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Insects as food and feed: a promising agricultural sector with special reference to India

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REVIEW ARTICLE

Abstract

Edible insects are natural resources that provide foodstuff to numerous ethnic groups in rural India. In spite of the dietary and ecological repayment, the consumption of insects is still restricted to a limited number of countries globally. Apart from the establishment of consumer acceptance, research is necessary to develop sophisticated and automatise cost-effective production of insect products. Insects have massive prospects as feed. As the protein feed ingredients are becoming expensive, several studies are in progress to establish insects as feed in the Indian market. Insect food and feed industry could be a proficient approach to consign the cost of living for the price-sensitive customers. Cross-linking between the industries and the farmers would be helpful for boosting the production rate of insect products. Extensive and systematic study of the edible insects would be desirable to ascertain food security and elude possible risks.

Keywords: edible insects, entomophagy, dietary, insect products

1. Introduction

As a result of evolution, over the past 400 million years, a wide variety of arthropod species have successfully adapted to diverse habitats globally. Among the 1.4 million described animal species, approximately 1 million are insects, with possibly millions awaiting their identification and description. Of those known, 5,000 species of insects are considered detrimental to human beings, crops, as well as livestock (Van Lenteren, 2006). In terms of the continued existence and adapting to their ecological framework, insects are the most successful of all the arthropods due to their ability to live in and adapt to diverse habitats and their ability to consume diverse resources. They possess a high reproductive capacity and the ability to escape quickly from their enemies. Insects provide numerous benefits to humanity as well.

Besides providing a variety of valuable products such as silk and honey, insects also serve as a source of food (Bodenheimer, 1951). In India, the use of different insects as food is common among different tribes especially from south (Andhra Pradesh, Kerala, Tamil Nadu and Karnataka) and north-east India (Assam, Arunachal Pradesh, Nagaland and Manipur) (Meyer-Rochow and Chakravorty, 2013). The tribes of Meghalaya, Mizoram and Odisha are also known to use insects as food (Hazarika, 2018). On the basis of traditional beliefs, regional and seasonal availability have led to certain species being accepted as food (Sangma *et al.*, 2016). The aim of this review article is to describe the advantages, promotion, and prospects of insects as food and feed with reference to India.

In view of consumers as well as the stakeholders, towards the use of insects as feed source for livestock, various researches have been carried out in India (Srivastava *et. al.*, 2009). In different parts of the globe, insects has received extensive attention as a potential source of protein for humans as well as the livestock (Tran *et al.*, 2015), insects can be fed biowastes with high feed conversion efficiency (Makkar *et al.*, 2014; Van Huis *et al.*, 2013). Collavo *et al.* (2005) reported that, two kilograms of feed biomass can produce minimum one kg of insect biomass.

In India, especially in the north-east and southern areas, tribal people often eat insects which are collected from the wild and presently in these areas, few insects are farmed. Insects, such as silk worms (*Bombyx mori*, Lepidoptera: Bombycidae), *Antheraea assamensis*, Lepidoptera: Saturniidae), honey bee (*Apis mellifera*, Hymenoptera: Apidae) are common examples (Yesadharan *et al.*, 2011). The leading prospect is to farm insects (*viz.* crickets, and fly larvae) on fruit waste and vegetables for the production of insect powder to be used as animal feed (Yesadharan *et al.*, 2011). In this context, economically weaker people have an opportunity since they can collect the waste and farm the insects in their backyards and sell them to commercial chicken farms.

2. Why insects as food and feed

Promotion of insects as food and feed could be looked at for three main reasons: health, environment, and livelihood factors. In various regions of the world, insects form a traditional part of their diet. Insects are healthy, nutritious, and serve as alternatives to other protein resources, such as chicken, beef, pork, and fish (Smil, 2002). Insects, generally, are rich in proteins, fats, carbohydrates, minerals, and vitamins (Bukkens, 2005; DeFoliart, 1991; Magalhaes *et al.*, 2012; Ritter, 1990; Rumpold and Schluter, 2013).

Most commercial livestock has a negative impact on the environment. They emit greenhouse gases substantially greater than edible insects (Alexander *et al.*, 2017). Other noxious odours, such as ammonia, also are produced at substantially greater levels by conventional livestock than farmed insects (Foley *et al.*, 2011). Unlike the other livestock, farming insects require less space and feed (Makkar *et al.*, 2014). Furthermore, unlike conventional livestock in general, insects can be fed organic wastes (Makkar *et al.*, 2014), and, depending on the investment, insect rearing can be low-tech, which offers a source of revenue opportunity for both rural and urban people (Verbeke *et al.*, 2015).

Insects have immense potential as feed. For example, rich in protein and fats, termites (Blattodea) are the second most edible insects throughout the world (Chakravorty *et al.*, 2016; Chung, 2010; Paoletti *et al.*, 2003). Acridids (grasshoppers) contain not only higher levels of proteins compared to other protein sources such as fishmeal and soybean meal but are also rich in the micro-nutrients, such as magnesium, calcium, zinc, copper, and iron (Chakravorty *et al.*,2014). Therefore, grasshoppers are well-known as one of the prospective feed components for poultry (Anand *et al.*, 2008). In the Philippines, chickens fed on pasture and grasshoppers are sold for a much higher price than chickens fed on commercial feed (Litton, 1993). Calvert (1979) reported that dried powder of house flies (Diptera: Muscidae) grown on chicken manure could be fed to chicks, which can completely replace soybean as a high-level source of protein for better weight gain. *Cirina forda* (Lepidoptera: Saturniidae) moth larvae are rich in protein similar to fishmeal. This protein, when used as a replacement for fishmeal, can be used as a feed for broiler chicks without impacting growth (Oyegoke *et al.*, 2006). Similarly, dried silkworm pupae (*B. mori*) meal can replace fishmeal, which results in better growth and egg production in the animals (Wijayasinghe and Rajaguru, 1977).

3. Entomophagy in India

India is the seventh largest country in the world, possessing a rich biological diversity of insects. Alfred *et al.* (1998) reported approximately 619 families consisting of 59,353 species of insects from India. Such diversity would indicate that India could be a potential habitat for the insect bio-resource to be utilised (Meyer-Rochow and Chakravorty, 2013).

Entomophagy in central and south parts of India

A review of the published literature reveals limited data on entomophagy in India. In Karnataka, it was reported that termites are consumed as food by the local tribes in Mysore (Forbes, 1813). The locust *Schistocerca gregaria* (Orthoptera: Acrididae), which contains high crude protein and fat, has also been used as food (Das, 1945). Roy and Rao (1957) reported the consumption of insect larvae, which is known as 'chin kara' by the Muria tribes in Madhya Pradesh. The tribe known as 'Irumbars' who inhabit the states of Tamil Nadu and Karnataka consume winged termites, which are commonly known as 'Eesal'. Interestingly, the queen termite is collected and fed raw to children who are weak (Rajan, 1987). Similarly, in Odisha, termite larvae are eaten raw or cooked with rice (Srivastava *et al.*, 2009). Wilsanand (2005), reported five different species of bees (Hymenoptera: Apidae) and ants (Hymenoptera: Formicidae) used as food. Furthermore, Yesadharan *et al.* (2011) reported five termite species used as food by the indigenous people of Parambikulam Wild Life Sanctuary, Western Ghats, Kerala.

Entomophagy in north-east India

So far, approximately 255 species of edible insects have been documented from different parts of India. In Arunachal Pradesh, 158 insect species are used as food (Chakravorty *et al.*, 2011a). The two major tribal groups, Nyishi and Galo, consume a robust number of species (102) as food (Chakravorty *et al.*, 2011b). They are distributed across a number of orders with 40 coleopteran, 12 hymenopteran, 26 orthopteran, 8 hemipteran, 3 ephemeropteran, 5 homopteran, 4 odonatan, 3 dictyopteran, 3 dipteran, 2 plecopteran, and 3 isopteran species.

In Dhemaji and Karbi Anglong districts of Assam, around 40 insect species, including silk worm, are consumed (Doley and Kalita, 2011; Ronghang and Ahmed, 2010). In Mizoram, Manipur, Assam and Tripura, the cinnamon bug (*Corizus hyoscyami*, Hemiptera: Rhopalidae) is consumed as food after cooking in oil (Thakur and Firake, 2012). Pentatomid bugs (*Ochrophora montana*, Hemiptera: Pentatomidae) are used as a delicacy by the people of Mizoram (Sachan *et al.*, 1987). In Nagaland, 42 species of insects, which include 9 species of Coleoptera, 11 species each of Orthoptera and Lepidoptera, and 8 species of Hemiptera were identified and reported to be used by the Ao Naga tribe as food (Meyer-Rochow and Changkija, 1997; Mozhui *et al.*, 2020; Singson *et al.*, 2016). Termites are used as one of the major sources of protein and carbohydrate in Meghalaya (Chakravorty *et al.*, 2016; Paul and Dey, 2011). In Manipur, around 41 species of insects belonging to 8 orders under 24 families are used as food (Shantibala *et al.*, 2012) (Table 1).

4. Advantages of eating insects

The nutritional value of the insect varies based on the stage of development (egg, larvae, pupa or adult) (Morales-Ramos *et al.*, 2015). Throughout the world, for preservation of food, drying is a traditional process. In addition to sun-drying, commercial procedures, *viz.* evaporation, drum, freeze-drying, and spray drying, are usually used to preserve the edible insects (Nyangena *et al.*, 2020). In typical drying methods, heating (*viz.* blanching or cooking) is an initial step to inactivate the enzymes and microorganisms present in the foodstuff which is followed by removal of water using heat (Grabowski *et al.*, 2016). Pretreatment of commercial edible insects by blanching leads to changes in the chemical composition due to leaching of soluble nutrients, which affect the protein content (Niamnuy *et al.*, 2008; Xiao *et al.*, 2014). Tiencheu *et al.* (2013) reported that sun-drying of *Rhynchophorus phoenicis* (Coleoptera: Curculionidae) resulted in high peroxide value compared to oven drying. In *Polyrhachis vicina* (Hymenoptera: Formicidae), appearing of aldehydes, increase of free fatty acids, decrease of ketone and very small amount of hydrocarbons were recorded during sun drying (Li *et al.*, 2009). In *Tenebrio molitor* (Coleoptera: Tenebrionidae), vacuum drying increases the protein solubility, whereas its content decreases while microwave drying (Kroncke *et al.*, 2018). Huang *et al.* (2018) reported that, in case of black soldier fly (BSF; *Hermetia illucens*, Diptera: Stratiomyidae) larvae, even though quality and content of protein were similar during microwave drying and oven drying, the digestibility of protein was highest in oven drying than the other processes of drying.

The quality of the foodstuff also depends on the preparation and processing methods like drying, blanching and frying (Kauppi *et al.*, 2019; Melgar-Lalanne *et al.*, 2019). For example, with yellow mealworm larvae, an officially recognised food ingredient by Korea, the food processing processes affects the quality of the food products (Baek *et al.*, 2015; Elhassan *et al.*, 2019; Ghosh *et al.*, 2017). During processing, increasing barrel temperature affects the texture of mealworm-enriched snacks (Azzollini *et al.*, 2018). Even different cooking conditions also affect the quality (sensory and physical properties) of mealworm larvae as food (Elhassan *et al.*, 2019). When the mealworm larvae are cooked using the microwave, values of various physical parameters, *viz.* hardness, fracturability, and texture were found to be higher than the larvae that were cooked by boiling. Also, the values of springiness, adhesiveness, and chewiness were higher when larvae were boiled than microwaving (Baek *et al.*, 2015). In terms of sensory properties, steaming and boiling of mealworms keep retain the shape and appearance of the fresh larvae and also helps in maintaining the size of the better than other cooking methods (Baek *et al.*, 2015).

Essential micronutrients present in edible insects include phosphorus, manganese, selenium, potassium, iron, copper, magnesium, zinc, essential amino acids, such as lysine, histidine, isoleucine, leucine, threonine, and valine as well as riboflavin, biotin, pantothenic acid and in some cases folic acid (Borthakur and Sharma, 1998; Chakravorty *et al.*, 2016; Habib and Hasan, 1995; Pereira *et al.*, 2003; Rao, 1994; Rumpold and Schluter, 2013). Hidden hunger, which is the incidence of micronutrient deficiency (especially iron and zinc), affects more than 2 billion people in low-income countries (IFPRI, 2016) and contributes to various disorders such as anaemia and stunted growth (Black *et al.*, 2013). The presence of high levels of protein and iron in edible insects could help prevent anaemia (Van Huis *et al.*, 2013). Insects' fats are comparable to fats present in poultry and fish and may contain more of the desired monounsaturated or healthy polyunsaturated fatty acids (Rumpold and Schluter, 2013).

Studies related to the antioxidant activity in edible insects are in progress. Dutta *et al.* (2016) reported the antioxidant potential of the aqueous extract of *Vespa affinis* (Hymenoptera: Vespidae), an edible insect species commonly used in north-east India, which mediates the therapeutic activities of the extract in oxidative stress-associated health disorders. Zielinska *et al.* (2016) investigated and reported the antioxidant activities of peptides obtained by *in vitro* gastro-intestinal digestion of edible insects. Anti-thrombotic, antioxidant and haemolysis activities of six edible insect species, *viz. Allomyrina dichotoma* (Coleoptera: Scarabaeidae), *T. molitor*, *Protaetia brevitarsis* (Coleoptera: Scarabaeidae), *Gryllus bimaculatus* (Orthoptera: Gryllidae), *Teleogryllus emma* (Orthoptera: Gryllidae), and *A. mellifera* against human red blood cells were studied by Pyo *et al.* (2020) and they reported that except *A. mellifera*, ethanol extracts of all other insects showed strong platelet aggregation activities. *T. molitor* showed concentration-dependent anti-coagulation activities, while *A. dichotoma*

Table 1. Checklist of different edible insect species consumed by different communities in India (Alemla and Singh, 2008; Chakravorty *et al.*, 2011b, 2013, 2014; Dagyom and Gopi, 2009; Doley and Kalita, 2011; Gope and Prasad, 1983; Hazarika, 2018; Meyer-Rochow, 2005; Meyer-Rochow and Changkija, 1997; Paul and Dey, 2011; Prasad, 2007; Rabha, 2016; Ronghang and Ahmed, 2010; Roy and Rao, 1957; Sachan *et al.*, 1987; Shantibala *et al.*, 2012; Singh and Chakravorty, 2008; Singh *et al.*, 2007a,b; Srivastava *et al.*, 2009; Thakur and Firake, 2012; Wilsanand, 2005; Yesadharan *et al.*, 2011).

Order	Family	Scientific name
Hymenoptera	Apidae	Apis cerana indica
	Formicidae	Oecophylla smaragdina
	Vespidae	Polistes stigma
	Formicidae	Myrmica rubra
	Apidae	Apis dorsata
	Apidae	Apis florea
	Vespidae	Vespa mandarinia
	Vespidae	Vespa tropica
	Vespidae	Vespa bicolor
	Vespidae	Polistes sp.
	Formicidae	Dorylus orientalis, Atta sp.
	Formicidae	Formica indica
	Apidae	Apis indica
	Apidae	Apis mellifera
Lepidoptera	Saturnidae	Antheraea assamensis
	Saturnidae	Samia ricini
	Saturniidae	Philosamia ricini
	Bombycidae	Bombyx mori
	Notodontidae	Anaphe infracta, A. reticulata, A. venata
Hemiptera	Belostomatidae	Lethocerus indicus
	Pentatomidae	Ochrophora montana
	Cicadidae	Pomponia imperatoria
	Naucoridae	Pelocoris femoratus
	Nepidae	Laccotrephes ruber
	Pentatomidae	Pentatomid sp.
	Belostomatidae	Belostoma indica (Lep. & Serv.)
	Nepidae	Laccotrephes maculatus Fabr.
Coleoptera	Dytiscidae	Cybister confuses Shp.
	Hydrophilidae	Hydrophilus olivaceus (Fabricius)
	Cerambycidae	Anoplophora glabripennis (Motchulsky)
	Scarabaeidae	Analeptestri fasciata
	Dytiscidae	Dytiscus marginalis
	Lyctidae	Hydrochera rickseckeri
Coleoptera	Buprestidae	Batocera horsefieldi
	Curculionidae	Rhynchophorus phoenicis
	Curculionidae	Rhynchophorus ferrugineus
	Cerambycidae	Dihammus cervinus
	Nitidulidae	Meligethes aeneus
	Cerambycidae	Batocera rufomaculata
	Lucanidae	Odontolabis cuvera
	Lucanidae	Lucanus elaphus
	Curculionidae	Cyrtotrachelus buqueti
	Dynastidae	Eurytrachelus titan
	Scarabaeidae	Megasoma elephas
Orthoptera	Gryllotalpidae	Gryllotalpa africana Palisot de Beauvois
	Acridae	Oxya hyla hyla Serville
	Gryllidae	Rachytrypes spp.
	Acrididae	Schistocerca gregaria
	Gryllidae	Acheta domesticus, Brachytrupes spp.
	Acrididae	Cytacanthacris aeruginosus unicolour, Hieroglyphus banian, Chondracris rosea
	Gryllotalpidae	Gryllus campestris
	Mantidae	Mantis inornate
	Acrididae	Locusta sp.
	Acrididae	Melanopus sp.
	Gryllidae	Schizodactylus monstrosus
	Gryllidae	Gryllus campestris
Odonata	Libellulidae	Acisoma panorpoides Rambur
	Aeshnidae, Libellulidae	Crocothemis servilia
	Aeshnidae	Aeshna mixta
	Libellulidae	Neurothemis fluctuans
	Libellulidae	Libellula carolina
Isoptera	Rhinotermitidae	Reticulitermes flavipes
	Rhinotermitidae, Termitidae	Odontotermes obesus, Macrotermes natalensis
Dictyoptera	Mantodea	Mantis religiosa
Diptera	Asilidae	Okanagan sp.

and *T. emma* showed strong antioxidant activities. Edible insects have significant prospective not just as a food source but as a novel bio-resource as well (Pyo *et al.*, 2020).

The hormone angiotensin causes vasoconstriction and a subsequent increase in blood pressure resulting in high blood pressure, which leads to preventable risk factors (Mills *et al.*, 2016). Angiotensin-converting enzyme (ACE) converts the hormone angiotensin I to the active vasoconstrictor angiotensin II which causes blood vessels to constrict. Therefore, the ACE inhibitors are used in drugs to control cardiovascular diseases. Naturally the CE inhibitory activity is widely present in a number of insects' wax, *viz.* the honeycomb moth (*Galleria mellonella*, Lepidoptera: Pyralidae), the yellow mealworm (*T. molitor*) and the silkworm (*B. mori*) (Cito *et al.*, 2017). Obesity and overweight are the leading preventable causes of death in human beings in many countries. Presence of bioactive compounds in yellow mealworm larvae powder reduces lipid accumulation and triglyceride content in adipocytes in mice leading to weight loss (Seo *et al.*, 2017). Endoplasmic reticulum (ER) stress condition found in obese and type 2 diabetes patients leads to the functional failure of cells, including insulin-producing beta cells (Laybutt *et al.*, 2007). Kim *et al.* (2016) reported when ethanol extract of the rhinoceros beetle (*A. dichotoma*) was injected into the brain tissue of obese mice; it caused ER stress-reducing effects as well as hormone-induced change in its feeding behaviour. In humans, chitin-containing fungi, arthropods, protozoa, and nematodes are targeted for recognition by the immune system. The enzyme chitinase present in the human digestive fluid degrade the chitin, and it has a crucial role in bacterial infections and inflammatory diseases (Di Rosa *et al.*, 2016; Paoletti *et al.*, 2007).

5. Insects as feed in India

In India, the protein feed ingredients such as fishmeal, vegetable feedstuffs are becoming expensive, and thus different insect species are used to feed fish, livestock, and pets. A few studies are in progress to establish the use of insects as feed in the Indian market.

The poultry and aquaculture industries in India are the fastest growing agro-business, but the survival of farmers is threatened due to increasing cost of maize used as a feed ingredient. Feeding sericulture waste to poultry, which was earlier used only for composting and production of biogas, has now resulted in a superior conversion rate than those attained through the exploitation of conventional food stuff (Krishnan *et al.*, 2011).

In 2018, the Indian poultry market consisting of eggs and broilers was worth INR 1,750 billion, and the market is projected to reach more than 4,000 billion INR by 2024, which is growing at a compound annual growth rate of 16% during 2019-2020. Despite the rapid growth of the industry, it has suffered various setbacks due to the increasing cost of feed. Corn and maize play a key role in the production of broiler as it constitutes more than 50% of broiler feed, and since the poultry market is growing at the rate of 10% annually, the demand for corn and maize is also increasing. In 1990, maize production in India was around 9.7 million tons, and in 2015 the production increased to only 25 million tons. Similarly, the production of soybean meal also increased at a slow rate from 3.5 million tons in 2000 to only 12 million tons in 2015 (Singh, 2019).

India's aquafeed market was valued at around 1.2 billion US dollars but the fish feed industry possessed a production capacity of 2.8 million metric ton only (John, 2020). Recently, national policy on marine fisheries prepared by Ministry of Agriculture, Government of India, stressed on dangers of the fish feed industry (John, 2020).

Black soldier fly

The larval stage of BSF (*H. illucens*) is a key insect that could serve as a cornerstone of the feed industry in India (Choudhury *et al.*, 2018; Gujarathi and Pejaver, 2013). It is a detritivore and is capable of bioconverting organic waste biomass to the tune of 50-90% in a short period of time (Yandigeri *et al.*, 2019). On organic waste, rearing of BSF reduces pathogenic microflora, odours emanated from the wastes, and breeding of houseflies by conversion of biomass (Choudhury *et al.*, 2018). BSF compost from kitchen waste can be prepared within 60 days, and it is reported that, due to higher amount of micronutrients, potassium, phosphorus, and nitrogen, it is of superior quality than sheep manure, vermicompost and farmyard manure (Choudhury *et al.*, 2018; Pathak *et al.*, 2015; Yandigeri *et al.*, 2019).

Amala *et al.* (2019), while studying the growth performance of tilapia (*Oreochromis niloticus*, Cichliformes: Cichlidae) reported that, fishes fed with BSF incorporated feed meal showed significantly superior final weight and feed conversion ratio than the other treatments. They also reported that prepupa of BSF contains more than 23% carbohydrates, 32% crude proteins, and 22% crude lipids.

Grasshoppers

As a result of competition between livestock and humans for maize and soybean, there is a shortage of feedstuff. Therefore, various researches have been carried out on the use of grasshoppers (acridids) as an alternate feed for farm animals. Studies on nutritional content of *Chondacris rosea* (Orthoptera: Acrididae), *Acrida exaltata* (Orthoptera: Acrididae), *Oxya fuscovittata* (Orthoptera: Acrididae), *Spathosternum prasiniferum prasiniferum* (Orthoptera: Acrididae) and *Hieroglyphus banian* (Orthoptera: Acrididae) have revealed that, these acridids have a higher protein content than the locally available conventional feed meal, *viz.* fishmeal and soybean (Anand *et al.*, 2008; Chakravorty *et al.*, 2014). The study revealed that fishmeal replaced with acridid diet (25-30%) showed better results compared to the control diet (100% fishmeal) where all the parameters including growth of the fishes were found to be higher. Diets with *Oxya* meal used for fed on Japanese quail (*Coturnix japonica*, Galliformes: Phasianidae) progressively substituted the fishmeal. The fishmeal diet replaced with *Oxya* meal (50%) showed better growth and an increase in the number of eggs laid by the Japanese quail was observed. Replacement of fishmeal with acridids (at least 50%) to feed poultry and fish could significantly reduce the demand of fishmeal and help to reduce the market prices (Haldar, 2012).

Silkworm pupae meal

In India, different types of silkworms, *viz. B. mori*, *A. assamensis*, *Antheraea mylitta* (Lepidoptera: Saturniidae), *Antheraea paphia* (Lepidoptera: Saturniidae), *Attacus ricini* (Lepidoptera: Saturniidae), *Antheraea royeli* (Lepidoptera: Saturniidae), *Antheraea pernyi* (Lepidoptera: Saturniidae), *Antheraea proyeli* (Lepidoptera: Saturniidae), are reared commercially for many purposes (Valerie *et al.*, 2015). Based on the region, the meal prepared from silkworm pupae are known by various names, *viz.* silkworm pupae meal (SWPM), silkworm meal, silkworm pupae, spent silkworm pupae, deoiled SWPM, defatted SWPM, muga SWPM or eri SWPM (Valerie *et al.*, 2015). SWPM has a high nutritional value and consists of protein-rich feed ingredients and does not contain any toxic components (Dutta *et al.*, 2012; Swamy and Devaraj, 1994).

Limited work has been carried out in India to substitute traditional animal protein supplements in animal feed with by-products of agro-industrial origin (Dutta *et al.*, 2012). After reeling the silk thread, the silkworm pupae in the silk industry are discarded, which contains not only a high level of proteins but also are an important source of lipids, zinc, potassium, essential fatty acids such as the linolenic acid and essential amino acids such as lysine, histidine, isoleucine, leucine, threonine, and valine. They have also been used experimentally as an animal feed for pigs, chicken, cattle, rabbits and fish (Borthakur and Sharma 1998; Habib and Hasan, 1995; Pereira *et al.*, 2003; Rao, 1994).

Due to the high amount of protein, SWPM can be use as supplement in ruminants diets (Ioselevich *et al.*, 2004). SWPM could also safely replace more than 30% of groundnut cake in the fattening diets feed for the Jersey calves without affecting the growth performance (Narang and Lal, 1985). Narang and Lal (1985) reported that, protein digestibility of the SWPM diet was more than that of the groundnut cake.

In India, SWPM could completely replace the fishmeal (100%) in the diet of pigs, and it does not cause any effect on carcass, blood parameters and the meat quality (Medhi, 2011; Medhi *et al.*, 2009a,b). The silkworm excreta can also be mixed in the pig diet at a maximum recommended inclusion rate of 7%. Several researchers have carried out experiments by replacing conventional protein sources with SWPM in poultry feeds (Table 2).

Termites

About 300 species of termites have been so far reported from India, and among them, the major mound building species available in south and north-east India are *Odontotermes formosanus* (Isoptera: Termitidae), *Odontotermes obesus* (Isoptera: Termitidae), *Odontotermes redemanni* (Isoptera: Termitidae), *Microtermes obesi* (Isoptera: Termitidae) and *Microcerotermes beesoni* (Isoptera: Termitidae) (Paul *et al.*, 2018; Rajagopal, 2002). The termites *O. formosanus* not only forms an important part of the diet of many south Indian tribes such as Kannukaran, Paniyan, Palliyan, Sholaga, Irular and Kota but is also utilised as a medicine (antimicrobial agent) and poultry feed (Wilsanand, 2005). Termites can be used an alternate to poultry diet which support both growth and maintenance of the poultry (Deori *et al.*, 2019). While studying the Japanese quail (*C. japonica*), a poultry species reared for commercial egg and meat production, Deori *et al.* (2019) reported that termite meal can be used as a promising protein source for economic production of Japanese quails.

6. Requirement of connecting food security system and conservation with entomophagy in India

There is a huge knowledge gap on the prevalence and extent of entomophagy in India. Therefore, the documentation of indigenous knowledge is important. Although entomophagy can be adopted as a response to the food crisis, in some traditions or cultures, entomophagy represents a normal part of the diet and an essential seasonal source of protein. To ensure better production, management, and conservation based on traditional ecological knowledge, sustainable harvesting of edible insects is important. The combination of food security and forest conservation issues provide edible insects an opportunity for their conservation. Edible insects provide an opportunity for insect conservation by combining food security and forest conservation issues (Vantomme *et al.*, 2004). Collecting insect pests in the wild by light or chemical (pheromone) traps from the established crop can be utilised to produce food supplements or stock food (Gahukar, 2020). Collections of those pests not only protect the crop, but also benefit the environment by reducing the need to use pesticides (Gahukar, 2020). Hence in India, to evaluate the insect biodiversity and its role in entomophagy for conserving the natural resources, using traditional knowledge is essential. Edible insects can be reared using modern tools and techniques in the home gardens and sold for delicacies (Meyer-Rochow and Chakravorty, 2013). Efforts should be made to popularise, increase the commercial value and availability on demand of edible insects as food, and feed in a sustainable manner, which will also help in conservation.

7. Current stress in India on poultry and aquaculture industry

In India, one of the fastest-growing economies in the world, the government is committed to strengthening the development of infrastructure and industrialisation to further boost economic intensification. Owing to the increase in awareness among consumers about the health

Table 2. Research carried out in India on silkworm pupae meal (SWPM).

Study	Findings	Reference
Egg laying hens: assessment of normal and alternative feeds for growth	Compared to other meals, silkworm meal improved technical and economical performance (feed cost, egg size and no mortality)	Saikia *et al.*, 1971
Layer chickens: replacement of 0-100% of fish meal	SWPM can be replaced up to 100% of fish meal	Virk *et al.*, 1980
broiler feeds: effect of mineral supplementation on the nutritive value of SWPM	Substitution of fish meal more than 50% had a negative impact on growth	Reddy *et al.*, 1991
Utilisation of SWPM as a source of protein in the diet of pigs	SWPM could partly replace the soya oil cake meal in diet and it did not show any negative impact on growth of the pig	Coll *et al.*, 1992
SWPM as protein supplement in broiler chicken	Replacement of normal feed with SWPM up to 50% did not show any detrimental impact but 100% replacement showed negative impact without supplementation of calcium and phosphorus.	Purushothaman and Thirumalai, 1995
Effect of locally available undeoiled, untreated SWPM on layer chicks	Diet based on SWPM (100%) reduced intake but gained weight	Deshpande *et al.*, 1996
Effect of dietary muga silkworm supplementation on the performance of broilers	Substitution of muga SWPM (100%) did not show any adverse effect on growth of the broilers	Sapcota *et al.*, 2003
Effect of dietary muga SWPM on the breeding performance of White Leghorn males	Replacement of fish meal with SWPM up to 50% did not show any detrimental impact but 100% replacement showed negative impact on breeding performance	Mahanta *et al.*, 2004
Effect of dietary SWPM on the carcass characteristics of broilers	100% replacement of fish meal diet with muga SWPM did not show any adverse effect on carcass characteristics of broilers	Sheikh *et al.*, 2005
Economy of feeding MSPM in the diet of broiler chicken	100% replacement of fishmeal with MSPM showed superior result in terms of economics of production	Sheikh and Sapcota, 2007
Effect of feeding SWPM with enzyme supplementation on growth performance of broilers	SWPM with enzyme supplementation increased growth and reduced feed intake. 50% SWPM with supplementary enzymes showed best performance in growth of broilers	Konwar *et al.*, 2008
Effect of replacement of fish meal by de-oiled silkworm pupae on the growth performance of broiler chickens	Replacement of fishmeal (100%) with de-oiled SWPM did not show any adverse effect on growth of the broilers	Sinha *et al.*, 2009
Effect of feeding SWPM on nutrient and mineral retention in broilers	50% SWPM diet showed higher nitrogen and calcium retention than the 100% fish meal diet	Sheikh and Sapcota, 2010
Growth of poultry chicks fed on formulated feed containing SWPM as protein supplement and commercial diet	Replacement of fishmeal (50%) with SWPM resulted increased growth and economically profit due to lower cost of SWPM than the fishmeal	Dutta *et al.*, 2012
Utilisation of fermented silkworm pupae in feed for broiler chicks	Substitution of fish meal with fermented silkworm pupae showed better feed conversion ration and nonappearance of fishy taint in the meat	Rao *et al.*, 2011
Effects of enzyme supplemented diet on pigs at different levels of SWPM in diet	SWPM could completely replace fishmeal diet. SWPM with enzyme supplementation increased growth and reduced feed intake without altering the blood parameters and meat quality of the carcass pigs	Medhi, 2011; Medhi *et al.* 2009b

benefits of protein, the protein market in India is growing at a fast rate. For many people, the consumption of edible insects as a prospective food is difficult to accept due to differences in culture and a feeling of repulsion towards insects. Conversely, for therapeutic purposes and to cure different diseases, various insects are used by different ethnic groups (Meyer-Rochow, 2017). From the Asia-Pacific region, India contributes more than 8% of total proteins and edible insects marketed. Applications of edible insects are mostly for use as animal feed, followed by use as fertilisers. In India, the poultry feed and aquaculture industries mainly rely on corn, soy, and maize. Increasing prices of maize, corn, and soy crops and their products as animal feed has resulted in a reduction of profit margins of the feed producers. Consequently, during the last few years, several companies searching for alternative raw materials have identified edible insects as an alternative to high costs of production. Since the insects do not produce greenhouse gases and offer substantial advantages to crop growth and soil fertility, the demand for insect-based natural fertiliser instead of artificial fertiliser has risen, and this would offer considerable enhancements to the edible insect industry in India (Research and markets, 2018).

8. Promotion and prospects of insects as food

Engagement of the public is crucial for establishing the industry of insects as food and feed. Entomophagy could be a proficient approach to relegate the cost of living for financially challenged customers. For those customers, income saved from acquiring comparable nutrition from the edible insects instead of other foods can be emphasised. Customers are concerned about the flavour as well as quality, and it is important to let people understand that edible insects are alike to the traditional protein sources (Tang *et al.*, 2019). Till today, some people have negative perceptions towards entomophagy (Ghosh *et al.*, 2018). For the promotion of insect products, different workshops should be held (Tan and House, 2018). Promotion on TV shows, radio talks would also help in implementation of entomophagy (Tang *et al.*, 2019). Along with these, it is more crucial to make improvements of edible insects as food. Instead of raw edible insects, diversified products derived from the insects would definitely be more intriguing for consumers (Feng *et al.*, 2018). Feng *et al.* (2016) reported that to enable people cook their own insect cuisines at home, publishing guidelines of cooking insects was proven useful.

In order to influence the customers, it is essential to optimise the processing flow along with rearing, handling, drying and storage of the insect products. For this, an apparent and inclusive framework of production would definitely be helpful in assuring the potential consumers (Tang *et al.*, 2019). Cross-linking between the industries and the farmers would definitely be useful for boosting the production rate. On the other hand, developing new medicine and healthcare products from the insects would be worthwhile. A wide-ranging and thorough study of edible insects would be desirable to ascertain food security and evade possible risks.

9. Conclusions

Insect as a food and feed sector is emerging fast in India. Investigations and research in edible insects' nutritional value indicate that it can serve as a replacement for meat in the diet. However, in terms of substituting other dietary items, insect products alone cannot save the world from hunger. There are many options to design products from edible insects to make them more acceptable to the consumer, thereby encouraging the inclusion of insect-based products into regular diets. Improvement and diversification of food products derived from the insects will attract consumers. In-depth research is necessary on the processes concerned with large scale production of edible insects, *viz.* insects' diet, hygiene practices during processing, handling, transport, and storage.

Despite the rapid growth of the poultry and aquaculture industries, India has suffered due to the increasing cost of feed. Replacement of traditional fishmeal to feed fish and poultry with BSF, grasshoppers, SWPM, termites, and other edible insects could significantly reduce the demand for fishmeal and help to reduce the market prices. For the advancement of the food and feed sector, intimate cooperation of the insect industry along with the government organisations, public society, and the academic sector is indispensable.

Conflict of interest

The authors declare that there are no conflicts of interest associated with this study.

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