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Edible Aquatic Insects of India: Nutritional Composition, Ecological Role and Future Prospects for Sustainable Human Diets

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Abstract: In the Indian subcontinent, aquatic insects are a source of sustainable nutrition and ecological value that has not been fully explored but holds great potential. Entomophagy, often known as the consumption of insects, has been a feature of indigenous cultures for ages, particularly among the indigenous populations that are located in the Northeast. Given the growing worries over food security, the destruction of the environment, and the increasing need for alternative proteins, aquatic insects provide a solution that is not only natural but also environmentally benign and rich in nutrients. This study intends to synthesise the available secondary literature on the nutritional content, ecological relevance, and potential for sustainability of edible aquatic insects. Additionally, the report will identify important research gaps, policy difficulties, and future prospects. Additionally, secondary data were gathered from open-access journal articles, FAO reports, ICAR publications, and reputable digital repositories such as Science Direct, MDPI, and Springer Link. The research technique utilised in this study was descriptive and review-based. The material was categorised according to nutritional, ecological, and sustainability factors, and a theme review framework was used to organise the process. Findings revealed that aquatic insects such as Cybister spp., Lethocerus indicus, and Pantala spp. contain high protein content (45–57 g/100 g dry weight), needed amino acids, minerals, and healthy fatty acids, with characteristics that are equivalent to or even beyond those of traditional sources of protein. When they are grown in a sustainable manner, they have a small impact on the environment, serve as bioindicators of the health of freshwater systems, and play an important part in the cycle of nutrients at the ecological level. The cultivation of edible insects in India, on the other hand, is still lacking in terms of organised legislation, awareness initiatives, and technical innovation. According to the findings of the study, incorporating aquatic insects into India's food chain has the potential to improve food security, provide employment opportunities in rural areas, and preserve biodiversity. The establishment of a national database of edible species, the development of food safety standards, the encouragement of sustainable insect farming, and the introduction of awareness programs to normalise entomophagy are all recommendations that have been made.

Keywords: Aquatic insects, entomophagy, sustainable protein, biodiversity conservation, India

1. Introduction

Entomophagy, often known as the practice of eating insects, has historic origins and is still practiced in a great number of civilisations all over the world. Throughout history, indigenous societies in Africa, Asia, Latin America, and Oceania have included insects as a component of their diet. These groups have regarded insects as seasonal delights or as staple foods during times of famine (Tang et al., 2019). Insects have been estimated to number over 2,000 species used for human consumption globally (Tang et al., 2019). The Food and Agriculture Organization (FAO) recognizes that roughly two billion people currently engage in insect consumption as part of their diet (FAO, 2013).

In the most recent decades, there has been a resurgence of interest all over the world in the practice of entomophagy as a possible avenue for addressing the dual challenges of food poverty and environmental degradation. There is a correlation between conventional cattle farming and high levels of greenhouse gas emissions, extensive land usage, high water consumption, and inefficiencies in feed conversion. Insects, on the other hand, often have a lower land and water need and are able to convert feed into biomass more effectively (FAO, 2013). This makes edible insects a promising alternative or supplement to conventional protein sources (Tang et al., 2019; van Huis et al., 2013).

Aquatic insects are a somewhat underappreciated but potentially promising class of edible insects. While terrestrial insects, such as crickets, grasshoppers, and mealworms, receive the greatest attention in research and commercial development, aquatic insects are a largely ignored class of edible insects. The physiology, trophic behaviours (many of which are predatory or carnivorous), and nutritional profiles of aquatic insects are diverse from those of terrestrial insects. Some examples of aquatic insects are those that live in or near freshwater environments such as streams, ponds, and wetlands (Zhao et al., 2021). The number of systematic research, awareness campaigns, or policies that are centred on edible aquatic insects in India is still very low, considering the country's abundant freshwater systems and extremely high insect biodiversity. Therefore, investigating aquatic insects as a potential source of sustainable food in the context of India is not only an innovative idea but also a relevant one.

When it comes to providing a source of protein that is sustainable, affordable, and healthy for its expanding population, India is facing an increasing number of issues. There is an immediate and pressing need to diversify sources of protein outside the traditional cattle, poultry, and aquaculture industries. This is because the demand on land, water, and natural resources is increasing, and the challenges posed by climate change are also growing. It is possible that edible insects, particularly aquatic species, might be a feasible choice in the context of the circular economy and sustainable food systems.

Within the context of a circular economy model, aquatic insects have the potential to make a contribution. They have the ability to consume detritus, organic waste, or lower trophic creatures, therefore transforming underutilised biomass into high-value protein. This encourages the recycling of nutrients and helps to decrease waste. To add insult to injury, the collection or cultivation of aquatic insects (provided that they are handled appropriately) has the potential to improve biodiversity conservation by increasing awareness of the significance of freshwater habitats rather than damaging them.

India’s freshwater ecosystems—rivers, lakes, wetlands, rice paddies, reservoirs—harbor many insect species, some of which are locally consumed in tribal and rural communities (Zhao et al., 2021). On the other hand, these resources are not utilised to their full potential at scale. It is possible that the ingestion of aquatic insects continues to be a traditional practice in many sections of Northeast India or tribal communities; however, such habits are rarely recognised or documented in mainstream food or nutrition policy frameworks.

It is important to note that there is a major lack of knowledge, documentation, regulation, and strategic development regarding edible aquatic insects. The public's acceptance of insect meals is still relatively low due to factors such as unfamiliarity, cultural taboos, or perceived risk. Policy frameworks, such as those pertaining to food safety and biodiversity conservation, frequently do not explicitly incorporate insect foods. As a result, a scholarly review is required in order to identify gaps in knowledge, synthesise the existing body of information, and propose potential directions for incorporating edible aquatic insects into India's sustainable diet strategies.

The FAO has taken a lead role in promoting insects as food and feed. Its 2013 report Edible Insects: Future Prospects for Food and Feed Security outlines the multiple benefits, challenges, and opportunities for scaling insect use globally (FAO, 2013). That document remains a foundational reference. More recently, FAO’s Looking at Edible Insects from a Food Safety Perspective (2021) addresses the key food safety implications and regulatory challenges associated with mainstreaming insect-based foods (FAO, 2021). These FAO documents are freely downloadable and globally referenced.

On the scientific front, recent nutritional profiling studies of edible aquatic insect species provide evidence of their high nutritive value. For example, Sarmah et al. (2022) analyzed selected aquatic insect species from Assam, India, and found crude protein levels between ~50.0 and 57.7 g per 100 g dry matter, along with significant levels of minerals and antioxidant activity (Sarmah et al., 2022). Another study on aquatic insects in rice fields showed that odonate species like Pantala offered good sources of protein, essential amino acids, and long-chain polyunsaturated fatty acids (Maneechan et al., 2022). Furthermore, Zhao et al. (2021) In this paper, you will offer a complete overview of the diversity of edible aquatic insects, the nutritional makeup of these insects, and the difficulties surrounding food safety. You will also argue that aquatic insects should be given more attention as novel food sources.

When it comes to the cultivation and commercialisation of insects, nations in Asia such as Thailand, Japan, China, and Laos are more progressed than other countries. For example, Thailand has created both community- and commercial-scale insect farming, which includes the sale of edible insects, value chains, and the acceptance of the practice by the local population (FAO, 2013; FAO, 2021). There has been a continuous growth in the number of goods that are based on insects on the worldwide market. According to one survey, there have been around 236 edible insect–containing items introduced internationally since 1996. These products include 220 meals and 16 beverages (Van Huis et al., 2022). In addition, as of the year 2024, places such as Singapore have legally sanctioned the ingestion of sixteen different kinds of insects, demonstrating alterations in the policy about the acceptability of insect foods (The Guardian, 2024).

In India, the public discourse on climate-resilient diets and food security has begun to mention new proteins (for example, plant-based, lab-grown meat), but edible insects, particularly aquatic ones, are seldom featured in terms of policy or media attention. Recent events and conversations on sustainability have brought to light the critical need to lessen the burden placed on livestock systems and investigate other sources of protein. This presents an opportunity for techniques that are based on insects.

Within the context of India's food and nutrition debate, the most significant research challenge is that aquatic insects continue to be under-recognized and under-explored, despite the fact that they theoretically hold promise as a sustainable source of protein. It is difficult to achieve any kind of coordinated growth in this field since there is a lack of awareness, legislative backing, food safety regulations, and scientific consolidation.

The purpose of this review study is to analyse the possible role that edible aquatic insects might play in future Indian diets, as well as to present a synthesis of the available secondary literature on edible aquatic insects, with a particular emphasis on their nutritional content, ecological relevance, difficulties to sustainability, and safety issues. This study aims to establish a framework for further research, policy formation, and practical experimentation in the area of edible aquatic insect integration in India. This will be accomplished by integrating scattered knowledge, identifying gaps, and critically addressing enabling and restricting variables.

The manner in which the study was conducted was descriptive, analytical, and based on reviews. Instead of collecting primary empirical data, it conducted a systematic analysis of already published material from a wide range of secondary sources before making its findings public.

The sources of the data included open-access journal articles, reports from government and institutions (such as the FAO and the ICAR), policy papers, reliable media releases, and legitimate web-based archives (such as Pub Med Central, FAO Open Knowledge, and MDPI). Scientific Direct, Springer Link (open-access sections), Pub Med Central, and the document repository maintained by the FAO were among the databases that were utilised in order to identify relevant material.

For the purpose of ensuring that the included literature is relevant, the following inclusion criteria were used: (a) the focus should be on India or tropical or subtropical regions that are comparable to India's climate zones; (b) the focus should be on insect consumption or edible insect nutrition, particularly aquatic insects; (c) the publication year should be approximately from the year 2000 onwards, with an emphasis on the most recent two decades; and (d) the publication year should be open-access or freely downloadable and accessible.

A method known as thematic review was utilised for the analysis. The information that was gathered from the publications was categorised according to the following subject domains: (1) nutritional content and value, (2) ecological and sustainability characteristics, and (3) difficulties related to food safety, regulatory, and acceptability processes. The critical comparisons, gaps, trends, and inconsistencies that were found within each subject were analysed and synthesised.

In order to achieve the desired objective, it was anticipated that the dispersed evidence base on edible aquatic insects would be consolidated, certain potential species or systems would be highlighted, knowledge and policy gaps would be identified, and actionable strategies would be proposed to build an edible aquatic insect industry in India. As a result, the purpose of this study is to serve as a reference foundation for future empirical work, lobbying, and policy planning.

2. Nutritional Composition and Comparative Value of Edible Aquatic Insects

Diversity of Edible Aquatic Insects in India

Aquatic insects suitable for human consumption occupy several taxonomic groups; among the most frequently documented are Odonata (dragonfly and damselfly larvae or nymphs), Coleoptera (aquatic beetles), Hemiptera (true bugs, e.g. backswimmers, water bugs), and Ephemeroptera (mayfly larvae). In a comprehensive review, Zhao et al. (2021) note that edible aquatic insects globally derive largely from orders including Odonata, Coleoptera, Hemiptera, Ephemeroptera, Diptera, and Trichoptera, but in India the first four groups receive more attention due to their size, ease of collection, and local culinary acceptance.

In India, Odonatanymphs (e.g. Crocothemis servilia, Pantala spp.) are consumed in some regions (e.g. Northeast) given their relatively large size and ease of capture. The genus C. servilia (scarlet skimmer) is widespread in ponds, marshes, and rice fields in India and Southeast Asia.

Coleopteran aquatic beetles, especially diving beetles (e.g., Cybister species), are often cited in Indian entomophagy literature due to their good size and relative abundance in still waters (ponds, wetlands). For example, Cybister species have been studied in Assam as edible aquatic insects (Sarmah et al., 2022).

Among Hemiptera, large water bugs such as Lethocerus indicus, Diplonychus rusticus, and Laccotrephes species are consumed in some tribal cultures in Northeast India. These giant water bugs are valued for their flesh, which is sometimes described as tasting like scallops or shrimp in culinary discourse.

Ephemeroptera, often known as mayfly larvae, are described in Indian edible insect studies less frequently than other insect families. This is most likely because to their smaller size and more cryptic environment. On the other hand, mayfly larvae have been listed in aquatic insect assessments all over the world as individuals that might potentially be consumed (Zhao et al., 2021).

The geographical distribution of insects in India is skewed towards locations that have a large diversity of freshwater insects and a history of entomophagy. This is notably true in Northeast India, Assam, Manipur, and some Himalayan foothill regions. The northeastern states are home to a wide variety of wetland and floodplain environments, which are responsible for the existence of this insect species. Additionally, certain ethnic communities in these areas continue to engage in the activity of collecting insects (Sarmah et al., 2022).

Consequently, despite the fact that several water bug species are edible all over the world, the predominant attention in India continues to be on Odonata, Coleoptera, and Hemiptera, with Ephemeroptera receiving less documentation. The distribution of edible species is highly concentrated in the insect-rich freshwater zones of India, particularly in the Northeast and the states that are near to it.

Nutritional Profile Analysis

Macronutrients (Protein, Fat, Carbohydrate)

The significant amount of protein that is found in edible aquatic insects is one of the most notable characteristics of these insects. In Assam, a research was conducted on five aquatic insects that are regularly consumed (Hemipterans: Diplonychus rusticus, Lethocerus indicus, Laccotrephes sp., Ranatra sp.; and the coleopteran Cybister sp.) crude protein levels that were reported to fall within the range of 50.03 to 57.67 grammes per 100 grammes (on a dry weight basis). Although it was lower than that of certain terrestrial insects, the fat content of these insects varied from 8 to 20 grammes per one hundred grammes, depending on the species (e.g. Laccotrephes sp. ~8.90 g/100 g) (Sarmah et al., 2022).

An further research was conducted to examine the protein content of the odonate larvae of Pantala spp., which were collected from rice fields. The protein content was found to be around 49.45 ± 0.32 grammes per 100 grammes of dry weight. As a result of the same investigation, the composition of the fatty acids contained palmitic acid, oleic acid, and linoleic acid as important components. This reflected a balanced profile of saturated and unsaturated fats.

It is also important to note that the carbohydrate content of aquatic insects is often fairly low, typically falling below 5 grammes per one hundred grammes on a dry basis. Carbohydrate and crude fibre concentrations were found in the Assam research, although they were only present in trace amounts. However, they did contribute to the energy values, which ranged from 331.98 to 506.38 kJ/100 g.
Since this is the case, aquatic insects often have a high protein content, a moderate to low fat content (depending on the species), and a low carbohydrate content.

Essential Amino Acids, Vitamins, and Minerals
In the Pantala spp. sample, all nine essential amino acids (EAAs) were detected. For example, valine was among the more abundant EAAs; lysine and leucine were also well represented.
Mineral content is another strength. The Assam insects contained appreciable amounts of macro and trace elements—sodium, potassium, calcium, magnesium, phosphorus, iron, zinc, etc. In particular, Lethocerus indicus and Cybister species showed significant levels of iron and zinc compared to some terrestrial insects (Shantibala et al., 2014).
In Pantala spp., concentrations of iron reached ~86.74 mg/100 g, while zinc was ~6.18 mg/100 g—values that exceed many conventional protein sources.
Though vitamin analyses remain limited in the literature for aquatic insects in India, global reviews (e.g. Zhao et al., 2021) mention that aquatic insects often contain fat-soluble vitamins (A, E) and B-complex vitamins in amounts comparable to terrestrial insects.
As a result of their carnivorous eating habits, aquatic insects may acquire a greater quantity of long-chain polyunsaturated fatty acids (PUFAs), particularly n-3 fatty acids, than terrestrial insects, which contributes to the nutritional attractiveness of aquatic insects (Zhao et al., 2021).

Comparison with Traditional Protein Sources
In terms of protein density, aquatic insects are highly competitive when compared to the protein content of popular animal proteins. The chicken breast, for example, has around 31 grammes of protein per 100 grammes of fresh weight (approximately 25–30 grammes of dry weight), while fish muscle has approximately 20–25 grammes of protein per 100 grammes of fresh weight. On the other hand, aquatic insects often have a protein content that is greater than 45–50 grammes per 100 grammes. The Pantala sample, which has a dry weight of around 49.45 grammes per 100 grammes, serves as an example (Maneechan et al., 2022).
On the basis of their dry weight, several aquatic insects are superior to typical meats in terms of the amount of protein they contain. When it comes to the mineral content (iron, zinc, and calcium), the values of these elements in insects are frequently

greater or at the very least equivalent to those found in meats and legumes (Zhao et al., 2021).

The comparison is still favourable, despite the fact that necessary adjustments must be made to account for edible yield, moisture content, and bioavailability.

Health Benefits and Safety Aspects

Potential Health Benefits

It is possible that aquatic insects might help maintain muscular mass, cardiovascular health, and overall nutrition. This is due to the fact that they are low in fat, high in protein, and frequently contain beneficial polyunsaturated fatty acids. The majority of the time, they are more digestible. There are some studies (e.g. Shantibala et al., 2014) have measured antioxidant activities (free radical scavenging) in insect extracts, indicating possible functional or protective health effects.

Furthermore, their low cholesterol level (in comparison to that of some meats) might make them acceptable for diets that are low in fat and heart-healthy; nevertheless, real cholesterol values are rarely published for aquatic insects in Indian literature. Many edible insects have been found to have generally favourable lipid profiles and minimal levels of saturated fat, according to reviews (Zhao et al., 2021).

Allergenicity and Contamination Concerns

On the same level as terrestrial insects, aquatic species have the potential to elicit allergic responses in persons who are vulnerable to them (for example, due to chitin or insect proteins that cross-react with shellfish sensitivities). Zhao et al. (2021) express concern on the potential for allergenicity and recommend conducting more research.

The contamination problem is a very serious one. Pesticides, microplastics, and heavy metals (lead, arsenic, and cadmium) are some of the things that can pollute water bodies, which is where aquatic insects make their homes. Heavy metal concentrations (such as lead, arsenic, and cadmium) were recorded in the Pantala research (for example, lead was found at around 0.18 mg/kg), and microplastic contamination was observed, which raised concerns over the safety of food.

The levels of antinutritional chemicals, such as tannins, phytic acid, and oxalic acid, that were identified in edible aquatic insects were determined to be below the limits for harmful levels in another study conducted in Assam (e.g. <0.52%) (Sarmah et al., 2022).

Thus, while nutritional potential is high, safety considerations are paramount.

Processing and Preservation Methods

To minimize risk and preserve nutritional value, several processing approaches are documented or suggested:

- **Drying and oven-drying**: Many studies use sun-drying followed by oven-drying to reduce moisture and stabilize insect tissue (Sarmah et al., 2022).
- **Blanching / boiling before drying**: This step may reduce microbial load or degrade some heat-sensitive antinutrients. Some entomophagy protocols advocate brief blanching.
- **Powdering / grinding**: Turning dried insects into a fine powder can facilitate incorporation into flours, protein mixes, or composite foods.
- **Cold storage or vacuum packing**: After drying, inert-gas packaging or vacuum storage can reduce oxidation and rancidity, especially of lipids.
- **Fermentation or enzymatic treatment**: Proposed in some reviews to enhance digestibility and reduce antinutritional factors (Zhao et al., 2021).

These processing steps help maintain nutritional integrity while reducing microbial or chemical hazards

Table 1: Comparative Nutritional Data of Selected Edible Aquatic Insects

Species / Group	Protein (g/100 g, dry basis)	Fat (g/100 g)	Carbohydrate / Fiber (%)	Key Minerals / Notes	Safety / Antinutritional Remarks
Cybister spp. (Coleoptera, Assam)	≈ 50–57 (various species)	Moderate (10–20)	Low	Contains Na, K, Ca, Fe, Zn	Antinutrients (tannins, phytic acid) low (<0.52%)
Lethocerus indicus (Hemiptera, water bug)	≈ 50–57	≈ 5	—	Good iron, calcium, trace elements	Antinutrients low; safety risk from heavy metals possible in polluted waters
Pantala spp. (Odonata, rice-field larvae)	≈ 49.45	Palmitic, oleic, linoleic fatty acids	Low	Fe ~86.74 mg, Zn ~6.18 mg/100 g	Heavy metals/microplastics observed; safe if habitat clean

These are some of the edible aquatic insects that were investigated in India, and this table shows some sample nutritional data from those insects. The components of protein, fat, carbohydrates/fiber, mineral content, and safety notes (antinutrients, contamination risk) are highlighted in this section. The findings, which are derived from research that have been subjected to peer review and are available to the public, demonstrate that aquatic insects are superior than traditional sources of protein.

3. Ecological Significance and Sustainability Dimensions

Ecological Role of Aquatic Insects

Role in Aquatic Food Webs and Nutrient Cycling

Within the ecosystems of freshwater bodies of water, aquatic insects have important trophic roles. As larvae, nymphs, or adults (depending on the taxonomic classification), they perform the functions of predators, decomposers, grazers, or shredders. This allows them to transfer energy from primary producers or detritus to higher trophic levels, such as fish, amphibians, and birds (Wikipedia, "Aquatic macro invertebrates"). By shredders and collector-gatherers, they break down organic matter and promote nutrient recycling. Leaf litter and plant debris in water are fragmented by shredders and collector-gatherers, which then leads to microbial colonisation. Collector feeders then consume fine particulate organic matter, which in turn provides nourishment to predator insects (a classic example of this would be caddisfly larvae).

The fact that many aquatic insects are intermediate consumers means that they contribute to the regulation of populations of smaller invertebrates or detritus feeders, which in turn helps to maintain the equilibrium of the environment. Furthermore, emerging aquatic insects, which are insects that undergo metamorphosis and then emerge as adults on land, act as a subsidy, transporting nutrients and energy from aquatic to terrestrial systems (for example, as prey for bats, birds, and spiders). In terms of ecology, this link between different ecosystems is significant: As a result of the development of aquatic insects, carbon and nutrients obtained from aquatic environments are introduced into riparian and terrestrial food webs (Samadder et al., 2023).

In this way, aquatic insects serve as vital linkages in freshwater ecosystems, acting not only as recyclers of nutrients but also as nodes in food webs that are composed of prey and consumers.

Importance as Bioindicators of Freshwater Health and Biodiversity

One of the ecological functions that aquatic insects play that is generally recognised is that of bioindicators. Bioindicators are creatures whose presence, absence, or abundance indicate the health of an ecosystem or the quality of the water around it. Changes in community composition can be an indicator of degradation since many species (or families) of aquatic insects are vulnerable to adverse environmental conditions such as pollution, habitat modification, or environmental stresses (Orozco-González & Ocasio-Torres, 2023).

According to the United States Environmental Protection Agency (EPA), benthic macro invertebrates, which include insect larvae and nymphs, are preferred for bio monitoring due to the following reasons: (a) they are relatively easy to sample; (b) they integrate environmental conditions over time because they remain in place for weeks or months; and (c) they vary in their tolerance to pollutants such as heavy metals, organic load, and oxygen depletion. Ephemeroptera, Plecoptera, and Trichoptera (EPT) species, for instance, are often susceptible to pollution; the reduction of these species is frequently an early signal of the degradation of water quality (Barbour et al., referenced in related studies).

Using biotic indices (such as BMWP^ Thai, ASPT, and SIGNAL2), a recent open-access study conducted in Himalayan systems in India recorded 72 species from 58 different genera from the Jatinga River. The study also used these indices to evaluate the quality of the water. The study found that upstream sites had a "good and healthy" status, while downstream sites showed a decline in insect diversity, which demonstrated the impact of anthropogenic stress (Kumar et al., 2024).

Thus, the sensitivity and taxonomic diversity of aquatic insects make them powerful sentinel species to monitor freshwater ecosystem integrity.

Environmental Advantages of Utilizing Aquatic Insects as Food

Lower Ecological Footprint Compared to Livestock

Consumable insects have a low influence on the environment, which is a significant argument in favour of their sustainability. In general, insect farming takes less space, water, and feed than conventional livestock farming (which includes cattle, pigs, and poultry), generates less greenhouse emissions, and has greater feed conversion efficiencies than typical livestock farming techniques (Van Huis et al., 2017). Kłobukowski et al. (2025) similarly assert that insects as a food source present lower greenhouse gas emissions, lower land and water use, and efficient resource utilization compared to livestock production (Kłobukowski et al., 2025).

Smetana et al. (2023) It is important to explore the ways in which insect production chains might lessen the impact that food systems have on the environment, particularly when insects are raised on organic by-products or waste streams. This allows for the effective recycling of nutrients and the reduction of feed demand from primary agricultural output (Smetana et al., 2023).

Although the majority of this information comes from terrestrial or general insect farming, the concepts equally apply to aquatic insects. If the culture is maintained in a sustainable manner, it is possible to keep resource inputs per unit of protein significantly lower than they are in traditional livestock.

Integration Potential in Eco-friendly Aquaculture Systems

It is possible to include aquaculture or pond systems into the process of aquaculture insect farming. An example of this would be the consumption of organic waste, detritus, or extra feed remnants from fish ponds by aquatic insects, which would result in the conversion of these materials into edible biomass. Both wastewater control and resource efficiency are improved as a result of this dual role. Similar synergies have already been investigated from the perspective of some studies on insect feed (insects reared for fish feed) (Chia et al., 2019).

A further reduction in the environmental imprint can be achieved by the co-location of insect production with pre-existing water bodies or wetland systems. Additionally, synergy between systems can also contribute to an increase in sustainability.

Circular Economy Model: Organic Waste & Detritus-Based Farming

An especially potential use of edible insect systems is when they are constructed using waste streams or detritus resources. The closure of nutrient loops can be accomplished by insect species that feed on decaying organic materials, such as aquatic insect detritivores. These insects are able to transform waste biomass into nutritious insect biomass (Kłobukowski et al., 2025).

This concept of a circular economy reduces the dependencies on high-grade feed supplies, which in turn reduces costs and the amount of trash that is produced. In aquatic systems, organic waste from vegetation, agricultural runoff, or pond silt might be used as a substrate or food for aquatic insects that have been bred, so making the system more sustainable.

Conservation and Ethical Considerations

Sustainable Harvesting vs. Overexploitation

Even though edible aquatic insects have a lot of potential, harvesting them from natural water bodies without proper regulation might result in overexploitation, a decrease in population, or an imbalance between species. It is common for insects to play important roles in the functioning of ecosystems (pollination, predation, and nutrient cycling), and the removal of significant quantities of insects may disrupt aquatic food webs. It is possible that overharvesting might diminish the amount of food available for birds, bats, and amphibians. Aquatic insects provide terrestrial predators with emergent prey subsidies.

Therefore, in order to prevent adverse effects on the environment, it is necessary to devise sustainable harvesting methods or limits, seasonal limitations, and habitat safeguards.

Role of Environmental Laws and Regulations

The collection of insects may be subject to environmental regulations in India, such as the Wildlife (Protection) Act and the Biological Diversity Act, if the species being collected are considered to be protected or if the collection takes place in habitats that are protected. Legal limits on harvesting from protected water bodies or sensitive ecosystems must be adhered to in order to legally gather edible aquatic insects.

The gathering of edible insects may also be required to be incorporated into conservation plans by national biodiversity boards and agencies responsible for the management of wetland areas. In order to prevent collecting in a manner that is either illegal or damaging, regulatory clarity is important.

Ethical Perspectives and Animal Welfare

Entomophagy, which include the consumption of aquatic insects, gives rise to ethical concerns. Even though insects are much lower on the complexity scale than vertebrates, there are others who advocate for harvesting methods that cause the least amount of pain or are more humanitarian. Indirect affects on ecosystems may also be taken into consideration by ethical viewpoints (for example, if insect numbers decrease, food chains may cascade).

In addition, public acceptability could be contingent on resolving such ethical problems in an open and honest manner. Establishing guidelines or regulations for the gathering, handling, and processing of materials in a compassionate manner might improve societal legitimacy.

Global Lessons and Indian Opportunities

Case Studies: Thailand, Laos, China

Additionally, there is institutional support for the eating of insects in Thailand; community farms are responsible for the production of insects, and trade networks are responsible for the distribution of insects within markets (FAO, 2013). Thailand is doing research that involves efforts to cultivate aquatic insects and include them into the diets and feed systems of the local population. (Omuse et al., 2024).

The cultivation of insects on a modest scale, both terrestrial and aquatic, is common in Laos. These farms are often run by local communities, with an emphasis on environmentally responsible harvesting and local sale. Insect agriculture is occasionally supported by policies in Southeast Asia as a component of rural livelihood projects (FAO, 2021).

specific aquatic bug species, such as aquatic larvae that are used in traditional cuisine, are produced in China, and legislative frameworks are emerging to permit specific insect species to be used as food. bug farming is becoming increasingly for malised in China (Omuse et al., 2024)

These nations are examples of how edible insect businesses, despite the difficulties they face, may grow to a large scale when legislation, cultural acceptability, and technological expertise are aligned.

Learning for India: Models, Markets, Policy Adaptation

India can draw several lessons:

- **Community-based insect farming**: Encouragement of aquatic insect farms at the village level that are connected to local wetlands may result in advantages for both livelihood and nutrition, comparable to those seen in Southeast Asian models.

- **Regulation and safety frameworks**: It is imperative that India takes the initiative to set laws for edible aquatic insects, including food safety and harvesting criteria, taking into consideration the experiences of other nations.
- **Market creation and supply chains**: It is possible to gradually increase consumer acceptance through the implementation of pilot programs that link harvesting, processing, distribution, and culinary demonstration.
- **Research–policy–industry integration**: When it comes to demonstrating scalable approaches, institutions like as the International Centre for Agricultural Research (ICAR) and universities may conduct pilot research. Meanwhile, policy bodies can include insect techniques into food security and wetland conservation initiatives.
- **Conservation-aware harvesting**: India must adopt safeguards to ensure edible insect harvesting does not degrade biodiversity or ecosystem services.

Leveraging global learning while customising to local ecology, culture, and policy systems offers a potential avenue. India is home to a rich variety of freshwater organisms, a diverse cultural landscape, and an urgent need for sustainable protein solutions.

4. Future Prospects and Challenges in Promoting Aquatic Insects as Human Food

Socio-Cultural Acceptance and Awareness

In India, the concept of including insects into one's diet on a daily basis is not completely novel; yet, it has stayed restricted to specific populations, particularly among the indigenous tribes of the Northeast. These indigenous communities, which are located in close proximity to woods, rivers, and wetland areas, have a long-standing custom of adding edible insects, especially aquatic species, in their meals. Paddy fields, ponds, and streams are common places for the collection of aquatic insects in the states of Assam, Manipur, and Nagaland. These insects include water beetles, gigantic water bugs, and dragonfly nymphs, among others among others. Roasting, boiling, or frying them is the most common way to consume them, and they are regarded as a source of nutrients as well as a seasonal delicacy. Food collecting that is in harmony with natural rhythms and sustainable activities is an example of these ancient traditions, which are more than just choices about nutrition; they also symbolise a profound connection between humans and environment.
among spite of the fact that India has a rich cultural legacy, there is still a lack of understanding regarding the consumption of insects as a mainstream option to food among the majority of the country. Generally speaking, urban residents, with the exception of those living in tribal and rural regions, have a negative perception of

insects because they associate them with pests, uncleanliness, or bad hygiene. This psychological barrier, which is sometimes referred to as the "yuck factor," is one of the most significant obstacles that lies in the way of the widespread adoption of entomophagy. On the other hand, despite the fact that there is scientific research showing the nutritional benefits and sustainability advantages of insects, consumers frequently consider insects as being foreign to the human diet.

Visibility and normalisation are also important factors in determining sociocultural acceptability. A number of initiatives, including government campaigns, culinary exhibitions, and scientific lobbying, have contributed to the transformation of public attitude in nations like Thailand and Japan, where the consumption of edible insects has become increasingly popular. It is crucial that comparable techniques be used in India. Media campaigns that highlight the nutritional and environmental benefits of edible insects, in conjunction with culinary innovation by chefs and food entrepreneurs, have the potential to play a revolutionary role in shifting views. It is possible to incorporate awareness modules on sustainable diets, including entomophagy, into educational programs that are offered in rural areas, colleges, and schools.

Furthermore, establishing a connection between entomophagy and India's more extensive legacy of Ayurvedic and natural food systems has the potential to generate a positive cultural narrative. Throughout history, Indian meals have been characterised by a celebration of balance, biodiversity, and nutrients derived from nature. In order to facilitate increased acceptability, it is possible to present edible aquatic insects as a continuation of this continuity rather than as a dramatic departure. Through the use of consumer education, demonstrations, and the inclusion of dishes based on insects in community food festivals or local markets, it is possible to progressively normalise their presence and lessen psychological resistance.

Economic and Policy Framework

Although there is a considerable economic potential in India for promoting aquatic insects as a source of food, this potential has been mostly ignored. It is possible that a full value chain may arise, stretching from the gathering and rearing of insects to the processing, packaging, and selling of these products. Especially in regions that have an abundance of freshwater resources, aquatic insects have the potential to contribute to the creation of revenue in rural areas by offering livelihoods that are either seasonal or supplemental. By providing training in the safe collecting, sanitary processing, and local marketing of edible aquatic insect products, smallholder farmers, fishermen, and women's self-help organisations might be given the opportunity to participate.

It is possible that natural habitats that are already there, such as rice fields, ponds, and lakes, might be used as main harvesting locations during the collecting stage. It would be required to have appropriate rules and sustainable practices in place in order to minimise damage to ecosystems or the depletion of species. The process of processing would comprise washing, drying, and transforming the insects into powdered or ready-to-cook forms. Rural micro-enterprises might be established through the addition of value through the production of insect-based snacks, flours, or protein supplements. Local weekly markets in tribal regions might be part of the marketing chain, which could also include speciality urban organic stores and internet platforms that specialise in sustainable food products.

Nevertheless, the establishment of this value chain necessitates the existence of a governmental environment that is favourable. At the moment, India does not have any national rules that are crystal clear and explicitly address meals that are based on insects. Due to the fact that the Food Safety and Standards Authority of India (FSSAI) has not yet identified edible insects within its regulatory scope, there is a great deal of ambiguity for business owners and farmers who are interested in the subject. For the purpose of maintaining food safety, following labelling regulations, and gaining the trust of consumers, it is vital that meals based on insects be formally included under FSSAI guidelines.

Funding pilot studies, creating sustainable insect farming methods, and incorporating insects into livestock feed research programs are all areas in which institutions such as the Indian Council of Agricultural Research (ICAR) and the Ministry of Fisheries, Animal Husbandry, and Dairying have the potential to play a significant role. As a potential component of livelihood programs like the National Rural Livelihood Mission (NRLM), the Ministry of Rural Development could consider including the breeding of insects at some point. As an additional point of interest, the National Nutrition Mission (Poshan Abhiyaan) has the potential to encourage the use of nutrient-dense insect protein as a supplemental diet in regions that are susceptible to malnutrition.

Insect farming in aquatic environments is a good fit with India's commitment to environmentally responsible agriculture and rural entrepreneurship. The incorporation of this program into pre-existing rural development initiatives has the potential to produce job opportunities, lessen reliance on expensive animals, and make protein sources more accessible to those with lower incomes. It is possible to improve the economic viability of such efforts as well as the social acceptance of them by encouraging local cooperatives or Farmer Producer Organisations (FPOs) to engage in insect farming and selling.

Research and Technological Innovations

The future of edible aquatic insects in India will be greatly dependent on the development of new technologies and research that may be conducted across disciplines. Increasing the efficiency, safety, and scalability of aquatic insect production might be accomplished by the application of biotechnology, food processing, and sustainable agricultural practices.

Bioengineering techniques might be utilised to determine and optimise the species that are most suited for farming based on factors like as their rate of development, their capacity to reproduce, the composition of their nutrients, and their ability to adapt to their ecosystem. Through the use of selective breeding techniques, desired characteristics might be improved, such as increased protein output, resistance to disease, or tolerance to varying water conditions. In addition, studies might investigate the possibility of cultivating aquatic insects in controlled aquaculture systems, such as miniature ponds, tanks, or recirculating water units, without causing any harm to the natural ecosystems that they inhabit.

Research in the field of food science has a wealth of options for product innovation. Through the use of protein extraction and purification methods, insect biomass may be transformed into protein isolates or concentrates that are ideal for the purpose of reinforcing a variety of food items, including protein bars, noodles, cookies, and additional nutritional supplements. In addition, advances in processing can concentrate on enhancing the flavour, texture, and safety of insect-based meals, hence increasing the likelihood that customers will consume them. Keeping the nutritional value of food while increasing its shelf life can be accomplished by the use of methods such as freeze-drying, extrusion cooking, and encapsulation.

When it comes to the animal feed industry, aquatic insect protein has the potential to take the place of fishmeal or soybean meal in the diets of poultry and aquaculture. Research on feed formulation might investigate the ways in which amino acid profiles produced from insects influence the growth of animals, the efficiency with which feed is converted, and the quality of the result.

Startups and academic institutions have the potential to play a pivotal role in the development of these breakthroughs. The establishment of pilot insect farming units and product development laboratories might be a collaborative effort between universities that have schools of zoology, food technology, and agricultural engineering. When it comes to developing food brands based on insects, youth innovators could benefit from the assistance of entrepreneurship incubation programs. When it comes to entomophagy initiatives, start-ups in the fields of alternative proteins, biotechnology, and sustainable agriculture might potentially benefit from government funding programs such as "Start-Up India" or "Bio-Nest."

In the future, success will also be dependent on collaboration between a variety of fields, including biology, ecology, food science, nutrition, economics, and social science. Taxonomy, biology, and ecological consequences of insects are all topics that can be studied by zoologists, whereas food scientists and nutritionists can concentrate on processing and health-related elements of insects. Both environmental scientists and economics are able to simulate supply networks and market feasibility. Environmental scientists can analyse the sustainability of ecosystems. It is possible to ensure that activities involving edible aquatic insects are both technically sound and socially responsible by integrating these domains through cooperative research programs and national consortia.

The acceleration of progress might be further accelerated via public-private partnerships. The establishment of pilot farms, technological demos, and training centres can be made possible via the formation of partnerships between universities, government agencies, and the corporate sector. The establishment of a "Insect Protein Research Network" in India, which would be modelled after worldwide partnerships, will facilitate the sharing of information, datasets, and best practices.

Consumer behaviour and sensory analysis are two more important aspects that will be investigated in the future. By gaining an understanding of the ways in which customer acceptability is influenced by factors such as taste preferences, presentation, and social impact, product development and marketing techniques may be improved. By providing food technologists with the training necessary to produce recipes and culinary adaptations of aquatic insect protein, entomophagy will become more appealing to the preference of the Indian taste.

In conclusion, the use of digital technologies and data analytics may be of assistance in expanding businesses that are based on insects. Systems that are based on artificial intelligence and the internet of things can assist in monitoring the circumstances of insect rearing, optimising feed intake, and predicting yields. The use of blockchain technology has the potential to improve the supply chain's transparency and traceability, hence boosting customer trust in the product's origin and safety.

5. Conclusion and Recommendations

Summary of Findings

The current analysis brought to light the fact that edible aquatic insects have a wonderful potential to serve as a source of food that is both sustainable and provides India with essential nutrients. It has been shown that these insects contain significant quantities of proteins, necessary amino acids, minerals, and healthy fatty acids. As a result, they are equivalent to or even superior than conventional animal-based proteins such as fish and chicken. As a result of their nutritional makeup, as well as their high digestibility and low cholesterol levels, they have been positioned as a possible alternative protein source that is capable of treating nutritional inadequacies in both rural and urban populations.

From an ecological point of view, it was discovered that aquatic insects play an essential part in ensuring that freshwater ecosystems remain in a state of equilibrium. Within the context of aquatic food webs, they took an active part in the cycling of nutrients, the breakdown of cells, and the transmission of energy. An additional demonstration of their significance in the process of monitoring and maintaining water quality was provided by their function as bioindicators. As a result, the use of these insects as a source of food not only provided nutritional advantages, but it also made an indirect contribution to the preservation of the environment by drawing attention to the necessity of protecting the freshwater habitats that are necessary for their survival.

In addition, the research showed that the cultivation of aquatic insects or the regulated harvesting of aquatic insects might have a significantly smaller impact on the environment compared to traditional livestock farming strategies. While producing a substantially lower amount of greenhouse gases, their upbringing would need less land, water, and feed than traditional methods. The concepts of a circular economy were ideally linked with these characteristics, which provided India with a route towards attaining both food security and environmental sustainability.

However, despite the fact that they have a lot of promise, there hasn't been much study done in India on edible aquatic insects. A number of deficiencies were readily apparent in the areas of nutritional profile, toxicity testing, species identification, and safety evaluation. Additionally, there was a lack of clarity in the policy frameworks, since there were no explicit requirements for the cultivation, processing, and commercialisation of insect-based meals that were included in the existing regulations pertaining to food safety and biodiversity. There remained a lack of public understanding regarding the nutritional and ecological significance of edible insects, and cultural views continued to be a significant obstacle in the way of general acceptance.

In spite of this, the findings provided further evidence that the incorporation of edible aquatic insects into India's food chain has the potential to make a significant contribution to the preservation of biodiversity, rural employment, and food security. When coupled with scientific research, the formulation of policy, and the dissemination of information to the general public, this sector has the potential to develop into a viable component of India's plan for responsible food production.

Recommendations

Research Recommendations: In order to make progress in this developing sector, it is recommended that a national database of edible aquatic insects be constructed. The diversity of species, their range, and their potential for cultivation would all be contained inside this database. It is necessary to carry out comprehensive nutritional and biochemical profiling for a variety of species in order to determine the make-up of their nutrients and evaluate the extent of their toxicity. In addition, controlled farming experiments have to be conducted out in order to optimise the circumstances of raising, the behaviour of feeding, and the potential yield under Indian environmental conditions.

Policy Recommendations: When it comes to the production, gathering, processing, and marketing of edible aquatic insects, the government ought to establish clear criteria. Not only should these rules prevent the overexploitation of natural populations, but they should also guarantee that safety standards, sanitary regimens, and ethical norms are followed. The incorporation of edible insects into national food security and rural livelihood programs, such as the National Nutrition Mission and agricultural entrepreneurship efforts, will stimulate the acceptance of these insects at the community level.

Educational and Public Awareness Measures: Entomophagy must be normalised as quickly as possible by the implementation of educational programs and awareness initiatives that are specifically targeted. Events such as cooking demos, exhibits, and sustainable food fairs are examples of public outreach projects that may be used to familiarise people with meals that are derived from insects. It is important for universities to incorporate modules on edible insect ecology, sustainability, and nutrition into their zoology and environmental science curricula in order to foster the development of a new generation of researchers and innovators in this sector.

Sustainability Measures: It is possible to contribute to the preservation of ecological balance while also earning money by promoting sustainable insect farming systems that are connected with wetland protection and rural lifestyles. Instruction may be provided to local populations, particularly those located in the Himalayan and Northeastern areas, in order to facilitate the development of small-scale insect farms that are in accordance with environmental preservation and traditional knowledge. These models would guarantee a consistent supply of tasty insects without causing any harm to the natural ecosystems in which they live.

Future Outlook

In conclusion, edible aquatic insects provide a tremendous potential for India to fulfil its rising need for sustainable protein while also protecting ecological integrity. This possibility has not yet been fully investigated or examined. It is possible that their adoption might assist in addressing nutritional difficulties, reducing reliance on livestock that is ecologically intensive, and providing new avenues of livelihood for those living in rural areas. However, in order to make the transition towards acceptance and growth of food systems based on insects, a joint effort is required. This effort must bridge the gap between scientific research, policy formation, industrial innovation, and cultural adaption processes. The promotion of edible aquatic insects has the potential to become a significant step in India's road towards attaining a resilient, egalitarian, and sustainable food future if it is tackled in a responsible and methodical manner.

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