep learning methods enhance prediction accuracy by identifying hidden features in multidimensional healthcare datasets (Quan *et al.*, 2026).

A predictive nutritional model can be mathematically represented as:

$$Y = f(X_1, X_2, X_3, \ldots, X_n)$$

where:

- Y represents the predicted nutritional outcome,
- $X_1, X_2, \ldots, X_n$ represent biomedical and nutritional features,
- f represents the machine learning prediction function.

Table 2 compares different machine learning models used in nutritional health-care applications.

Table 2: Comparison of machine learning models in nutritional healthcare

Model	Accuracy	Complexity	Application
Decision Tree	Moderate	Low	Dietary Classification
SVM	High	Moderate	Disease Prediction
Random Forest	High	Moderate	Nutritional Risk Analysis
Neural Network	Very High	High	Personalized Nutrition
Deep Learning	Very High	Very High	Biomedical Analytics

AI-driven nutritional healthcare systems also integrate wearable devices, mobile healthcare applications, and electronic health records to provide continuous dietary monitoring and intelligent recommendations (Choudhry *et al.,* 2024).

Biomedical Informatics for Personalized Nutrition

Biomedical informatics blends healthcare research, data analytics, and compu- tational intelligence to enhance patient care and medical decision-making. In nutritional healthcare systems, biomedical informatics enables personalized di- etary planning based on genetic, physiological, and lifestyle characteristics.

Personalized nutrition tries to improve health outcomes by adapting dietary advice to individual needs. Biomedical informatics systems analyze various healthcare data, such as blood glucose levels, calorie intake, metabolic conditions, physical activity, and illness history (Zeevi *et al.*, 2025).

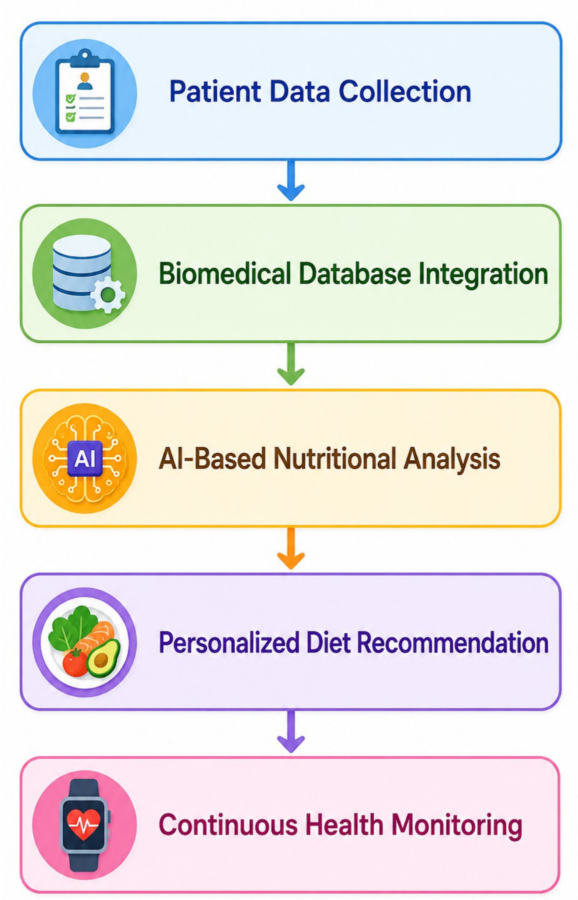

Fig. 2: Framework for Nutritional Quality Prediction of Algal

Proteins Wearable healthcare technology and IoT-enabled gadgets enhance nutritional monitoring by collecting real-time physiological data. These systems provide predictive healthcare and early disease detection (Manickam *et al.,* 2022).

Cultivation Systems of Algal Proteins

The cultivation of algae plays an important role in determining the nutritional quality, protein concentration, and commercial applicability of algal biomass. Algae can be grown in controlled environments using open pond systems, pho- tobioreactors, and hybrid cultivation methods. Open pond culture is the most economically viable of these approaches due to its cheap operational costs and large-scale output capabilities. Contamination, environmental changes, and low production remain significant concerns in open cultivation systems.

Photobioreactors offer a controlled growing environment that boosts biomass productivity, protein concentration, and nutrient uniformity. Light intensity, temperature, pH, food availability, and carbon dioxide content all have a sub- stantial influence on algae growth and protein synthesis. Advanced sensor-based monitoring systems and IoT-enabled cultivation platforms improve productivity by real-time environmental monitoring and automated nutrient management (Manickam *et al.,* 2022). Machine learning methods are increasingly being used in algae culture systems to optimize biomass output and nutrient profiles. Predictive analytics can estimate growth rate, protein yield, and environmental stress conditions utilizing previous datasets of cultivation. Such intelligent methods help to promote sustainable algae cultivation and increase nutritional outcomes.

Table 3: Comparison of algal cultivation systems

Cultivation Method	Cost	Productivity	Advantages
Open Pond	Low	Moderate	Economical
Photobioreactor	High	Very High	Controlled
Environment Hybrid System	Moderate	High	Better Stability

Protein Extraction Techniques

Protein extraction is an important step in the use of algal biomass for nutritional and medicinal purposes. Efficient extraction procedures increase protein recovery, digestibility, and functional characteristics. Several mechanical, chemical, and enzymatic approaches are utilized to isolate algal proteins.

Mechanical processes such as bead milling, ultrasonication, and high-pressure homogenization are routinely used to break down algal cell walls. These approaches increase protein accessibility and extraction efficiency. Chemical extraction procedures include solvent-based treatments and alkaline extraction methods that improve protein solubility. Enzymatic extraction methods boost digestibility by breaking down complicated cellular structures and releasing bioactive peptides.

The protein extraction efficiency can be represented mathematically as:

$$E = \frac{P_e}{P_t} \times 100$$

Data-driven optimization methods can enhance extraction parameters by ex- amining temperature, pH, solvent concentration, and processing duration. Arti- ficial intelligence models are increasingly being used to discover ideal extraction conditions to maximize nutritional quality and digestibility (Hassan *et al.,* 2023).

Section: Factors Affecting Digestibility of Algal Proteins

Multiple biological, environmental, and industrial factors influence algal protein digestibility. One of the most significant obstacles in algal digestibility is the presence of stiff cell wall features that limit nutrient accessibility. Variations in polysaccharide composition and protein organization differ between species and have an impact on nutrient absorption.

Food processing procedures such as drying, fermentation, enzymatic treat- ment, and thermal processing all have a substantial impact on protein digestibility. Controlled processing methods increase protein bioavailability by reducing cellular barriers and enhancing enzymatic accessibility. Additionally, gut microbial composition influences nutrition metabolism and digestive efficiency.

Factors Affecting Digestibility of Algal Proteins

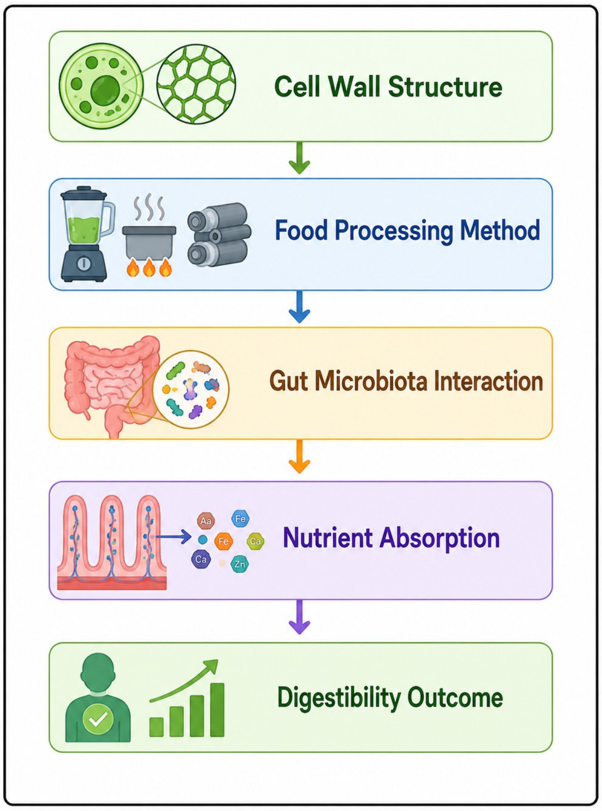

Fig. 3: Factors Affecting Digestibility of Algal Proteins

Biomedical informatics tools, paired with predictive analytics, can evaluate these aspects and create personalized nutritional recommendations for improved healthcare outcomes (Kussmann *et al.*, 2023).

Uses of Algal Proteins in Functional Foods and Healthcare

Algal proteins have numerous applications in the food industry, nutraceuticals, medicines, and biomedical healthcare systems. Because of their excellent nutri- tional value and bioactive qualities, algal proteins are rapidly being employed in dietary supplements, functional beverages, protein-rich snacks, and therapeutic nutrition products.

Microalgae, such as Spirulina and Chlorella, are commonly used in functional meals due to their antioxidant, anti-inflammatory, and immune-boosting characteristics. Biomedical informatics systems improve healthcare applications by integrating nutritional databases, patient records, and wearable device data. AI- powered healthcare platforms can analyze eating trends and offer personalized algal protein-based nutritional programs to manage obesity, diabetes, cardiovascular disease, and malnutrition (Wu *et al.*, 2025).

Case Studies and Real-World Applications

Several healthcare and culinary businesses are using algal proteins into com- mercial nutritional products. Spirulina-based supplements are widely used to increase protein intake and alleviate micronutrient deficiencies. Clinical investi- gations have demonstrated that algal proteins help to improve immunological function, antioxidant activity, and metabolic regulation.

For diabetics, predictive healthcare systems can quantify the nutritional impact of algal protein consumption using machine learning algorithms and biological datasets. These systems enhance dietary planning and preventative healthcare management (Nzomo & Moodley, 2026).

Advanced Deep Learning Approaches for Nutritional Healthcare

Deep learning algorithms have greatly enhanced biomedical analytics and nutri- tional healthcare systems. Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs), and Long Short-Term Memory (LSTM) models are becoming more popular for analyzing multidimensional nutritional datasets.

Deep learning systems can use food photos, wearable sensor data, electronic health records, and microbiome datasets to forecast nutritional status and assess illness risk. Advanced explainable AI techniques enhance transparency and interpretability in healthcare applications (Tahir and Loo, 2021).

Comparative Analysis with Conventional Protein Sources

Algal proteins are increasingly being compared to traditional protein sources like soy, whey, beef, and egg proteins. Algal proteins have a lesser environmental impact, are grown more sustainably, and emit fewer greenhouse gases than animal proteins.

Table 4: Comparison between algal proteins and conventional proteins Protein Source Sustainability Protein Quality Environmental Impact

Algal Proteins	Very High	High	Low
Soy Protein	High	High	Moderate
Whey Protein	Moderate	Very High	High
Meat Protein	Low	Very High	Very High

Challenges and Future Research Directions

Despite major advances in computational nutrition and biomedical informatics, there are still several difficulties to building intelligent nutritional healthcare systems. One significant difficulty is the availability of high-quality nutritional datasets. Healthcare data frequently contain inadequate, inconsistent, and noisy information, which reduces prediction accuracy.

Another problem is the privacy and ethical concerns around healthcare records and wearable sensor data. Secure data management frameworks and privacy-preserving machine learning algorithms are required to ensure healthcare confidentiality.

The interpretability of machine learning models is also critical in biological applications. Healthcare professionals want AI systems that are transparent and explainable in order to grasp prediction results and clinical suggestions. Explainable artificial intelligence (XAI) approaches are gaining importance in healthcare informatics (Salimparsa *et al.,* 2025).

Future study may concentrate on incorporating blockchain technology, federated learning, digital twin systems, and advanced deep learning models into nutritional healthcare applications. Furthermore, combining algal protein analytics with precision nutrition systems can greatly improve preventative healthcare and long-term illness management.

Conclusion

Data-driven modelling of the nutritional quality and digestibility of algal pro teins has emerged as a key study field in biomedical informatics and intelligent healthcare. Algal proteins are a sustainable, nutrientdense, and environmentally friendly alternative to traditional protein sources. The combination of computer intelligence, biomedical analytics, and machine learning provides precise predic- tions of nutrient absorption, dietary responses, and health effects.

Modern AI-powered healthcare systems can help clinicians, nutritionists, and researchers provide personalized food advice and preventive health initiatives. Biomedical informatics technologies are also useful for continuous health monitoring, chronic disease prevention, and precision nutrition applications.

The integration of nutritional science and artificial intelligence lays a solid foundation for future smart healthcare systems. Continued research in this subject can lead to more efficient, personalized, and data-driven healthcare solutions that improve global nutritional well-being.

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