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Review Article

Spider Parental Care and Awe-Inspiring Egg Sac (Cocoon)

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Spiders (Arachnida, Araneae) represent one of the largest groups of organisms on Earth with more than 45,000 recorded species found in nearly all terrestrial communities. In these communities, spiders are obligate predators and generalist consumers regulating the density of pests. Spiders have a stupefying array of prey hunting strategies ranging from ambushing to the use of complex silk nares. Spider silk is incredibly tough and can be used for many applications such as wrapping and immobilization, catching prey, as dragline to connect spiders to the web, as ballooning to aid dispersal of juveniles, as shelters in burrows, for mating, and as egg sacs (or cocoons). Typically, spider egg sacs are multilayered, complex structures that physically protect the eggs and hatchlings against parasitoids, predators as well as changing temperatures. Much research has been undertaken to elucidate the ecological role of spiders and the mechanical characteristics of silks. However, few studies have examined the parental care of spiders and the role of egg sacs. This review goes into great detail about spider parental care and the functions of egg sacs.

1. Introduction

Spiders belong to the class Arachnida and make up the biggest order in said class, called Araneae. They are one of the most abundant and diverse arthropods with over 45,000 known species under 4,209 genera and 128 families found throughout the world [1–3]. Spiders are ubiquitous in almost every terrestrial community except Antarctica where they play important ecological roles as they occupy a key spot in the food chain, as both predator and prey [4].

Spiders are considered an important generalist predator and efficient in preying upon many pest species [5, 6]. Different types of spiders employ different hunting strategies. For example, some species of spiders, such as *Pardosa milvina* ((Hentz, 1844) (Lycosidae) and *Philodromus dispar* (Walckenaer, 1826) (Philodromidae), are active cursorial predators and active foragers [7, 8]. Similarly, other species of spiders, *Tegenaria domestica* (Clerck, 1757) (Agelenidae) and *Arbanitis rapax* ((Karsch, 1878) (Idiopidae), pounce or ambush unwary prey [9, 10]. Additionally, spiders can build remarkably conspicuous and intricate webs from silks in open areas to ensnare a wide variety of prey as observed in *Anelosimus eximius* (Keyserling, 1884) (Theridiidae) and *Gasteracantha cancriformis* (Linnaeus, 1758) (Araneidae) (Keyserling, 1884) [11–13].

Spider silk is a very sturdy protein fiber with a very light and high ductile strength produced by various glands for different purposes [14, 15]. The silk is used for a variety of applications including in webs, safety draglines, and egg sacs due to its high mechanical stability, biocompatibility, smoothness, and thinness [16, 17]. A female egg sac can contain several to a thousand eggs with hatchlings inside and protects them against parasites, parasitoids, predators, and fluctuating temperature. Some females guard their egg sacs or carry them in their jaws or attached them to spinnerets while they are moving [18, 19]. Despite the important role of the egg sac, detailed descriptions of parental care, functions of egg sacs, and recent advances in the egg sacs are scarce. In this review article, we provide additional characteristics and functions of a variety of spider egg sacs and parental care and explore new findings to reveal the nanostructure, molecular details, and antimicrobial properties of spider egg sacs.

2. Ecological Significance of Spider

As generalist predators, spiders can fulfill a wide variety of ecological niches allowing them to intercept and consume an array of pests [20]. The predatory behaviors of spiders are particularly advantageous in enabling them to function as a biological control agent within agricultural ecosystems where they contribute to pest suppression [21].

Web-building spiders are the best-known group of trap builders, and the primary function of their webs is indeed the trapping (i.e., interception and retention) of insects. Web-building spiders build a wide variety of different types of webs, ranging from very simple trip lines that hardly hinder prey movement and mainly serve to alert the spider of the prey's presence to very effective, specialized sticky webs [22]. Some families of spiders, such as orb weavers (Araneidae, Tetragnathidae, and Uloboridae), cellar spiders (Pholcidae), and cobweb weavers (Theridiidae), are rarely out of contact with their webs. While others, like Erigoninae spiders, will often build small webs near the ground which they leave regularly to hunt itinerantly, whilst Linyphiidae spiders produce larger sheet webs several centimeters higher in the vegetation [22]. Spiders often use their legs to detect vibrations in the web's silk to determine when prey is tangled in the web.

Surprisingly the majority of spiders do not build webs [23]. Nonweb spiders are ground spiders also known as "wandering" spiders. Nonweb spiders do not build webs to capture prey; they hunt their prey with lightning-quick speed. They are fast and stealthy, ambushing pests that are either unaware of their presence or unable to flee fast enough, for example, wolf spiders chase and pounce on bare soil and leaf litter [24]. Some lycosids and pisaurids, however, can walk and sail on the surface of the water as they forage aquatic organisms [25, 26]. Other species of spiders such as crab spiders (Thomisidae) and *Phaeacius* (Salticidae) are typically described as ambush predators, remaining concealed in the vegetation before ambushing prey that comes near [27, 28].

3. Spider Silks and Web Building

Spiders use multiple kinds of silk fibers in different web-building strategies to actively tangle prey [29]. The silks are produced by seven silk-producing glands with each responsible for producing a silk protein for a particular function ([30, 31]. The seven distinct silk-producing glands include the aciniform gland (produces silk that binds up and envelops prey), major and minor ampullate glands (produce non-sticky dragline silk and frame thread to their web), flagelliform gland (provides sticky silk for prey capture, preventing prey from getting out of a web), pyriform gland (makes silk for attachments to a surface or to another thread), aggregate gland (coats the silk with adhesive deposits) and cylindriform gland (produces egg sac silks) [32–34]. To uncover the construction and functional aspect of spider egg sacs or cocoons, we explore in depth the characteristics of the cylindriform gland.

3.1. Cylindriform (Tubuliform) Gland Silks. Cylindriform (tubuliform) gland silks are used for the construction of egg sacs during the reproductive seasons of female spiders. The silk is often used as the tougher outer silk of the egg sac. Analysis of the physical structure of egg sacs as observed in the black widow spider *Latrodectus Hesperus* has shown that egg case sacs consist of two different diameter fibers [35]. The larger fiber diameter contains the fibroin TuSp1 while the AcSp1-like gene product is assembled into the small diameter fibers of the egg sac of *Latrodectus hesperus* [36]. The silks are usually sticky since they are covered with liquid and adhere at least weakly to each other [37]. Cylindriform silk is distinctive among the seven types of silk produced by the silk glands in reference to amino acid composition, production period, and mechanical properties. The cylindriform (tubuliform)silk has low glycine and high serine content but a high serine content with a high percentage of large side-chain amino acids [38, 39]. The unique amino acids composition is responsible for the unusual mechanical properties such as high tensile strength with a low elasticity, which distinguishes it from other silk types [40]. Furthermore, it is made up of a wide range of proteins, including TuSp1, egg case protein 1 (ECP1), 2 (ECP2), 3 (ECP3), cysteine-rich protein 2 (CRP2), 4 (CRP4), fasciclin, and translated scaffold ID #129 [40].

4. Incredible Egg Sacs

Egg sacs of most spiders are glutinous and stick together allowing them to be laid in a continuous stream into the partly built silk egg sac. Spider egg sacs vary greatly in size, shape, and color. The egg sacs can vary in color from pearly white to green, for example, *Benoitia lepida* (O.P.-Cambridge, 1876) (Agelenidae) constructs a shiny white egg sac that could be clearly observable from a long distance [41]. Female *Peucetia viridans* (Hentz, 1832) (Oxyopidae) generally constructs a light-green cocoon which eventually becomes straw colored with age [42]. The brown recluse spider *Latrodectus geometricus* (Koch 1841) (Theridiidae) produces a spheroidal, pale yellow egg sac with silk spikes on the surface [43]. In addition, the huntsman spider, *Heteropoda venatoria* (Linnaeus, 1767) (Sparassidae) newly constructed cocoons (diameter 13–21 mm) are creamish white but turn greyish over time [19]. Other sparassids, the *Delana cancerides* (Walckenaer, 1837) (Sparassidae), for example, produces creamish white egg sac (diameter 19–22 mm) which turns dull brown color camouflaging with pseudostems in banana agroecosystem may reduce conspicuousness [18]. Studies have shown that spectral characteristics of the egg sac reduce conspicuousness against the background and low environmental light available may help to camouflage [44]. *Nephila clavipes* (Linnaeus, 1767) (Araneidae) constructs a golden yellow egg sac 2.5 to 3 cm in diameter consisting of several hundred eggs [45]. Egg sacs also vary in thickness. There are two major layers, the internal basal and outer cover plate which serve as the mechanical barrier and thermal insulation against fluctuating ambient temperature. The female extrudes a viscous liquid into which the eggs are laid and adhere to one another and to the basal disc [46]. Then the female spider covers the outer mass with a layer of silk which constitutes the cover plate (outer layer) that serves as a mechanical barrier and thermal insulation against fluctuating ambient temperature.

5. Egg Sac Construction, Location, and Parental Care

Spiders deliberately construct and transport their cocoons to a variety of locations based on certain environmental variables [47]. The cocoon can be buried in the soil, hung in a web, attached to a leaf, or can be found elsewhere. Some spiders that construct multiple egg sacs do have an inclination to desert them. Female *Pardosa milvina* (Hentz, 1844) (Lycosidae) can recognize her egg sac [48]. In contrast, *H. venatoria* cannot differentiate between her cocoon and that of another; she may even pick up and carry the egg sac of another female [19].

The European cave spider *Meta menardi* (Latreille, 1804) (Tetragnathidae) selects suitable areas for the deposition of their egg sac based on two environmental variables, namely airflow velocity and the distance from the cave entrance within a particular cave [49]. Female *M. menardi* places her egg sac in a specific location to avoid thermal variations [50]. In the banana plantation agroecosystem, the huntsman spiders (Sparassidae) intuitively construct and guard their egg sacs in microhabitats such as under banana pseudostem barks and banana bunches [18, 19, 51]. These microhabitats are known to provide architectural support for brood care, mating, and shelter [19]. Microhabitats also provide climatic variables, such as wind direction, moisture, and temperature [52].

Egg sac construction varies across spider species. For example, two weeks after mating, the female huntsman spider *Heteropoda venatoria* produces a circular, flattened, creamy white egg sac (1.27 to 2.54 cm in diameter) and 3.18 to 6.35 mm thick [19, 53]. During the construction of the egg sac, the female *H. venatoria* bends over and assumes a C-shaped posture, then deposits a network of silk from her spinnerets on the underside of a flat surface for approximately 20 minutes. She gently moves around the circumference of the egg sac several times depositing more silk strands until the spherical disk is transformed into a saucer-shaped structure of about one millimeter. Afterward, she walks for a few seconds around the saucer-shaped structure and then settles on it to oviposit about 250 eggs for around 2 mins [19]. Next, she reassumes the C-shaped posture depositing more silk strands to eventually seal the egg sac around the edges [19]. She then compresses the cocoon with her abdomen for about two minutes prior to peeling it off the substrate with the aid of her pedipalps. The female *H. venatoria* picks up the egg sac and carries it with her pedipalps underneath her body during the incubation period for about 30 days (Figure 1) and she does not feed during this time [19].

Figure 1: Female *Heteropoda venatoria* guarding her egg sac.

Afterward, she may moisten the egg sac open, helping her spiderlings to emerge. In some species of Saprassidae, for example, the Isopeda, the female will produce a flat, oval egg sac of white silk, and oviposits around 200 eggs. She then places it under bark or a rock, and stands guard over it, without eating, for about three weeks. During this period the female can be quite aggressive and will rear up in a defensive display if provoked. The female *Delena cancerides* spider produces an egg sac (21 ± 0.6 mm) in which she oviposits about 70 eggs and stands guard over it without eating [18]. *D. cancerides* are social spiders and sometimes at least two females can be seen guarding a single egg sac (Figure 2) [18]. The female *Holconia insignis* spider lays about 238 eggs and guards over it [51] for weeks. The female may sometimes moisten and tear the egg sac open, helping her spiderlings to emerge. The mother stays with them for several weeks.

Female *Peucetia viridans* (Hentz 1832) (Oxyopidae) spiders construct a light-green egg sac around 20–28 days after mating. The egg sac is rounded with 1.5 to 2.5 cm in diameter and flattened on one side and for the most part, constructed in the upper branches of a woody shrub, the *P. viridans* then spins a disk consisting of a cushion-like mat of silk with a bowl like opening. She gently oviposits about 600 eggs through the opening into the sac. Afterward, she covers the egg sac with all its embellishments. Lastly, she guards the egg sac continuously (Figure 3) and vigorously until spiderling dispersal [54]. The eggs hatch after 11–16 days depending on air temperature. The female will usually hang upside down from the sac threatening any intruders [42].

Wolf spiders (family Lycosidae) are unique in the way that they carry their eggs and are known to provide parental care for their young to increase the survivability of their spiderlings [48]. The female spider usually constructs and tends to her egg sacs in silk-lined safe areas such as burrows, under rocks, or logs. The biology of one group within this family (genus *Pardosa*) has been studied extensively. The wolf spider *Pardosa milvina* (Hentz 1844) is a common species of wolf spider found near rivers and in agricultural sectors in eastern parts of the United States of America. Soon after mating a female *P. milvina* lays close to 100 eggs in an

Figure 2: Female *Holconia insignis* spider guards over her egg sac.

Figure 3: Female *Peucetia viridans* protecting her egg sac.

Figure 4: *Pardosa milvina* female with egg sac.

oval-shaped, compact silk egg sac. The abdomen must be held in a raised position to keep the egg case from dragging on the ground, however, despite this handicap they are still capable of hunting. The size and weight of the egg sac make it hard for the female to attack prey and deter predators. She carries the egg sac on her spinnerets (Figure 4) for about 30 days and on rare occasions, drops the egg sac. After this carrying period (when the eggsare mature), the female rips it open enabling the spiderlings to emerge and climb on her back. The female *P. milvina* carries the spiderlings on her back for about 7 days before leaving the spiderlings to fend for and feed for themselves [55]. Unlike female *P. milvina* spiders and other Lycosidae species, female *Arctosa littoralis* (*Hentz* 1844) spiders typically hide their egg sacs under rocks or within burrows. *A. littoralis* is found in North and Central America at higher altitudes associated with lichen or heath habitats and sandy substrates in grass-shrub [56]. Female *A. littoralis* produces an egg sac containing about 80 eggs which typically hatch in nine to thirteen days. Once spiderlings fully emerge, they climb on the back of the mother and remain there for 11–14 days, after which they disperse.

Benoitia lepida (O. Pickard-Cambridge, 1876) common in the Negev desert, Israel has unique characteristics. The egg sacs are usually dull in color with multilayered structures. The first layer has a shiny surface due to a thin papery envelope. Below this layer is a thin outer, loose layer of silk enclosing the thick dirt layer which may consist of soil particles, stones, snail shells, and feces. This layer is held together by means of silk thread. The inner silk layer is continuous with the string, while the outer three layers are packed around both. Some females usually attach the egg sacs to the side of the vertical branch while other egg sacs are connected to the female's web [41].

6. Egg Sac Functions

Spider egg sacs have evolved to demonstrate a wide range of functions. Egg sacs protect the enclosed egg and spiderling stages from desiccation [57]. The multilayers of egg sacs also constitute a physical barrier protecting eggs from microbial infections against pathogens such as *Bacillus subtilis* as seen in a study performed on *Tegenaria domestica* and *Nephila clavipes* [58–60]. Furthermore, the egg sac provides an antibacterial barrier for the developing spiderlings which allows them to shift their energy to growth and organogenesis [59]. The maternal activity of spiders helps to attenuate parasitism and predation [15, 61]. Nevertheless, this protection is sometimes contravened by parasitic wasps that succeed in laying their eggs or infiltrating their larvae among or within the spider's eggs. Spiders like redbacks lay many eggs and make several egg sacs to ensure that enough eggs survive these seasonal onslaughts. Some spider species are known to disguise the egg sacs with silk stabilimenta [62]. The decoration consists of combinations of silk and debris and differs between species and even within the same species [15]. Multilayered cocoons or egg sacs are built to outmaneuver predators such as ichneumonid wasps or Mantispidae, which have evolved specifically to feed on spider eggs [15]. Transmission electron microscopy (TEM), a high-resolution imaging technique, reveals threads of two types of fibrils that are associated with eco immunological roles in spider embryonic development as seen in cocoons of *Parasteatoda tepidariorum* (C. L. Koch, 1841) (Theridiidae) [63]. Egg sacs also protect the eggs from direct sunlight providing protection from thermal variations [64]. Also, resisting temperature fluctuations and maintaining optimal microclimate for embryological development as demonstrated by Clubiona [47, 65, 66]. The protection offered by the egg sac is not limited to the temperature. *Agelenopsis aperta's* egg sacs are also heavily involved in protecting eggs from floods [67].

7. Application of Spider Egg Sacs

Spider egg sac silk is a promising fiber for many applications due to its biological and mechanical properties. The silk fibers are made of nontoxic amino acid hydrolysis products which make the silk a good candidate for creating bioresorbable textile scaffolds [68]. The egg sac silk of *Meta menardi* is composed of fibers very densely and randomly packed making it one of the most stretchable egg sac silk stalks which could be used in the future to make parachutes and other useful products [69]. Egg sac threads can be very useful for biomedical applications, like sutures, cell support, and scaffolds. The chondrocyte cells can adhere to spider cocoon silk threads combined with their antibacterial chemical properties will expedite wound healing and cartilage regeneration without any definitive synthetic implants [68]. Furthermore, spider egg silks minimize inflammation during subcutaneous implantation in rodents [15].

8. Conclusion

Spiders are among the most abundant arthropods with more than 45,000 known species living in a wide variety of different habitats where they play a major role in controlling pests [2]. It is believed that one of the reasons spiders are so successful is because the females are multivoltine-producing egg sacs or cocoons containing several to a thousand eggs. Females exhibit parental care after oviposition which varies among spider species. Some female species carry their egg sacs on their spinnerets (e.g., *Heteropoda venatoria*) while other species rigorously guard egg sacs until the eggs hatch (e.g., *Peucetia viridans*). The egg sacs are multilayers and typically protect the eggs and embryos from natural enemies and create essential microenvironmental conditions for embryonic development. The protective egg sac surrounding the eggs is made of silk produced by the tubuliform gland. The egg sac silk has high tensile strength with a low elasticity which can be useful for biomedical and industrial applications.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

A.J.E wrote the first draft of the manuscript and contributed to the interpretation of all data. K.A contributed to the manuscript revision, and read and approved the submitted version.

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