*Review Article*

Silkworm Pupae as a Sustainable Superfood: A Review on Nutritional Composition, Applications, and Potential in Human and Animal Diets

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ABSTRACT

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| As the global demand for sustainable, nutritious, and affordable protein sources continues to rise, silkworm pupae (SWP), once considered a sericultural by-product, have emerged as a promising alternative superfood for both human and animal nutrition. This review comprehensively explores the nutritional potential of silkworm pupae, highlighting their rich protein content, essential amino acids, beneficial fatty acids, and micronutrients. In the context of human consumption, SWP demonstrate significant dietary value, offering an eco-friendly and efficient alternative to traditional animal proteins. Their applications extend to poultry, aquaculture, livestock, and rabbit nutrition, where they have been shown to improve feed efficiency, growth performance, and production economics without compromising health or product quality. Additionally, their inclusion reduces dependency on costly ingredients like fish meal and soybean meal.  Despite these advantages, challenges remain concerning food safety, including allergenicity, microbial contamination, antinutrients, and chemical residues. The review also underscores the importance of proper processing techniques to mitigate such risks and enhance digestibility. Furthermore, studies suggest that fermented or defatted forms of SWP yield better outcomes in animal performance.  Overall, this review supports the broader inclusion of silkworm pupae in future food and feed systems, aligning with global efforts toward sustainable nutrition, circular economy, and reduced environmental impact. Continued research and regulatory measures are essential to fully unlock the potential of silkworm pupae as a mainstream dietary component. |

*Keywords: Silkworm Pupae Meal, Alternative Protein Source, Sustainable Animal Nutrition, Poultry Feed, Aquaculture Feed, Livestock Diets, Nutritional Composition, Feed Conversion Efficiency*

1. INTRODUCTION

In recent years, the global demand for alternative and sustainable food sources has intensified, driven by the need to meet the nutritional requirements of both humans and animals. Edible insects, particularly those considered safe for human consumption, have gained considerable attention due to their impressive nutritional profiles, offering high-quality protein, essential fatty acids, vitamins, and minerals (Wu *et al.,* 2021). Among these, **silkworm pupae**, a byproduct of the silk industry, have emerged as a promising candidate. Traditionally consumed in several Asian countries, silkworm pupae are now being recognized worldwide for their potential as a nutrient-dense and eco-friendly food source. This growing interest is shaped by a broader context of global challenges. Humanity is currently facing a multitude of interlinked issues, including rapid population growth, climate change, increasing food insecurity, and the degradation of ecosystems and biodiversity (Rodríguez-Ortiz *et al.,* 2024). The projected increase in global population is expected to place unprecedented pressure on food systems, necessitating not only a greater quantity of food but also enhanced dietary diversity and intensified research to mitigate emerging risks (Burki, 2022). Within this framework, insects that have traditionally been consumed in regions such as Asia, Africa, and Latin America are now being reconsidered as practical, eco-friendly, and nutrient-rich food sources (de Castro *et al.,* 2018).Against this backdrop, silkworm pupae stand out not only for their nutritional richness but also for their potential to contribute to waste reduction in sericulture. Their integration into modern food systems presents a dual opportunity: promoting circular bioeconomy practices and addressing the urgent need for sustainable protein alternatives in both human and animal nutrition.

Food production is closely linked to several environmental challenges. Agriculture alone accounts for nearly 70% of global freshwater withdrawals from natural sources such as aquifers, rivers, and lakes (FAO, 2021). Additionally, the agriculture, forestry, and land use sectors contribute approximately 22% of total global greenhouse gas emissions (Lee *et al.,* 2023). In light of these concerns, identifying alternative food sources that can reduce the environmental footprint of conventional food systems has become a pressing global priority. Ideally, these alternatives should be resource-efficient, environmentally sustainable, and relatively easy to produce. Edible insects, in particular, have emerged as a promising solution due to their low ecological impact and high nutritional value (Van Huis, 2013; Lumanlan *et al.,* 2022). Among these, silkworms have gained considerable attention in recent years as a potential sustainable food resource, driving increased interest and research into their production and utilization (David-Birman *et al.,* 2019; Alcaraz *et al.,* 2021).

Beyond its remarkable potential as a protein-rich food for human consumption, silkworm pupae also serve as a valuable supplement in animal nutrition. Their rich nutrient composition positions them as a viable and sustainable alternative to conventional protein sources commonly used in animal feed, such as soybean meal and groundnut cake (Rashmi *et al.,* 2022). Growing scientific interest has led to numerous studies evaluating the inclusion of silkworm pupae meal in animal diets, particularly as a substitute for fishmeal in aquaculture (Wu *et al.,* 2022) and livestock production systems. Furthermore, recent investigations into their use in ruminant diets suggest potential environmental benefits, such as reduced methane emissions, without compromising feed intake or nutrient digestibility (Thirumalaisamy *et al.,* 2022). In poultry nutrition, where energy-dense and high-protein diets are critical- especially during early growth phases, silkworm pupae meal has demonstrated potential for use in pre-starter and starter feeds (Gous *et al.,* 2018). As a result, the integration of insect-based protein sources, particularly silkworm pupae, is gaining traction as a sustainable strategy in modern animal feeding practices. Despite increasing interest, comprehensive analysis of the nutritional, functional, and environmental benefits of silkworm pupae for human and animal use remains scarce. This review compiles existing knowledge on their composition, health benefits, sustainability potential, and applications, aiming to support future research, policy, and practical adoption in advancing global food and feed security.

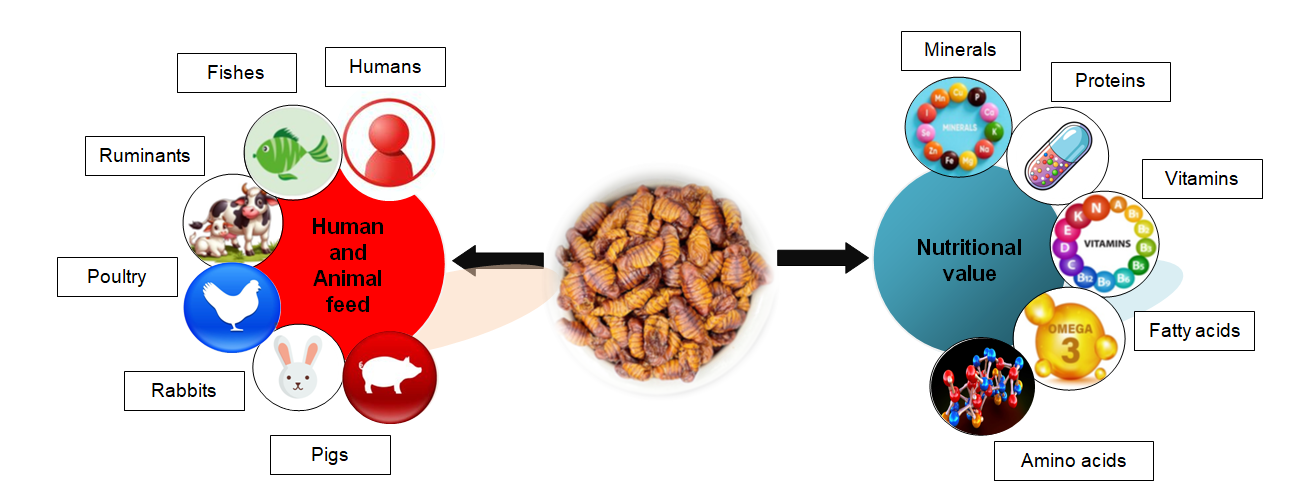
2. Silkworm pupae

Silkworm pupae are a significant by-product of the silk reeling industry, generated during the unwinding of silk from cocoons (Datta &Nanavaty, 2005). Globally, over 200,000 tonnes of spent silkworm pupae are produced annually, primarily from four silkworm varieties such as mulberry, eri, tasar, and muga-with mulberry pupae being the most abundant, especially in major silk-producing countries like China and India, followed by Brazil, Thailand, Indonesia, Vietnam, and South Korea (Yeruva *et al.,* 2023). Despite their high volume, silkworm pupae are often underutilized in commercial applications related to silk processing (Thirupathaiah *et al.,* 2018). For every kilogram of raw silk produced, approximately 8 kilograms of wet pupae or around 2 kilograms of dry pupae are generated as residue (Patil *et al.,* 2013).

In many cases, these pupae are discarded in open environments, which raises environmental concerns due to their high moisture content and rapid decomposition. Improper disposal in large quantities can pose a serious ecological threat (Wang *et al.,* 2010). However, silkworm pupae possess remarkable nutritional value, containing 50 - 80% protein (Ichim *et al.,*2008; Ioselevich *et al.,* 2004),8 - 10% lipids, and a rich array of micronutrients including vitamins E, B1, and B2, nicotinic acid, pantothenic acid, and trace elements like copper, iron, and selenium (Ichim *et al.,*2008). Studies have shown that spent pupae protein is 130% superior to casein and 90% more digestible than pepsin, highlighting their potential as a high-value nutritional ingredient (Vishnu *et al.,* 2024).

In addition to their nutritional attributes, spent pupae contain a wide range of biologically active compounds that make them suitable not only for human and animal consumption, but also for pharmaceutical and agricultural applications, such as organic fertilizers and crop enhancers (Javali *et al.,* 2015). Utilizing this by-product effectively could significantly reduce environmental stress while contributing to circular economy goals.

Anatomically, the silkworm pupa represents a transitional stage in the insect’s metamorphosis, encased within the cocoon. Structural analysis reveals that non-living components such as the cocoon shell and dehydrated prepupal skin constitute roughly 16.2 ± 1.0% of the total body mass (Blossman-Myer& Burggren, 2007). Although the dehydrated skin only accounts for 3.0 ± 0.1%, it holds biochemical potential that remains largely unexplored (Bharath *et al.,* 2024). These findings further support the need for innovative research into full-value utilization of all components of the silkworm pupae for food, feed, and industrial use (Fig. 1).



**Fig. 1 Nutritional Composition and Applications of Insect Pupae as a Sustainable Source of Human and Animal Feed**

3. Nutritional Profile of Silkworm Pupae

Silkworm pupae meal contains a high concentration of protein, ranging from 50% to more than 80%. This protein has a good amount of crucial amino acids. The limiting amino acids in cattle, such as methionine and lysine, are found in appreciable percentage in the silkworm's pupa protein (Chandrasekaraiah *et al.,* 2002, Chandrasekaraiah *et al.,* 2003). Because of the presence of chitin, truly digested protein contributes for only 73% of total crude protein composition. Silkworm pupa contains several attractants and appetite stimulants (Tuigong *et al.,* 2015; Wei *et al.,* 2009), which enhance acceptance and hence growth (Nandeesha *et al.,* 1988). It is regarded as a high quality protein with a good nutritional source due to presence of essential amino acid profile along with fatty acid profile particularly polyunsaturated fatty acid especially α linolenic acid around 27.99% and has more than 68% total unsaturated fatty acids (Wei *et al.,* 2009). Because of its nutritional profile, it grabbeb the interest of many researchers towards it and found that it can be used in feeds of animals, especially in monogastric species (poultry, pigs and fish) and ruminants (Trivedy *et al.,* 2007; Makkar *et al.,* 2014; Rashmi *et al.,* 2023) and evidences showed that polysaccharides such as silkrose or dipterose, extracted from silkworm possess immunostimulatory effects that could improve the health status of mammals and aquatic species (Motte *et al.,* 2019).

The nutritional composition of silkworm pupae can vary significantly depending on their processing state whether fresh, fatted, or defatted. Table 1 presents a comparative overview of key nutritional components, highlighting the changes in crude protein, fat content, fiber, and mineral levels across different forms. Notably, defatted silkworm pupae exhibit the highest protein content, making them particularly suitable for use in high-protein diets, while fatted forms retain more energy-dense ether extract. These variations are critical for determining appropriate applications in both human nutrition and animal feed formulations.

**Table 1.Comparative Nutritional Composition of Fresh, Fatted, and Defatted Silkworm Pupae**

|  |  |  |  |
| --- | --- | --- | --- |
| **Component** | **Fresh silkworm pupae** | **Dried, fatted silkworm pupae** | **Dried, de fatted silkworm pupae** |
| Crude protein(% DM) | 58.8 | 60.7 | 75.6 |
| Crude fibre (% DM) | 5.8 | 3.9 | 6.6 |
| Dry matter(% as feed) | 26.2 | 91.4 | 93.8 |
| Ash (%DM) | 4.9 | 5.8 | 6.8 |
| Ether extract (% DM) | 28.5 | 25.7 | 4.7 |
| Calcium (g/kg DM) | 1.5 | 3.8 | 4.0 |
| Phosphorus(g/kg DM) | 9.0 | 6.0 | 7.0 |
| GE (MJ/kg DM) | 26.5 | 25.8 | 22.0 |

Source: Sahib *et al.,* (2024)

**3.1 Essential amino acid composition of silkworm pupae**

Silkworm pupae are increasingly recognized for their high-quality protein content, particularly due to their rich amino acid composition. Certain essential amino acids such as methionine, lysine, threonine, and tyrosine are found in significantly higher concentrations in silkworm pupae compared to traditional sources like milk proteins (Rao, 1994). Specifically, deoiled silkworm pupae powder contains about 5.36% lysine and 2.39% methionine on a dry matter basis, underscoring its value as a protein-rich supplement (Jintasataporn*et al.,* 2011).

A detailed profiling by Yeruva *et al.,* (2023) further confirms the abundance of both essential and non-essential amino acids in silkworm pupae. Among the essential amino acids, lysine was found at 40.6 ± 0.92 mg/g, followed by methionine (35.7 ± 1.04 mg/g), phenylalanine (27.2 ± 0.0 mg/g),leucine (25.6 ± 0.0 mg/g), histidine (17.1 ± 0.32 mg/g), valine (15.2 ± 0.33 mg/g), tryptophan (14.9 ± 0.4 mg/g), and threonine (11.7 ± 3.2 mg/g). In terms of non-essential amino acids, the dominant ones include glutamic acid (45.9 ± 0.31 mg/g), aspartic acid (36.4 ± 0.11 mg/g), proline (24.9 ± 0.39 mg/g), arginine (22.3 ± 0.0 mg/g), serine (20.3 ± 0.78 mg/g), alanine (11.4 ± 3.2 mg/g), cysteine (0.444 ± 0.05 mg/g), and glycine (0.01 ± 0.0 mg/g). These findings highlight the high-quality protein content of silkworm pupae, which includes a well-balanced composition of essential amino acids important for both human and animal nutrition.

While the crude protein content does not vary drastically between defatted and non-defatted silkworm pupae meal, the defatted form is generally preferred in animal nutrition due to its lower ether extract, improving digestibility, handling, and shelf-life (Vishnu *et al.,* 2024). The comparative amino acid composition of both forms is presented in Table 2, offering critical insights into their suitability for diverse applications in food and feed industries.

**Table 2.Comparative Amino Acid Composition of Defatted and Non-Defatted Silkworm Pupae**

|  |  |  |
| --- | --- | --- |
| **Amino acids** | **Non-defatted(g/16g Nitrogen)** | **Defatted (g/ 16g Nitrogen)** |
| Alanine | 5.8 (5.5, 6.1) | 4.4 ± 0.2 |
| Arginine | 5.6 (4.4, 6.8) | 5.1 ± 0.3 |
| Aspartic acid | 10.4 (9.9, 10.9) | 7.8 ± 0.7 |
| Cystine | 1.0 (0.5, 1.4) | 0.8 ± 0.5 |
| Glutamic acid | 13.9 (12.9, 14.9) | 8.3 ± 0.7 |
| Glycine | 4.8 (4.6, 4.9) | 3.7 ± 0.3 |
| Histidine | 2.6 (2.5, 2.7) | 2.6 ± 0.1 |
| Isoleucine | 5.1 (4.4, 5.7) | 3.9 ± 0.2 |
| Leucine | 7.5 (6.6, 8.3) | 5.8 ± 0.2 |
| Lysine | 7.0 (6.5, 7.5) | 6.1 ± 0.4 |
| Methionine | 3.5 (2.3, 4.6) | 3.0 ± 0.4 |
| Phenylalanine | 5.1 (5.1, 5.2) | 4.4 ± 0.3 |
| Proline | 5.2 (4.0, 6.5) | 5.20 ± 0.1 |
| Serine | 5.0 (4.7, 5.3) | 4.5 ± 0.2 |
| Threonine | 5.2 (4.8, 5.4) | 4.8 ± 0.3 |
| Tryptophan | 0.9 | 1.4 ± 0.2 |
| Tyrosine | 5.9 (5.4, 6.4) | 5.5 ± 0.2 |
| Valine | 5.5 (5.4, 5.6) | 4.9 ± 0.2 |

Source: Miles & Chapman (2006); Makkar *et al.,* (2014), Sadat *et al.,* (2022) & Sahib *et al.,* (2024)

**3.2Fatty acid profile of silkworm pupae**

Silkworm pupae are a notable source of lipids, particularly rich in polyunsaturated fatty acids (PUFAs). Extracts from the pupae have been shown to contain approximately 27.99% α-linolenic acid, contributing to a total unsaturated fatty acid content exceeding 68% (Wei *et al.,* 2009). Among these, linolenic acid (18:3) is especially abundant, with reported values ranging between 11% and 45% of the total fatty acid content (Ioselevich *et al.,* 2004), highlighting the nutritional and functional potential of silkworm oil.

In terms of fiber content, silkworm pupae contain about 11% neutral detergent fiber (NDF) and between 6 – 12% acid detergent fiber (ADF) on a dry matter basis (Finke, 2002; Rashmi *et al.,* 2023). These levels contribute to the structural composition of the pupae and influence digestibility in animal feed applications.

Lipid content varies significantly between non-deoiled and deoiled silkworm pupae meals. The non-deoiled form typically contains 20 – 40% fat on a dry matter basis, while deoiled pupae meal contains less than 10% fat, making it more suitable for inclusion in high-protein, low-fat feed formulations (Sahib *et al.,* 2024). The detailed fatty acid composition of silkworm pupae, including both saturated and unsaturated components, is summarized in Table. 3 providing a comprehensive understanding of its lipid profile for nutritional and industrial applications.

**Table 3.Composition of Fatty Acids in Silkworm Pupae**

|  |  |
| --- | --- |
| **Fatty acids** | **Amount (%/100 g)** |
| Unsaturated | 70.1 |
| Saturated | 20.7 |
| Linoleic acid | 24.6 |
| Palmitic acid | 14.0 |
| Oleic acid | 9.10 |
| Linolenic acid | 14.0 |
| Others | 8.40 |

**Source:** Sadat *et al.,* (2022); Sahib *et al.,* (2024) & Vishnu *et al.,* (2024)

**3.3Vitamin and Mineral Composition of Silkworm Pupae**

Silkworm pupae also offer a valuable source of essential minerals and vitamins, contributing to their overall nutritional profile. Studies on Assam muga silkworm pupae have reported calcium and phosphorus contents of 0.26% and 0.80%, respectively, on a dry matter basis (Bora& Sharma, 1965), indicating their potential to supplement dietary mineral requirements. In addition to minerals, silkworm pupae contain a range of vital water-soluble vitamins, including riboflavin (B2), thiamine (B1), pyridoxal (B6), folic acid (B9), and ascorbic acid (vitamin C), enhancing their nutritional value (Koundinya & Thangavelu, 2005). These micronutrients play critical roles in metabolic function, immune support, and growth regulation. A detailed breakdown of the vitamin and mineral composition of silkworm pupae is presented in Table 4, highlighting their relevance as a functional food and feed ingredient.

**Table 4.Different minerals and vitamin composition of silkworm pupae**

|  |  |  |  |
| --- | --- | --- | --- |
| **Mineral** | **Amount** | **Vitamin** | **Amount** |
| Calcium (mg/100 g) | 102.31 | Vitamin A(µg/100 g) | 273.99 |
| Phosphorus (mg/100 g) | 1369.94 | Vitamin B1(mg/100 g) | 1.91 |
| Magnesium (mg/100 g) | 287.96 | Vitamin B2(mg/100 g) | 5.43 |
| Potassium (mg/100 g) | 1826.59 | Vitamin B3(mg/100 g) | 15.20 |
| Iron (mg/100 g) | 9.54 | Vitamin B5(mg/100 g) | 12.49 |
| Sodium (mg/100 g) | 274.57 | Vitamin B7(µg/100 g) | 144.51 |
| Zinc (mg/100 g) | 17.75 | Vitamin B9(mg/100 g) | 0.41 |
| Manganese (mg/100 g) | 1.04 | Vitamin B12(mg/100 g) | 500.00 |
| Copper (mg/100 g) | 1.04 | Vitamin C (mg/100 g) | 5.70 |
| Selenium (µg/100 g) | 80.00 | Vitamin E (IU/kg) | 51.45 |

Source: Vishnu *et al.,* (2024)

4. Silkworm pupae as superfood for Human and Animal

**4.1Human**

In recent years, the search for nutrient-dense, sustainable, and functional foods has brought edible insects like silkworm pupae into the spotlight. Traditionally consumed in various Asian cultures, silkworm pupae are now gaining global attention for their exceptional nutritional profile. Rich in high-quality protein, essential amino acids, healthy fats, vitamins, and minerals, they offer a natural and efficient alternative to conventional animal-based foods. With growing interest in environmentally friendly diets and the need to combat malnutrition, silkworm pupae are emerging as a promising superfood with the potential to support both health and sustainability.

Scientific evidence highlights the well-balanced nutritional profile of silkworm pupae, making them highly suitable for human consumption. Essentially, silkworm pupae are a good source of protein, fat, minerals, and vitamins. Compared to conventional food, they have higher content of three calorigenic nutrients (protein, fat, and carbohydrates), providing up to 230 kcal per 100 g (Wu *et al.,* 2021). The values of key nutrients in silkworm pupae compared with other common foods are listed in Table 5.

**Table 5.Comparative Key Nutritional Values per 100 g of Silkworm Pupae and Selected Common Foods**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Name** | **Edible Part (%)** | **Energy (kcal)** | **Water (g)** | **Protein (g)** | **Fat (g)** | **Carbohydrate (g)** | **VA (µg)** | **B1 (mg)** | **B2 (mg)** | **B3 (mg)** | **VE (mg)** | **Na (mg)** | **Ca (mg)** | **Fe (mg)** |
| Silkworm pupae | 100 | 230 | 57.5 | 21.5 | 13 | 6.70 | 0 | 0.07 | 2.23 | 2.2 | 9.89 | 140.2 | 81 | 2.6 |
| Egg (white part) | 87 | 138 | 75.8 | 12.7 | 9 | 1.50 | 310 | 0.09 | 0.31 | 0.2 | 1.23 | 94.7 | 48 | 2 |
| Milk | 100 | 54 | 89.8 | 3 | 3.2 | 3.40 | 24 | 0.03 | 0.14 | 0.1 | 0.21 | 37.2 | 104 | 0.3 |
| Chicken | 66 | 167 | 69 | 19.3 | 9.4 | 1.30 | 48 | 0.05 | 0.09 | 5.6 | 0.67 | 63.3 | 9 | 1.4 |
| Pork (lean meat) | 100 | 143 | 71 | 20.3 | 6.2 | 1.50 | 44 | 0.54 | 0.1 | 5.3 | 0.34 | 57.5 | 6 | 3 |
| Sea shrimp | 51 | 79 | 79.3 | 16.8 | 0.6 | 1.50 | 0 | 0.01 | 0.05 | 1.9 | 2.79 | 302.2 | 146 | 3 |
| Tilapia | 55 | 98 | 76 | 18.4 | 1.5 | 2.80 | 0 | 0.11 | 0.17 | 3.3 | 3.1 | 19.8 | 12 | 0.9 |

*\*Abbreviations: B1, Thiamin; B2, Riboflavin; B3, Niacin; Ca, calcium; Fe, Iron; Na, Sodium; VA, Retinol; VE, Tocopherol*

Source: Wu *et al.,* (2021)

The protein content of silkworm pupae is approximately 21.5% on a fresh weight basis and can reach 49–54% on a dry weight basis (Longvah *et al.,* 2011; Nowak *et al.,* 2016), surpassing many conventional animal products. The proteins of silkworm pupae are considered complete, containing all essential amino acids in ideal proportions, as recommended by FAO/WHO guidelines (Köhler *et al.,* 2019; Ni *et al.,* 2003; Wang *et al.,* 2009; Yang *et al.,* 2009; Zhou & Han, 2006). In general, insect proteins are highly digestible (Finke, 2008). The amino acid score and protein digestibility- corrected amino acid score of silkworm pupae are 100 and 86, respectively (Longvah *et al.,* 2011). Furthermore, the amino acid score of proteins in silkworm pupae protein was 100 with respect to the amino acid profile of a 2– 5- year- old child (FAO/WHO, 1985; Longvah *et al.,* 2011). Therefore, silkworm is a good source of protein that could be used as an alternative dietary source of protein for human nutrition.

Unlike other edible insects such as termites or weevil larvae, which are rich in saturated fats, silkworm pupae contain healthier fats dominated by unsaturated fatty acids (Payne *et al.,* 2016). Based on World health organization guidelines, limiting the dietary intake of saturated fat minimizes the risk of cardiovascular disease. Silkworm pupae lipids are considered high-quality edible fats with pharmaceutical applications (Shanker *et al.,* 2006; Wang *et al.,* 2013). For instance, after eating silkworm pupae oil for 18 weeks, rats showed a notable increase in high- density lipoprotein cholesterol levels, with significantly reduced triglyceride and total cholesterol levels (Longvah *et al.,* 2012). Silkworm pupae oil also regulates plasma lipid and lipoprotein levels in the serum of rats by activating apoproteins and lipid- metabolizing enzymes. Thus, it could be used to treat hyperlipidemia (Wu *et al.,* 2021). Therefore, silkworm pupae represent a good source of fats for human consumption.

Minerally, silkworm pupae are a rich source of essential elements such as calcium, potassium, iron, magnesium, and zinc (Kouřimská & Adámková, 2016). Notably, they contain high potassium levels (34 mg/g), a favorable sodium-to-potassium (Na/K) ratio of 0.08, and significant zinc concentrations (36 μg/g), all crucial for maintaining health and physiological functions (Zhou & Han, 2006). Table 5 illustrates a comparison of key nutrient values in silkworm pupae with other conventional foods.

Although silkworm pupae are highly nutritious, they may contain certain antinutritional factors as a result of their mulberry leaf-based diet. These include phytates (ranging from 72.89 to 110.16 mg/g), phytin phosphorus (20.54 to 31.03 mg/g), along with other compounds such as tannins, alkaloids, flavonoids, saponins, and oxalates. However, the concentrations of these antinutrients are relatively low and remain within the acceptable limits for human consumption, posing no significant health risk (Omotoso, 2015). Importantly, their presence does not outweigh the nutritional benefits of silkworm pupae. Rich in high-quality protein, essential fatty acids, vital minerals, and key vitamins, silkworm pupae stand out as a valuable and safe food source that can contribute meaningfully to a balanced human diet.

**4.2Animal**

**4.2.1 Poultry**

In the pursuit of cost-effective and nutritionally rich alternatives to conventional poultry feed, silkworm pupae have emerged as a promising superfood. Traditionally viewed as a by-product of sericulture, these pupae are now gaining recognition for their impressive nutrient composition, particularly their high protein and lipid content. With rising feed costs and the growing demand for sustainable livestock nutrition, silkworm pupae offer an eco-friendly, protein-rich option that supports optimal poultry growth and productivity. Their well-balanced profile of essential amino acids, fatty acids, vitamins, and minerals makes them a valuable feed ingredient capable of improving overall poultry health and performance.

Insect meal is increasingly being recognized as a sustainable alternative to traditional poultry feed ingredients (Elahi *et al.,* 2022). A wide range of insect species are suitable for use in poultry nutrition and can be incorporated in various forms, including live, paste, or dried preparations (Elahi *et al.,* 2020). Among these, the dried form is particularly preferred due to its lower moisture content, which minimizes the risk of spoilage and reduces the likelihood of unwanted chemical reactions such as the Maillard reaction (Kröncke *et al.,* 2019). Compared to conventional feed sources, insect meals are generally richer in essential amino acids, contributing to improved nutritional value (Al-Qazzaz and Ismail, 2016). Among the different insect-based feed options, silkworm pupae meal is one of the most widely used in poultry diets. It serves as a cost-effective yet nutritionally valuable alternative protein source, offering a viable replacement for more expensive ingredients such as fishmeal and soybean meal (Sheikh *et al.,* 2018).

The partial substitution of conventional protein sources, such as fish meal, with silkworm pupae meal (SWPM) has shown promising results. Replacing up to 50% of fish meal with SWPM has been reported to be safe, although additional mineral supplementation may be necessary to maintain nutritional balance (Sahib *et al.,* 2024). Research on broiler finisher diets indicates that the inclusion of silkworm meal in place of soybean meal does not adversely affect carcass quality or blood biochemical profiles. Notably, optimal feed intake and body weight gain were observed when 75% of soybean meal was replaced with SWPM in commercial broiler finisher diets (Ullah *et al.,* 2017). Furthermore, complete replacement of fishmeal with *Antheraea assamensis* (muga) silkworm meal did not negatively influence carcass traits, and economic analyses highlighted this substitution as highly cost-effective (Sheikh *et al.,* 2005; Sheikh and Sapcota, 2007). Additionally, performance enhancement in broilers has been observed when 70% acetone-treated SWPM was incorporated into their feed (Yhoung-Aree *et al.,* 1997).

An experiment performed to assess the effect of feeding silkworm pupae meal in young RIR pure line layers revealed that growth, egg production performance and profitability was significantly higher for the group containing diet with 6% silkworm pupae meal when compared to groups fed on diets containing 0% and 8% pupae meal (Khatun *et al.,* 2005).Khan *et al.* (2020) conducted a trial on white leghorns to evaluate the effect of replacing soybean meal with graded levels of silkworm pupae meal on egg production performance, serum biochemistry and intestinal histological features. The study showed no negative effect on growth, egg production, intestinal health and serum biochemistry.

A study on growing chicks has demonstrated that the growth-promoting effect of silkworm pupae may be associated with the presence of the hormone ecdysteroid, which plays a key role in the metamorphosis process of the insect (Fagoonee, 1983). In another study involving geese, the inclusion of silkworm pupae in the diet resulted in excellent amino acid digestibility specifically, 95% for methionine and 94% for lysine highlighting its nutritional efficacy (Penkov *et al.,* 2002).

Several studies conducted across various countries have explored the inclusion of silkworm pupae meal in poultry diets. The outcomes of these investigations, highlighting its effects on poultry performance and nutritional benefits, are summarized in Table 6.

**Table 6.Comparative Key Nutritional Values per 100 g of Silkworm Pupae and Selected Common Foods**

|  |  |  |  |
| --- | --- | --- | --- |
| **Country** | **Trial** | **Result & Inference** | **Reference** |
| Thailand | Effect of Silkworm pupae meal inclusion in broiler using Eri Silkworm | Incorporating 10% eri pupae meal into the poultry diet produced crude protein levels comparable to those of soybean meal, while also yielding improved growth performance evidenced by greater final body weight, reduced feed conversion ratio (FCR), and enhanced cold carcass weight (CCW). | Kongsup *et al.,* (2022) |
| Hungary | Incorporating defatted Silkworm Pupae Meal for Broiler chicken diets | Silkworm pupae meal has proven to be a viable protein source in broiler diets, as it supports normal growth rates and maintains carcass quality without causing any adverse effects. | Zsedely *et al.,* (2022) |
| India | Replacement of 0-50% of fishmeal (5% diet) | A 50% replacement of fishmeal with silkworm pupae meal led to enhanced body weight gain in broilers, along with better feed conversion efficiency, indicating its effectiveness as an alternative protein source. | Banday *et al.,* (2009) |
| Japan | 100% of protein concentrate replaced by silkworm pupae meal in layers | Complete replacement of conventional protein concentrate with silkworm pupae meal (SWPM) yielded the most favorable and economical outcomes, significantly improving egg quality, egg size, and shell thickness. | Wang *et al.,*(2010) |
| Bangladesh | Inclusion of Silkworm Pupae in Rhode Island Red pure line chickens | Incorporating silkworm pupae (SWP) into poultry diets at levels up to 6% has been shown to enhance growth performance effectively. | Khatun *et al.,* (2005) |
| India | Substitution 0–100% of fishmeal | Substituting 50% of fishmeal with tasar silkworm meal in poultry feed proved to be a more economical option without compromising nutritional value. | Sinha *et al.,* (2009);  Rao *et al.,* (2011);  Dutta *et al.,*(2012) |

The findings from various countries highlight the consistent benefits of incorporating silkworm pupae meal into poultry diets, showing improved growth, egg quality, feed efficiency, and economic returns. Its high nutritional value, digestibility, and affordability make it a practical and sustainable substitute for conventional protein sources like fishmeal and soybean meal in poultry sector.

**4.2.2Fish**

Over the past few decades, aquaculture has expanded significantly, keeping pace with the increasing global demand for fish as a key dietary protein source (FAO, 2018). Current projections suggest that aquaculture will contribute approximately 52% of the fish consumed worldwide (FAO, 2020). This growth has been accompanied by notable advancements in culture techniques, with greater diversification in both species and farming systems, resulting in an impressive average annual growth rate of 8.61% (FAO, 2024). However, as production systems become more intensive, feed management has emerged as one of the most critical and cost-intensive components. Feed must meet the complete nutritional requirements of cultured species and typically accounts for 60–70% of the total operational expenses in aquaculture (Boyd & Tucker, 1992), primarily due to reliance on fish meal and fish oil (Hodar *et al.,* 2022).

Fish meal has long been a preferred protein source in aquafeeds due to its excellent digestibility, balanced amino acid profile, high palatability, and content of essential long-chain omega-3 fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which aid in nutrient absorption and overall growth (Karthick *et al.,* 2019; Olsen *et al.,* 2012). Historically, fish meal was an economical ingredient used mainly in livestock feeds, comprising about 80% of global production in 1988, while only 10% was utilized in aquaculture. However, with increasing demand for aquafeeds, this trend shifted significantly by 2010, with aquaculture consuming 56% of global fish meal output compared to 32% by terrestrial livestock (Huntington & Hasan, 2009). In light of rising costs and sustainability concerns, the industry is increasingly turning to alternative protein sources. Silkworm pupae, once discarded as waste from the silk industry, are now emerging as a promising superfood in fish nutrition. Rich in high-quality proteins, essential amino acids, and beneficial lipids, silkworm pupae meal offers a cost-effective and environmentally friendly alternative to traditional fish meal. Its nutrient-dense profile supports healthy fish growth, enhances feed conversion efficiency, and reduces pressure on marine resources making it a viable component in sustainable aquafeed development.

Extensive research has been conducted to assess the potential of silkworm pupae as an alternative protein source in aquaculture. In a study by Kurbanov *et al.,* (2015), fingerlings were fed a diet containing 40% crude protein at a feeding rate of 5% of their body weight over a 40-day period. The results revealed that the highest growth rate and most efficient feed utilization occurred in fish fed a diet with a balanced blend of fish meal and silkworm pupae meal in a 50:50 ratio. In contrast, diets comprising solely fish meal or silkworm pupae meal resulted in comparatively lower performance. Significant differences were also noted in key performance indicators such as weight gain, relative growth rate, feed conversion ratio, and protein efficiency ratio.

Chowdhary *et al.,* (2012) investigated the impact of various protein sources on the growth performance of Asian catfish (*Clarias batrachus*) fingerlings. Silkworm pupae were included in the diets at levels of 20.30% without soybean meal and 15.20% along with an equal proportion (15.20%) of soybean meal. The study found that the best growth outcomes were achieved in fish fed diets containing the higher level of silkworm pupae without the inclusion of soybean meal, highlighting its potential as an effective standalone protein source in aquafeeds.

According to a study conducted by Oso & Iwalaye (2014), in *Claris garienpinus* juveniles, the diets containing different inclusion level of silkworm pupae significantly improved weight gain, specific growth rate, and protein efficiency ratio. Best results were observed at 25% silkworm pupae in the diet. Sawhney (2014) studied the growth promoting role of silkworm pupae at inclusion level of 25% in the diet of *Tor putitora* fingerlings and concluded that inclusion of silkworm pupae in the fish diets promises an economical fish production. According to an experiment conducted by Ji *et al.,* (2013) on juvenile Jian carp (*Cyprinus carpio* var. Jian)evaluated the replacement of fish meal (FM) with silkworm pupae meal (SP) at levels of 0–80%. Results showed that up to 50% FM replacement supported optimal growth and muscle protein content, while higher inclusion levels (60–80%) significantly reduced growth performance and triggered oxidative stress, liver and intestinal damage, and altered enzyme activities. The findings suggest that SP can safely replace 50% of FM in carp diets, but higher levels may negatively impact fish health.

Rangacharyulu *et al.,* (2003) observed notable improvements in survival rate, feed conversion ratio, and specific growth rate in fish fed with fermented silkworm pupae compared to those fed with unprocessed fresh pupae. Their findings highlighted that fermentation or ensiling enhances the nutritional quality of silkworm pupae, making it a more effective feed ingredient in aquaculture.

The growing interest in silkworm pupae as a sustainable and nutritionally rich alternative to fish meal reflects a broader shift in aquaculture towards eco-friendly feed solutions. As evidenced by multiple studies, silkworm pupae whether used raw, partially substituted, or fermented can significantly enhance growth performance, feed efficiency, and survival rates across various fish species when included at appropriate levels. However, careful attention must be given to inclusion rates and processing methods, as excessive substitution may compromise fish health and growth due to physiological stress. These findings collectively position silkworm pupae not only as a waste-to-resource innovation but also as a practical step forward in reducing dependence on traditional marine-based proteins while supporting the goals of sustainable aquaculture.

**4.2.3Livestock**

*4.2.3.1 Ruminants*

Silkworm pupae meal has increasingly found a place in livestock nutrition, primarily due to its rich protein content (Trivedy *et al.,* 2008). Notably, its bypass protein fraction provides valuable levels of methionine and lysine, essential amino acids crucial for ruminant health and productivity (Sampath *et al.,* 2003). Research has shown that defatted silkworm pupae meal can replace conventional protein sources entirely up to 100% without negatively impacting nutrient digestibility and rumen fermentation (Rashmi *et al.,* 2018). Further, including up to 30% defatted pupae meal in cattle diets in place of soybean meal did not lead to any significant alteration in nutrient utilization and rumen fermentation patterns (Rashmi *et al.,* 2022). In terms of digestibility, silkworm-based diets have demonstrated superior protein utilization compared to groundnut cake-based rations. For example, non-defatted silkworm meal was shown to economically substitute up to one-third (by weight) of groundnut cake in Jersey calf fattening diets without compromising animal performance (Narang & Lal, 1985). Additionally, feeding defatted Tasar pupae to sheep alongside wheat straw and molasses yielded a crude protein digestibility of approximately 70%, underscoring its value as a viable protein supplement (Khan & Zubairy, 1971). Building on this, a recent study on pre-ruminant crossbred calves demonstrated that silkworm pupae meal could effectively replace up to 50% of fish meal in their diet without negatively impacting feed intake, nutrient absorption, growth performance, or overall health (Sahib *et al.,* 2023). This further supports the growing evidence that silkworm pupae offer a practical and sustainable alternative protein source in young livestock diets.

*4.2.3.2Pigs*

Research on the use of silkworm pupae meal in pig nutrition remains limited, but available studies show promising outcomes. In particular, un-defatted silkworm pupae meal has been used to completely replace soybean meal in the diets of growing pigs without compromising growth performance or carcass traits. However, inclusion levels above 50% were associated with reduced feed intake, possibly due to lower palatability or increased dietary energy density. Interestingly, the higher lysine content in silkworm meal may have improved feed conversion efficiency, offsetting the lower intake (Coll *et al.,* 1992). Further studies revealed that silkworm pupae meal could also substitute fish meal entirely up to 100% in diets of growing and finishing pigs without adversely affecting carcass quality, meat characteristics, or blood parameters (Medhi *et al.,* 2009a; Medhi *et al.,* 2009b; Mehdi, 2011). Additionally, Choudhury *et al.,* (2021) reported that supplementing diets with 2% and 4% Muga silkworm pupae improved growth performance and production efficiency in Large White Yorkshire pigs while also reducing overall production costs. These findings highlight the potential of silkworm pupae as a sustainable and cost-effective protein alternative in pig production.

*4.2.3.3Rabbit*

In China, silkworm pupae meal has traditionally been included in rabbit feed, particularly as a substitute for soybean meal in diets for growing rabbits. Its incorporation in dried form has shown no adverse effects, making it a viable alternative for balanced nutrition. Gugolek *et al.,* (2021) found that replacing up to 5% of soybean meal with silkworm pupae meal did not alter gastrointestinal physiology. Even at a 10% inclusion level, the impact on digestive health remained minimal. However, increasing the proportion of silkworm pupae meal in the diet led to a slight reduction in nutrient digestibility and a marked decline in nitrogen retention. At the 10% level, rabbits exhibited increased digesta mass in the small intestine, cecum, and colon, alongside reduced bacterial enzyme activity and lower concentrations of short-chain fatty acids in the cecum, accompanied by elevated caecal pH. Based on these observations, it is recommended that silkworm pupae meal can be safely included in rabbit diets up to a 5% level without compromising digestive efficiency or nutrient utilization.

In an another study, Kowalaska *et al.,* (2020) reported that incorporating dried silkworm pupae meal at a 4% inclusion level in rabbit diets had no negative impact on growth performance or the nutritional and sensory quality of rabbit meat. Notably, rabbits fed with the silkworm-based diet exhibited an increase in omega-3 polyunsaturated fatty acid (PUFA-3) content and a reduction in tissue cholesterol levels, suggesting potential benefits for meat quality and health value.

Collectively, these findings suggest, silkworm pupae meal emerges as a promising, nutrient-rich alternative to conventional protein sources across various livestock species. Its high-quality protein, particularly rich in essential amino acids like methionine and lysine, supports growth, feed efficiency, and overall health in ruminants, pigs, and rabbits. From enhancing protein digestibility in cattle and sheep to improving production performance in pigs and enriching rabbit meat with beneficial fatty acids, silkworm pupae offer a sustainable and cost-effective feed solution. As research continues to affirm its versatility and safety, integrating this insect-derived protein into livestock diets could play a vital role in meeting future demands for efficient and eco-friendly animal nutrition.

5. Safety and Regulatory aspects

Although silkworm pupae are widely appreciated for their rich nutritional profile and promise as an eco-friendly protein alternative, certain food safety challenges remain that need to be carefully managed to ensure their safe inclusion in animal and human diets.

**5.1Allergenicity**

The consumption of silkworm pupae has been linked to allergic responses in certain individuals. Specific proteins found in the pupae, including arginine kinase, α-amylase, and tropomyosin, are identified as potential allergens. These compounds may trigger hypersensitivity, particularly in people with pre-existing shellfish allergies, due to possible cross-reactivity between the allergens (De Marchi *et al.,* 2021).

**5.2Chemical Residues**

Silkworm pupae may accumulate chemical contaminants like pesticides and heavy metals, especially when reared in polluted environments (Fan *et al.,* 2024). To minimize this risk, it is essential to implement controlled rearing conditions and conduct routine residue monitoring to ensure levels remain within safe, acceptable limits.

**5.3Microbial Contamination**

If not adequately processed, silkworm pupae may serve as a host for harmful microorganisms. Bacterial species such as *Bacillus*, *Clostridium*, *Staphylococcus*, *Streptococcus*, and *Vibrio* have been identified as potential contaminants, posing significant health concerns for consumers (Tan *et al.,* 2024). To safeguard public health, it is vital to maintain strict hygiene protocols across all stages of pupae production and processing.

**5.4Antinutritional Factors**

Silkworm pupae naturally contain certain antinutritional factors such as phytates, tannins, alkaloids, flavonoids, saponins, and oxalates, which may impair nutrient absorption and metabolic utilization if consumed in excess (de la Luz Sánchez-Estrada *et al.,* 2024). However, these compounds are typically present in low concentrations and can be effectively minimized through proper processing techniques, thereby reducing their potential health risks.

**6. Conclusion**

Silkworm pupae, once considered a by-product of sericulture, are steadily emerging as a valuable resource in human and animal nutrition due to their impressive nutrient profile and wide-ranging applications. Rich in high-quality protein, essential fatty acids, vitamins, and minerals, they offer a sustainable and eco-friendly alternative to conventional protein sources like fishmeal and soybean. From enhancing poultry and aquaculture performance to supporting growth in livestock and improving meat quality in pigs and rabbits, silkworm pupae demonstrate remarkable versatility and nutritional efficacy. Moreover, their potential as a superfood in the human diet aligns well with global trends toward sustainable food systems.

While their nutritional promise is undeniable, challenges such as allergenicity, chemical contamination, microbial risks, and the presence of anti-nutritional factors must be carefully managed. With advancements in processing techniques, quality control, and standardization, these concerns can be mitigated effectively. The integration of silkworm pupae into food and feed systems not only supports circular economy models by reducing waste but also contributes to food security, especially in protein-deficient regions. Overall, this review highlights silkworm pupae as a scientifically grounded, economically viable, and environmentally sound resource with immense potential for the future of sustainable nutrition.

**7. Future Prospects and Research Gaps**

Silkworm pupae have shown tremendous promise as a sustainable, nutrient-rich ingredient for human consumption, animal feed, and industrial applications. Their high protein content, favorable fatty acid profile, and abundance of essential amino acids make them a strong candidate for addressing global nutritional security. However, despite their potential, there are still several areas that require deeper investigation to fully unlock their utility.

One major area needing attention is the standardization of processing techniques. Variations in pupae preparation—such as defatting, drying, fermentation, and heat treatment—can significantly influence nutritional quality, digestibility, and the presence of allergens or antinutritional factors. More research is needed to determine the most effective processing methods that enhance safety while retaining maximum nutritional benefits.

Food safety and regulatory frameworks also need further strengthening. Although silkworm pupae are widely consumed in many parts of Asia, global acceptance requires robust risk assessments regarding allergenicity, microbial load, and potential accumulation of heavy metals and pesticide residues. This calls for comprehensive studies under diverse farming and environmental conditions.

In animal nutrition, while positive results have been reported in poultry, fish, and livestock, species-specific feeding trials must be expanded. These should include long-term performance, health parameters, and economic feasibility, especially under commercial farming systems. The role of silkworm pupae in improving gut health, immunity, and productivity also offers fertile ground for research.

Finally, public perception and market development remain underexplored. Consumer acceptance studies, value chain analysis, and cost-benefit assessments are crucial for mainstreaming silkworm pupae as a viable protein alternative. Promoting awareness through education and policy support can drive adoption at scale, particularly in regions battling protein deficiency and food insecurity. In summary, the future of silkworm pupae as a superfood lies in bridging these scientific and socio-economic gaps through collaborative, multidisciplinary research efforts.

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