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The Fagara Silkworm (*Attacus Atlas L.*) under Utilized Vanya Silkworm of India

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Abstract

Non-commercial rearing of fagara silkworm (*Attacus atlas L.*) for their silk is done in India for the purpose of substituting conventional silks with 'fagara silk'. The silk has been shown to have the potential to replace ordinary silk due to the quality of the thicker cocoons, less strenuous rearing conditions, and effective fiber characteristics. It is primarily found in the tropical and subtropical rainforests of the Asian continent. The *A. atlas* is a multivoltine (2 generations/year-3 generations/year). It completes its life cycle from egg to adult within 62 days-100 days. The larvae is highly polyphagous and folivorous in nature. They feed on over 80 species of host plants, of which 6 species (*Meyna laxiflora, Terminalia catappa, Sapium insigne, Ficus carica, Juglans regia,* and *Moynalaxi flora*) can be considered as primary food plants based on rearing performance. Depending on the types of leaves the caterpillars consume, the yarns and fabrics can be golden brown or darker brown in color. The *A. atlas* has immense importance for ecosystem services as well as biomedical applications. Therefore, commercial exploration of *A. atlas* is need of the hour for the Vanya silk industry and other by-product development. It can enhance the livelihoods and sustainability of the many tribal peoples in the forest areas of India. Hence, the review article provides comprehensive and updated information on fagara silkworm and its sericulture.

Keywords: *Attacus atlas* • Biomaterial • Fagara silkworm • Host plants • Vanya silk

Introduction

Silk connotes elegance and luxury. No other fabric can rival silk's shine and elegance, even today. It has unquestionably ruled as the queen of textiles throughout history. Mulberry and non-mulberry (wild) silks are the two primary categories for natural silk. Forest or wild sericulture is the common name for non-mulberry (Vanya) sericulture. Wild silk varieties obtained globally include the Asian wild silk (Muga, Tasar, Eri and Fagara), the European silk (Coan) and the African wild silk obtained from indigenous wild silkmoths belonging to the genera *Anaphe, Gonometa, Argema* and *Epiphora* [1]. India holds a unique distinction in producing all the three kinds of non-mulberry silks, *viz*., Tasar, Eri, and Muga silks, produced by *Antherae amylitta* Drury and *Antheraea pernyi, Samia cynthia Ricini* Boisduval, and *Antheraea assamensis* Westwood, respectively, belonging to the family Saturniidae. The northeast region of India is an ideal natural home for a variety of silkworms. A total of 47 species of silkworms are recorded from India, out of which 24 are reported from the northeast region [2]. Wild silk moth culture not only has an economic bearing on the local inhabitants of north-eastern India but also helps to save the forest ecosystem [3]. There is a great potential to develop a sericulture industry based on wild silkworm moths, which will help the people earn some coins for their better livelihood rather than traditional cultivation [4]. India, which ranks second in the world for silk production, is renowned for its diversity. The country produced a total of 34,903 MT of raw silk during 2021-2022. Of which mulberry silk is 25, 818 MT and Vanya (wild) silk is 9,087 MT while contribution of each Vanya silk towards total production are, 1.466 MT, 7,364 MT, and 255 MT of Tasar, Eri, and Muga silks, respectively. A total of Rs. 1848.96 crore (US$ 248.56 million) is made on silk exports [5].

A gigantic saturniid moth that is unique to the woodlands of Asia is called the fagara moth (*Attacus atlas L.*). The name *Atlas* comes from the Greek mythological Titan of the same name (due to its size). The Cantonese term "snake's head moth" refers to the conspicuous forewing extension that resembles the head of a snake in Hong Kong [6]. It is widely distributed in the tropical and sub-tropical forests of Southeast Asia and India [7]. This species has also been reported from the Western Ghats, Deradhun, the Konkan region, Assam, Sikkim, Nagaland, and Tripura in India [8]. The large cocoons of *Attacus atlas* have similar properties to those of the silk moth *Bombyx mori* and thus offer an alternative form of silk production [9]. The tan to brown silk of *Atlas* moths has been used in East Asia to weave the naturally brown textile fagara silk [10]. Its fiber silk character is acknowledged to be better than the mulberry silk, especially for its

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softness, coolness, not easily crumpled, better hot resistance, and also possesses antibacterial activity [11]. Durable silk made from its cocoon is known in India as "fagara silk" and in Assam as "Kotkori Muga." To avoid confusion with some ikat fabrics made of mulberry silk from Uzbekistan, which are also known as *atlas* silk, the Javanese refer to it as *atlas* silk. Atakas's silk has a very high potential to be promoted as an export commodity either as raw material or as a derivative product [12]. Thus, *A. atlas* conservation and exploitation in silk production is an essential component of wild silk technology development in India [13].

The cocoons of *Attacus atlas* can be processed into biocompatible film for medical applications [14]. Natural brown silk biomaterial from *A. atlas* is a biopolymer that has many advantages compared to commercial silk from *Bombyx mori L*. [15]. The *A. atlas* fibers show considerably higher attachment and proliferation of cells than *B. mori* silk and extensive growth of F-actin, demonstrating that the fibers are biocompatible and that they are suitable for the tissue culture and other medical applications [16]. Degummed fibers of *A. atlas* can be used for culture of human osteosarcoma cell lines as a regenerative medicine. The *A. atlas* silk has potential for surgical suture thread as new biomaterial expectation. A biocompatible fiber for future application as sutures is possible to be prepared by *A. atlas*. The *A. atlas* cocoon extract has also been proven to protect Bt from UV damage. Due to its sericin content, *A. atlas* extract is thus able to improve the pathogenicity of baculovirus (NPV) in controlling lepidopteron pests. *Atlas* moths act as tree defoliators as larvae. It may allow more light to reach the forest floor, thus allowing new plants to grow. Due to their ease of care and docile activity levels, *Atlas* moths are popular in the pet trade due to their example of insect diversity and adaptation [17].

Literature Review

Species diversity and their distribution

The genus *Attacus linnaeus* has been revised taxonomically where the immature and adult stages are characterized morphologically. The moths are known by region specifically 'Spinner' in Germany; 'Kupu and Gajah' in Indonesia, 'Vlinder' in Netherlands, 'A Wujiao Can' and 'Zhu-Ze Can' in china. The preferred scientific name was *Attacus atlas* (Linnaeus) and preferred common name are *Atlas* moth. There are 48 names proposed to date, it was found that only 12 represent valid species they were *Attacus atlas baliensis* Jurriaanse and Lindemans, *Attacus atlas burmaensis* Jurriaanse and Lindemans, *Attacus atlas chinensis* Bouvier, *Attacus atlas gladiator* Fruhstorfer, *Attacus atlas simalurana* Watson, *Attacus atlas sumatranus* Fruhstorfer from southeastern Asia and the Greater Sunda Islands, *Phalaena arcuata vitrea* Perry, *Samia atlas* Kawada and *Saturnia silhetica* Helfer. and some of the related species are *A aurantiacus* W. Rothschild from the Key Islands; *A. caesar* Maassen from the southern Philippines; *A. crameri* C. Felder from the Moluccas; *A. dohertyi* W. Rothschild from Timor; *A. erebus* Fruhstorfer from Celebes; *A. inopinatus* Jurriaanse and Lindemans from Flores and Sumba; *A. intermedius* Jurriaanse and Lindemans from the Tanimbar Islands, *A. lorquinii* C. and R. Felder from the Philippines; *A. mcmulleni* Watson from the Andamans; *A. taprobanis* Moore from Sri Lanka and southern India; and A. wardi W. Rothschild from northern Australia. The EPPO (European and Mediterranean Plant Protection Organization) code for *Attacus atlas* is ATTCAT to recognize globally.

The *Attacus atlas* is primarily found in tropical and subtropical rainforests. These forests do not have four seasons, but rather a dry and a wet season. They are characterized by closed canopies, broad-leafed evergreen trees, and temperatures approaching but not exceeding 25°C. The *A. atlas* is widely considered to occupy habitats at elevations ranging from sea level to 1500 m to 2000 m. Some of the species are Java (six subspecies), India (five subspecies), Sumatra (four subspecies), southern China (three subspecies), Sri Lanka (one subspecies), Malaya (one subspecies), Andamans (one subspecies), Simalur (one subspecies), Borneo (one subspecies), Sulawesi (one subspecies), Bali (one subspecies), and four subspecies in Myanmar, Thailand, Laos, and Vietnam [18]. The *A. atlas* formosanus Villiard. Huang, et al., is the largest moth and the endemic subspecies of Taiwan.

General biology and life cycle

The life cycle of *Attacus atlas* occurs in four main life stages typical of Lepidoptera, undergoing complete metamorphosis. It produces one generation in 78 days to 100 days, with egg, larval, and pupal stages lasting 8-10, 32-45, and 38 days-45 days, respectively. The fertilized eggs are laid on a host plant by the female moth, where they emerge a week or two later as first instar caterpillars. Instars are the distinct larval periods of growth that are separated by ecdysis (the shedding of the exoskeleton). *Atlas* moths have five larval instars, though a sixth instar has recently been recorded. The final larval instar, the caterpillar, spins silk around itself to form the cocoon where it pupates for about one to one and a half months. The pupa may go through diapause in the winter. The adult moths emerge from the cocoon during the morning and remain there for 8 hours to 10 hours while their wings expand and harden [19]. They are sexually mature at this stage and will seek mates of the opposite sex for reproduction.

Stages

Egg: The eggs are yellowish white to pale yellow and are oval, having polygonal punctuations and flattened, consistent with all moths in the family Saturniidae (Bhawane et al., 2011). They are covered in a gummy substance used for attachment to each other and the leaves (Sathe and Kavane). The size ranges from 2.7 mm to 3 mm in length and 2.1 mm to 2.7 mm in width. The eggs' weight is roughly 0.0078 g ± 0.001 g. The incubation period of eggs ranged from 6 to 12 days, with a mean period of 9.2 days [20].

Larva: The larvae are pale green with orange or brownish speckles and a bright orange ring on the anal somite, and have 5-6 instars.

First instar: The newly hatched larvae have a smooth, black head. pinkish-gray body with brownish stripes. In the inter-segmental area, there are black irregular marks. Tubercles are pale in colour and have black setae. The larvae measure 1.12 cm ± 0.28 cm in length and 0.19 cm ± 0.07 cm in width, with a weight of around 0.017 ± 0.02 g. The first instar larval duration is 4 days-5 days.

Second instar: The larva is dull white with irregular markings and whitish tubercles. Deep orange elongated markings appear in the anterior and posterior lateral regions of the body. The pro-thoracic hood is soft, transparent, and whitish in colour. The larvae measure

1.96 ± 0.40 cm and 0.72 cm ± 0.29 cm in length and breadth, respectively, and weigh 0.32 g ± 0.10 g. The duration of this stage is 8 days-10 days. There is a white waxy substance on the dorsal side of the larval body which begins developing in the 2nd instar. The first two instars have darker heads and body coloration between the scoli.

Third instar: The body is ice white to greenish, with or without white fleshy tubercles. The length, breadth, and weight of the larvae are 3.82 cm ± 1.14 cm, 1.2 cm ± 0.22 cm and 3.612 g ± 0.98 g, respectively. The instar duration is 13 days-14 days.

Fourth instar: The larva is greenish and the whole body is covered with a lime-like powder. The length, breadth, and weight are 6.38cm ± 0.69 cm, 1.8 cm ± 0.28 cm and 18.0 g ± 0.28 g respectively. This instar lasts for 10 days-11 days.

Fifth instar: The larval body is greenish but covered with a lime-like sticky powder. The dorsal tubercles are whitish, whereas the lateral tubercles are blue with black tips. The thoracic legs are conical and carry sharp distal claws. Each abdominal segment from 6th to 9th bears a pair of abdominal legs, which are fleshy and flat at the end. The terminal end looks like a disc with a series of inwardly curved hooks arranged in a semi-circle. While dorsal tubercles project backward, the lateral tubercles project forward. The length, breadth, and weight are 10.06 cm ± 0.82 cm, 2.08 cm ± 0.11 cm and 25.08 g± 1.22 g respectively. This instar lasts for 12 days-13 days.

Sixth instar: The larva is the same as the fifth instar larva. In terms of size, weight, and larval duration, the difference is observed only in the sixth instar. The length, breadth, and weight are 12.8 cm ± 0.89 cm, 2.87 cm ± 0.11 cm and 30.39 g ± 1.5 g respectively, with a larval duration of 14 days-15 days. The body length varies from 8 to 10 mm in the first instar to 88 mm to 92 mm in the fifth and sixth instars. The 1st, 2nd, and 3rd somites have dorsal protrusions. The 4th through 11th somites have dorsal and subdorsal blueish green scoli (branched, thickened spines protruding from the body) and black lateral scoli below the spiracles.

Note: There are a few key differences between the larvae of *A. atlas* and the related species *Attacus lorquinii* and *Attacus caesar*. The scoli of *A. atlas* are flattened and greenish, whereas those of A. lorquinii are rounded yellow knobs about 2 mm long, and those of *A. caesar* are flattened and yellowish.The patch on the anal prolegs of mature *A. atlas* larvae is a light greenish blue surrounded by a bright orange ring. In *A. lorquinii*, the patch is solid brownish orange and in *A. caesar* it is solid brownish orange with a bright yellow edge.

Pupa: The *A. atlas* pupae are typically lepidopteran obtects. The Pupa's colour is brownish yellow to dark brown. The length of the pupa ranged from 35 to 40 mm, with a mean of 38.7 mm. The pupal duration ranged from 35 days to 45 days, with a mean of 40.5 days. In the Indonesian climate, the pupal period in *A. atlas* ranged from 27 to 31 days. The pupal sex dimorphic characters observed are larger and heavier for female pupae than for male pupae. The average weight of female pupa was 5.34 g and 4.20 g for male pupa. Antennal covers are wider in males than in females. In the female pupa, there are two openings at the ventral and posterior sides of the pupa. The elongated slit like midventral side of the 8th abdominal segment is the opening of Bursa copulatrix, that is, ostium bursae, and on the midventral side of the 9th abdominal segment is the female genital opening, or gonopores, for egg deposition. In the male, a single oval opening is observed on the mid ventral side of the 9th abdominal segment. A blunt pair of sustentores on the ventral side of the 10th abdominal segment, the cremaster is prominent, blunt and rounded.

Adult: The female *Atlas* moths are larger than the males. The body length is ranged from 39 mm to 40 mm in females and 30 mm to 36 mm in males, and the wingspan ranged from 240 mm to 250 mm in females and 210 mm to 230 mm in males. The forewing in males is 73 mm to 125 mm long with a mean of 102 mm, and the hindwing is about 48 mm to 72 mm long with a mean of 69 mm. In females, the forewing is 93 mm to 131 mm long (a mean of 119 mm) and the hindwing is 76 mm to 101 mm long. The wingspan is among the top five largest moths in the world. The shape of the wings is rounded, with the forewing having a protrusion from the anterior distal edge. The base of the wing is colored deep orange, soft brown, or deep reddish brown and is patterned with white, black, brown, and pink coloration, with a large white triangular hyaline spot in the centre of each wing. The protrusions and edges of the wings resemble the head and body of a snake. The undersides of the wings are pattered the same as the dorsal sides but may be paler in color. The mouthparts of the adult are non-functioning, with some parts disfigured or completely absent. They have two large compound eyes. They have two yellowish brown bipectinate antennae, meaning the antennae are comb like on both sides. The antennae measure 23 mm to 39 mm long and 10 mm to 13 mm wide in males and 17 mm to 21 mm long and 3 mm wide in females. The body is reddish to orangish brown and can vary in shade.

Note: The *Attacus atlas* is distinguishable from other similar moth species in the genus *G. Attacus* by the presence of a patch of yellow or orange above and below the red dash in conjunction with a prominent white component of the postmedian and antemedian lines. The red dash is longer and thicker in *A. atlas* than in *A. mcmulleni*, which bears a similar resemblance. Large wings, each with a large hyaline triangular spot that is more or less irregular: forewing triangular; costa much arched, apex lengthened, convex and falcate, exterior margin oblique, posterior angle rounded; cell short, broad, open; subcostal with five branches, first emitted at one-half distance between base and fourth, second near to first, bifid, the third starting from below at a short distance from its base; median recurved, arched at its base, three-branched, lower branch at half the The orange-brown colored antenna is about 19 mm to 20 mm in length and 3 mm to 4 mm in breadth. Immediately after the emergence from the cocoon, adults remain in the cocoon for a few hours till the wings get spread. Adults are large crepuscular flying moths. Antennae are bipectinate in both sexes. The legs are short and hairy, with no spurs., thorax, and abdomen are all dark red. The basal segment and abdomen are pale, and each segment is fringed with pale fringe. Females are usually larger than males. The body length of females ranged from 39 mm to 40 mm, with a mean of 39.4 mm. The wing expanse of females ranged from 240 mm to 250 mm with a mean of 246 mm, while in males the body length ranged from 30 mm to 36 mm with a mean of 35 mm. The wing expanse in males ranged from 210 mm to 230 mm, with a mean of 217 mm.

Reproduction

Female and male moths are sexually mature upon emergence from the pupal stage. Female moths attract males by releasing pheromones, which are detected by the large feathery antennae of the males, who follow the pheromones in order to find the female.

They are active at dusk and pair for up to 24 hours, during which time the male deposits sperm into the female to fertilize her eggs. Males may be able to mate multiple times depending on how long it takes to find a mate and couple with her, but females are monandrous (only mate with one male). The only documented case of polyandry in the moth family Saturniidae is with *promethea* moths. Therefore, *atlas* moths do not likely exhibit polyandrous mating. The female *atlas* moths are oviparous, laying 134 eggs to 169 eggs scattered on the leaves of host plants, which are identified in the "Food Habits" section and include cardamom, mango, and tea plants. They are semelparous, mating once and laying eggs during a single week of their adult lives (Figure 1).

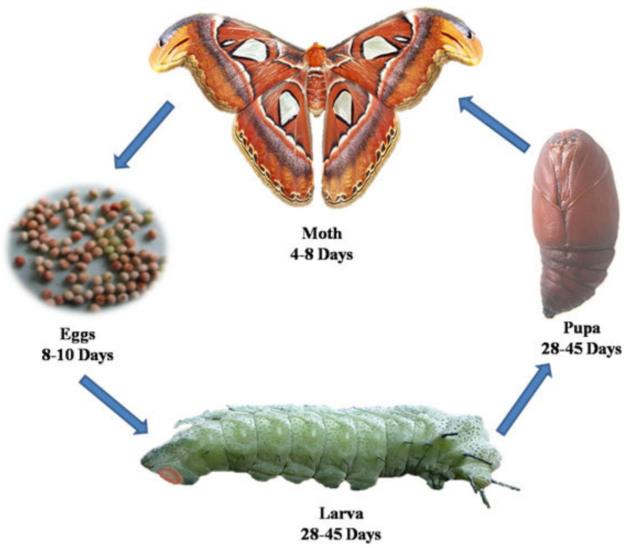

Figure 1. General life cycle of the fagara silkworm (*Attacus atlas L.*).

Ethology

The *Atlas* moths spend the majority of their lives on a single tree: Laying on the leaves as eggs, eating the leaves as larvae, pupating off the branches, and resting in wait for a male mate as an adult female. The caterpillars have three pairs of true legs on the thorax and four pairs of prolegs on the abdomen that assist in the slinking, worm-like walking of caterpillars as well as aid in grasping onto plant material. The larvae spend the majority of their time eating leaves in trees and only stop once they are fully grown and ready to pupate. Once adults emerge, the large wings of the moths allow them to fly in order to find mates and escape predators. While more than one moth may live in the same tree, these animals are solitary. The adults are crepuscular, active at dusk and dawn, with the males flying to find a female to mate with in the evenings. *Atlas* moths perceive the environment primarily through chemoreception (taste and smell), and secondarily by mechanoreception (touch). Interestingly, female *atlas* moths do not respond to the mating pheromones they or other females of their species produce. The lifespan of *A. atlas* varies slightly, depending on the host plant the larvae are reared on. The longevity of adults will vary depending on their activity levels since adults do not feed. Instead, they live off stored fat from the larval stage. Females typically live longer than males. The longest life stages are the larval and pupal stages. The 1st larval instar is the shortest and the 5th larval instar is the longest.

Genetics, genomics and breeding

The *Attacus atlas* chromosomes are numerous, *i.e.* haploid chromosomes n=31,32,33,34, chromosomal shape holocentric type (have a lot of the centromere) and small size. Variations in chromosome number proceed from holocentric chromosoms are easy due to fragmentation and there are supernurerary chromosomes. The mitogenome of *A. atlas* is a circular molecule of 15,282 bp long, and its nucleotide composition is heavily biassed towards As and Ts, accounting for 79.30%. This genome comprises 13 Protein Coding Genes (PCGs), two ribosomal RNA genes (rRNAs), 22 transfer RNA genes (tRNAs), and an A+T-rich region. It is of note that this genome exhibits a slightly positive AT skew, which is different from the other known Saturniidae species. All PCGs are initiated by ATN codons, except for COI with CGA instead. Only six PCGs use a common stop codon of TAA or TAG, whereas the remaining seven use an incomplete termination codon of T or TA. All tRNAs have the typical clover leaf structure, with an exception for tRNASer (AGN). The *A. atlas* A+T rich region contains non-repetitive sequences but harbours several features common to the Bombycoidea insects. The maximum likelihood phylogenetic relationships provide a well supported outline of Saturniidae, which is consistent with traditional morphological classification and recent molecular work. Pratiwi (2014) analyses the genetic variation of *A. Atlas* based on ISSR markers, which were obtained from different geographic locations. There was large variation in the hybrid progeny of distant hybridization between *Attacus atlas* (♀ and *Attacus cynthia* (♂ and their characteristics are intermediate between those of the parents. Using the hand pairing technique, a hybrid cross has been performed between *Attacus lorquinii* (male) and *Attacus atlas* (female). This hybrid cross has resulted in viable but sterile offspring. Adults show features of both species, and hybrid eggs hatch at a low percentage, generally 20% to 50%.

Host plants

Peigler identified over 80 species in over 40 genera of plants that are host plants for species in the genus *Attacus*. Of these, *Averrhoa carambola* (carambola), *Cinchona officinalis* (Cinchona tree), *Elettaria cardamomum* (cardamom), *Litchi chinensis* (lichi), *Mangifera indica* (mango), *Persea americana* (avocado), *Psidium guajava* (guava), *Swietenia macrophylla* (big leaf mahogany), and *Syzygium samarangense* (water apple) are the main hosts of *Attacus atlas*. An additional 21 hosts have also been identified, including tea, cocoa, and pepper plants (Table 1).

Name of host plant	Family	References
Camellia sinensis	Theaceae.	Handschin, 1946
Araucauria sp.	Araucariaceae	Michener, 1952

Phyllanthus emblica	Phyllanthaceae	Peigler,1989
Ocimum sanctum	Lamiaceae	Peigler,1989
Sapium insegne	Malpighiales	Peigler,1989
Avicennia alba	Verbenaceae	Murphy, 1990
Syzygium aromaticum	Myrtaceae	Nazar, 1990
Rhizophora mucronata	Rhizophoraceae	Veenakumari et al., 1992
Rhizophora apiculata	Rhizophoraceae	Veenakumari et al., 1992
Vitex sp.	Lamiaceae	Veenakumari et al., 1992
Zanthoxylum sp.	Rutaceae	Veenakumari et al., 1992
Meyna laxiflora	Rubiaceae	Saikia ans Handique, 1998
Terminalia arjuna	Combretaceae	Rajadurai et. al, 1998
Terminalia tomentosa	Combretaceae	Rajadurai et. al, 1998
Zizipus mauritiana	Rhamnaceae	Rajadurai et. al, 1998
Embelia acutipetalum	Primulaceae	Palkar, 2008
Xylocarpus granatum Koen	Meliaceae	Jugale et al., 2010
Ficus carica	Moraceae	Kavane and Sathe 2011
Holorrhena antidysentrica	Apocynaceae	Bhawane, 2011
Terminalia catappa,	Combretaceae	Bhawane, 2011
Ailanthus excelsa	Simaroubaceae	Ahmed, 2013
Eucalyptus sp.	Myrtaceae	Kavane, 2015
Thespecia populnea	Malvaceae	Kavane, 2015
Citrus lemon	Euphorbiaceae	Kavane, 2015
Mangifera indica	Anacardiaceae	Kavane, 2015
Casurina sp.	Casuarinaceae	Kavane, 2015
Ricinus communis	Euphorbiaceae	Kavane, 2015
Psidium guajava	Myrtaceae	Kavane, 2015
Annona squamosa.	Annonaceae	Kavane, 2015
Barringtonia asiatica	Lecythidaceae	Hidayati and Nuringtyas, 2016
Cananga odorata	Annonaceae	Nindhia et al., 2017
Erythrina variegate	Fabaceae	Nindhia et al., 2018.
Annona muricata	Annonaceae	CAB International, 2020
Camellia sinensis	Theaceae.	CAB International 2020
Ceiba pentandra	Malvaceae	CAB International, 2020
Cinnamomum verum	Lauraceae	CAB International, 2020
Elettaria cardamomum	Zingiberaceae	CAB International, 2020
Rosa-sinensis	Malvaceae	CAB International, 2020
Persea americana	Lauraceae	CAB International, 2020
Swietenia macrophylla	Meliaceae	CAB International, 2020
Syzygium aqueum	Myrtaceae	CAB International, 2020

Syzygium samarangense	Myrtaceae	CAB International, 2020
Vernicia montana	Euphorbiaceae	CAB International, 2020
Averrhoa carambola	Oxalidaceae	CAB International, 2020
Carica papaya	Caricaceae	CAB International, 2020
Cinchona officinalis	Cinchonaceae	CAB International, 2020
Cinnamomum camphora	Lauraceae	CAB International, 2020
Curcuma longa	Zingiberaceae	CAB International, 2020
L*itchi chinensis*	Sapindaceae	CAB International, 2020
Nephelium lappaceum	Sapindaceae	CAB International, 2020
Swietenia mahagoni	Meliaceae	CAB International, 2020
Syzygium malaccense	Myrtales	CAB International, 2020
Theobroma cacao	Malvaceae	CAB International, 2020
Litsea polyantha	Lauraceae	CAB International, 2020

Table 1. List of *Attacus atlas* host plants.

Influence of host plants on the silkworm's physiology: *Atlas* moths are folivores as larvae, consuming only the leaves of host plants rather than flowers, woody stems, roots, or any other plant parts. They prefer the mature leaves of small trees (2 meters-5 meters in height) and do not tend to consume developing leaves. Because the other life stages (egg, pupa, and adult) do not consume food, the large growing larvae must consume large amounts of leaves to store enough energy to carry out future life processes. According to Hamamura, good quality of moisture, protein, fat, and fiber content in leaves would increase feeding activity and feed consumption of *A. atlas*. The suitable feed for larvae should contain complete nutrition to produce a good quality silkworm, *A. atlas*. Villard noted that greater success in the rearing of *Attacus larvae*, particularly later instars, could be achieved by feeding them on a mixed diet. Bhawane et al, attempted to identify potential *A. atlas* food plants by using the leaves of *Embelia ribes, Holorrhena antidysentrica, Terminalia tomentosa, Terminalia arjuna, Terminalia catappa, Ficus carica*, and *Sapium insigne*, but the caterpillars preferred only the *Sapium insigne* leaves.

Saikia and Handique studied the life cycle of *A. atlas* by providing the main food plant, *Meyna laxiflora*, under which the incubation period of eggs was 10 days, the larval period was 28 days, and the pupal duration was 28 days. The adult male survived for 2 days-3 days and the female lasted 4 days-6 days. The rearing of the fagara silk moth *A. atlas* was done on *Terminalia catappa* under indoor rearing conditions. The *A. atlas* completed its life cycle from egg to adult within 62 days. Incubation period, larval (six instars), and pupa period: 10 days, 27.5 days, and 25 days, respectively. The findings of *T. catappa* as a potential new host for fagara silkworm have opened new vistas in promoting Vanya silk. Kavane and Sathe studied its biology on the host plant *Ficus carica*, and the silkworm completed its life cycle in 64.5 days, as previously reported. The cocoon formation takes place within 35 days to 43 days (average 40 days) when *A. atlas* silkworms are reared on Angeer (*Ficus carica*) leaves. The cocoon weight, shell weight, length of shell, width of shell, and shell thickness were 9.42 g, 1.82 g, 4.4 cm, 1.4 cm and 0.21 mm, respectively, while the shell ratio was 19.32 percent. The rearing success of *A. atlas* silkworms on Angeer (*Ficus carica*) leaves was 22 percent. On an average, a single mated female laid 147.0 eggs and produced 22 offspring, with an average sex ratio (m: f) of 1:0.75. The longevity of adult moths averaged 4 days in males and 6 days in females. The embryonic period and total larval duration were 10.8 days and 41 days, respectively, while the pupal period was recorded at 20 days in males and 21 days in females. The cocoon weight, shell weight, and shell ratio were measured as 12.98 g, 1.698 g, and 13.06% in males and 15.65 g, 1.790 g, and 11.45% in females when reared on *Litsaea monopetala Juss*.

The cocoons of *A. atlas* are very similar to Eri cocoons when the larvae feed on *Moyna laxiflora* leaves and are useful for commercial silk production. The average cocoon weight is 14.11 g and 10.29 g for males and females, respectively. When the *A. atlas* was fed Ailanthus excelsa, the average shell weight of a single cocoon was 2.04 g and 1.84 g for female and male, respectively, which is five times more than the shell weight of the domesticated Eri silkworm, *Samia ricini*. The coloration of cocoons of *A. atlas* varies according to the host plant, from brownish black to brownish yellow and whitish. Larvae fed on *Citrus medica* L. made a cocoon of pale yellow, drying to white, whereas caterpillars reared on *Psidium guajava* made a cocoon of brick red, drying to a rather dirty brown. The caterpillars are reared on *Sapium insegne*, and the larvae are made into greyish to light brown cocoons. Feeding the silkworm with *cananga odorata* results in a cocoon that is rich in Calcium (Ca) with a cubic crystal shape while feeding the larvae with *Erythrina variegate* resulting the cocoon contains rich Chlorine (Cl) around 2.96 mass percentage. *A. atlas* silkworms that are fed *Barringtonia asiatica* will produce cocoons containing secondary metabolites such as alkaloids, tannins, and flavonoids.

Rearing technology

Due to environmental changes and effects, the mortality rate of *A. atlas* was very high, which may have reached 90%. The main natural problems related to environmental factors that cannot be controlled, such as temperature, humidity, rainfall, light, types of feed available, and diseases caused by parasites and predators, were suggested as factors associated with such high mortality. Therefore, one of the alternative solutions to improve productivity is to apply intensive management by keeping the insect in an appropriate housing system with feeding and suitable environmental conditions. *A. atlas* often encountered some natural problems, including the unbalanced number of males and females in the population for fair matings, the shorter life cycle of males than females, and some of the eggs produced are infertile. Therefore, optimum use of imago in mating systems, appropriate feed, and feeding through intensive management may improve the reproductive performance of *A. atlas*.

Kavane and Sathe developed a preliminary new technology for fagara silkworm rearing under indoor conditions. Desmawita et al, reported the desirable environmental (temperature, humidity, and light) conditions in the rearing house for fagara silkworm. Further, the optimum and efficient time suggested for mating is six hours, resulting in high egg production. The walnut leaves feed have a better effect on the first and second instars of larvae, while the guava leaves affect the following instars. In terms of production, four times the feeding frequency per day has higher productivity and is recommended in the cultivation management of *A. atlas*. A mature repining larva constructs its cocoon on fresh leaves and suspends it from the twig with the help of a long stalk. It spins its silk fiber around its body with the help of spinnerets and tubercles. The cocoon quality has shown to be satisfactory when silkworms are grown in the indoor rearing technique, which is normally spun by the worms in naturally growing conditions (Table 2).

Instars	Duration (Days)	Feeding time per day	Total Feeding time	Feeding dose (Kg)	Leaf proportion (g)	Leaf order taken for feeding	Leaf size	No. of boxes	No. of trays	Box/ Tray cleaning time	Moulting duration	Humidity (%)	Temperature (°C)	Bed size (Sq ft)
First	5	1	5	1-15	40-50	2-3 (Top)	Whole	1	-	2	24	75	28-30	1
Second	04-May	2	9	2-2.5	50-60	3-4(top/ medium)	Whole	1	-	2	48	75	28-30	3
Third	4	2	8	03-4	50-60	Medium/ Matured	Whole	-	1	3	72	80	28-30	6
Fourth	6	5	12	4.5-5	65-75	Medium/ Matured	Whole	-	1	once at every morning	72	80	28-30	10
Fifth	7	2	18	4.5-5	75-85	Medium/ Matured	Whole	-	1	once at every morning	-	80	28-30	16

Table 2. Requirements for rearing one DFL(50 eggs) for *A. atlas* silk worms.

Artificial diets: The *Atlas* moth has been reared on an artificial diet with modifications of diet ingredients originally developed for *Antheraea mylitta* by Situmorang. The diet was modified by replacing arjun (*Terminalia arjuna*) leaf powder with *Barringtonia* and *Chlorella* with bee pollen. Sukirno et al. evaluated four plant species such as *barringtonia* (*Barringtonia asiatica*), cheesewood (*Nauclea orientalis*), soursop (*Annona muricata*), and mahogany (*Swietenia mahagoni*) as the basic components of each diet. The survival, cocoon quality, and hemolymph protein content of larvae fed the *Barringtonia* diet are higher than those of larvae fed mahogany-, cheesewood-, and soursop based artificial diets. The average adult emergence of those fed the *Barringtonia* based diet was 74.5%. The weights of the cocoons in this treatment with the pupa and the empty cocoons were 7.0 g and 1.1 g, respectively. The hemolymph of the larvae fed the *Barringtonia* based artificial diet had the highest concentration of protein, with an average of 28.06 mg/ml. The *atlas* moth reared on the *Barringtonia* based artificial diet was comparable with those reared only on *Barringtonia* leaves (Table 3).

Ingredients	Quantity
Leaf powder (g)	35
Cellulose powder (g)	5
Corn bee pollen (g)	30
Low fat soya bean powder (g)	5
Vitamin C (g)	1.5
K_2HPO_4 2- (g)	0.8
$CaCO_3$ (g)	0.96
Fe_2PO_3 (g)	0.16
Chloramphenicol (g)	0.08

Acrylic acid (ml)	0.8
Vitamin B complex (g)	0.06
Sorbic acid (g)	0.08
Agar (g)	8.43
Distilled water (ml)	400

Table 3. The ingredients of the *Barringtonia* based artificial diets.

Natural enemies

Predation and defense: As larvae, the green coloration of *Attacus atlas* offers camouflage against the green host leaves. The wax secreted by the caterpillars may also discourage predation by mimicking bird droppings or a dead larva infected with a white fungus, though this has not been tested. Caterpillars also spray irritating compounds, including vertebrate neurotransmitters, from small holes in their abdominal scoli when vigorously touched, likely as a defense against birds. The hanging cocoons are hidden among the leaves of host plants and hang so that if pecked they swing back and forth and thus are more difficult for birds to pierce. The large size of *A. atlas* in its adult stage aids in defense against vertebrate predators, especially mammals and birds, by discouraging attack and perhaps frightening them. The wings of moths in the genus *Attacus* resemble snakes and, if threatened, may drop to the ground and thrash around like a snake uncoiling, or else feign death and attempt to blend in with the ground. Furthermore, since predators, especially birds, tend to attack the circular spots and the elongated sections of the wings, the moth can escape from an attack with its body intact and retain the ability to fly even with large amounts of wing damage. Because *A. atlas* occupies a large number of host plants, parasites and predators are less likely to learn to target only a few plants in search of hosts and prey.

Parasites: Each metamorphic stages of Atacus moth are associated or affected with the arthropod parasites. Eggs specific parasites are *Agiommatus attaci, Anastatus colemani, Anastatus menzeli, Mesocomys menzeli, Ooencyrtus phoebi, Telenomus attaci* and Tetrastichus. The larval stages have Commensal relationship with *Apanteles, Blepharipa wainwrighti, Enicospilus plicatus,* and *Exorista bombycis* parasites. Similarly, the most physiologically active and physically inactive pupal stage are affected by *Theronia zebra, Xanthopimpla brullei* and *Xanthopimpla konowi*.

Silk technology

Cocoon characters: The *Atacus atlas* larvae spin light-brown cocoons with distinct peduncle peduncles of varying lengths (2 cm to 10 cm). Usually, cocoons are spun into highly variable shapes, sizes, coloration, and textures. The length, breadth, and weight are 8.2 cm ± 1.02 cm, 2.8 cm ± 0.22 cm and 12.98 ± 0.89 g for the male cocoon and 9.24 cm ± 1.18 cm, 3.46 cm ± 0.32 cm, 15.65 g ± 0.66 g for the female. The coloration of cocoons of *A. atlas* varies according to the host plant, from brownish black to brownish yellow and whitish. The *A. atlas* cocoons are constructed in three distinct layers. The outer layer was loosely attached, was paper-like, and had a thickness of 0.5 mm ± 0.2 mm and accounted for approximately 23% of the total weight of the cocoon. In comparison, a middle or intermediate layer with a thickness of 0.6 mm ± 0.2 mm formed the bulk of the cocoons and accounted for 43% of the weight of the cocoon. The intermediate layer contains most of the fibers and is loosely connected to the outer layer but very tightly connected to the inner layer. The innermost layer accounted for approximately 34% of the weight of the cocoon and had an average thickness of 0.20 mm ± 0.09 mm. The size of the layers decreased progressively from the outer layer to the inner layer. *A. atlas* cocoon contains 2 types of protein, fibroin protein and sericin protein. Fibroin protein makes up 70%-80% of *A. atlas* silkworm cocoon layer while sericin protein makes up 20%-30% of the cocoon layer of *A. atlas* (Figure 2).

Figure 2. A Fagara cocoon.

Silk reeling: The *A. atlas* cocoons are manually divided into three layers. The three layers have to be degummed individually using ethylenediamene and sodium carbonate. Cocoon layers are immersed for 1 hour at 80°C in a solution of 10% ethylenediamine and 0.5 percent sodium carbonate, with a solution to cocoon ratio of 20:1. After that, the cocoons are rinsed in water and retreated for 15 minutes in an ethylenediamine and sodium carbonate solution at 80°C to finish the degumming and yield loose fibres. Among the three layers of the cocoons, the outer layer of *A. atlas* cocoons had the highest degumming loss of 22%, followed by the inner and intermediate layers with degumming losses of 10% and 7.3%, respectively. Degummed silk is properly washed in water and dried at room temperature. However, Nindhia, et al. reported that cocoons treated with 100 mM NaOH concentration and thorough washing are beneficial for reeling in *A. atlas* cocoons. Furthermore, the cocoons obtained after degumming or without degumming are hand-woven similar to spun yarn. Also, recently, the reeling of *A. atlas* by wet reeling in water at room temperature at a reeling speed of 103 mm/s demonstrates that the reeling of *A. atlas* cocoon is easier than that of Tasar, Muga, and Eri cocoon but more difficult than that of mulberry cocoon. The woven fabric is always the natural brown and beige colors, but no evidence of coloring of *A. atlas* cloth has been documented so far. Ipele, handbags, shoes, coats, shirts, lampshades, and scarves are among the items commercially available in markets. The "*Attacus silk*," as it is known in Indonesia, is also sold to Japan for the production of obis. An obi is a long, broad belt worn with a kimono (Figure 3).

Figure 3. Fabric of 100% fagara silk (*Attacus atlas L.*)

Discussion

Properties of fagara silk fiber

Morphology of the fibers: The morphology of the *A. atlas* fibers after degummed fibers has a clean and smooth surface, is flat and ribbon like, and has a solid cross-section. The morphology of the *A. atlas* fibers is similar to that of the wild silk but different than the *B. mori* silk that has a triangular cross-section.

Chemical properties: Silk produced by A. atlas has a considerably different composition of amino acids than common silk. Among the major amino acids, *A. atlas* has more than twice the tyrosine and about 53% higher alanine but about 50% lower glycine and 56% lower serine content than *B. mori* silk. However, the alanine and glycine content in *A. atlas* silk is similar to that of the wild silks. The glycine/alanine ratio for *A. atlas* silk is 0.5, much lower than that of mulberry (1.5) and the common wild silks (0.8). The amount of glycine and alanine determines the crystallographic form of the proteins. The lower ratio of glycine to alanine in *A. atlas* silk suggests that *A. atlas* silk could have a considerably different crystallographic structure compared to mulberry and wild silks. *A. atlas* silk has much higher amounts of hydrophobic amino acids (67%) compared to the hydrophilic amino acids (23%), indicating that the *A. atlas* silk may have lower moisture absorption and lower absorption of dyes and chemicals if the crystal structures and percentage crystallinity are similar (Table 4).

Aminoacids%	*A. atlas*	*B. mori*	*A. mylitta*	*A. pernyi*	*P. ricini*
Alanine	45	29.4	34.1	34.7	36.3
Tyrosine	11.4	5.2	6.8	5.1	5.8
Glycine	22.2	44.6	27.7	28.4	29.4
Serine	6.8	12.1	9.9	9.1	8.9
Aspartic acid	3.2	1.3	6.1	5	3.9
Arginine	2.2	0.5	5	4.7	4.1
Glutamic acid	3.6	1.8	1.3	1.4	1.3
Histidine	2.2	0.1	0.8	0.7	0.8

Table 4. Comparison of the amino acid composition of the silk from the fiber layer in *A. atlas* cocoons with *B. mori* and three varieties of common wild silks.

Physical properties: The X-ray diffractogram of *A. atlas* fibers has been compared to *B. mori* silk fibers. It has been suggested that the nature of crystals in silk is dependent on the alanine/glycine ratio. The higher alanine content provides a better crystallographic form for the *A. atlas* silk compared to *B. mori* silk. The crystallinity of *A. atlas* fibers was 32.83%, close to the high end reported for *B. mori* (20%-41%) silk fibers. The fineness, tensile properties, and moisture regain of the silk fibers come from the three layers of *A. atlas* cocoons. The fibers from the outer layer of *A. atlas* cocoons are coarser than the fibers from the intermediate and inner layers. However, the *A. atlas* silk fibers from all the three layers are coarser than *B. mori* silk fibers but much finer than *A. mylitta* and *P. ricini* silk fibers. Although the inner layer of *A. atlas* cocoons contains the finest fibers, the breaking tenacity of the fibers in the inner layers (3.6 g/den) was lower than the fibers in the outer and fiber layer.

The breaking tenacity of the fibers from the outer and intermediate layer is similar to that of *B. mori* silk and better than that of *P. ricini* silk. The average breaking elongation (15%-17.3%) of the *A. atlas* fibers is similar to that of *B. mori* silk fibers but lower than that of the wild silks whereas the Young's modulus of the *A. atlas* silk fibers is lower than that of *B. mori* but higher than that of P. ricni silk fibers. The variations in the tensile properties of the silk fibers from different insects should be due to the differences in the composition,% crystallinity and arrangement of the crystals in the fibers. The moisture regain of the *A. atlas* silk fibers was higher than that of the other silk fibers. Overall, the tensile properties of the *A. atlas* fibers are similar to that of *B. mori* silk than the common wild silks.

The breaking tenacity of the fibers from the outer and intermediate layers is similar to that of *B. mori* silk and better than that of *P. ricini* silk. The average breaking elongation (15%-17.3%) of the *A. atlas* fibers is similar to that of *B. mori* silk fibers but lower than that of the wild silks, whereas the Young's modulus of the *A. atlas* silk fibers is lower than that of *B. mori* but higher than that of *P. ricni* silk fibers. The variations in the tensile properties of the silk fibers from different insects should be due to the differences in the composition, crystallinity, and arrangement of the crystals in the fibers. The moisture regain of the *A. atlas* silk fibers was higher than that of the other silk fibers. Overall, the tensile properties of the *A. atlas* fibers are similar to that of *B. mori* silk than the common wild silks (Table 5).

S.no	Parameters	Outside the cocoon	Intermediate the cocoon	Inside the cocoon
1	Fineness, denier	2.7	2	1.7
2	Strength, g/den	4.1 ± 1.5	4.3 ± 0.	3.6 ± 0.6
3	Elongation,%	17.3 ± 8.6	18.7 ± 9.3	15.0 ± 6.4
4	Modulus, g/den	53 ± 18	48 ± 18	60 ± 12
5	Moisture regain,%	11.6	12	12.4

Table 5. Mechanical properties silk fibers of *A. atlas* cocoon.

Conclusion

India has a great demand for its unique Vanya silks produced by the Muga, Tasar, and Eri silkworms. The Vanya sericulture industry in India is most suitable for tribal people to sustain their livelihoods. The *A. atlas* silkworm is not commercially cultivated because of its broken strands of silk *i.e.* discontinuous filament. However, there is a greater scope of spinning of cocoon to get the yarn like Eri silk. This brown, wool like silk is thought to have greater durability. In recent years, the rearing techniques of the fagara silkworm have been standardized and can produce two to three crops per year. Furthermore, the fagara silk has been shown to be more applicable for biomaterial manufacture. Hence, further research need to be undertaken for the exploration of the fagara silkworm towards the Vany silk industry in India.

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