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Insects and their practical role in the functioning of human societies

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Abstract. It is well established that insects are the most biodiverse group of animals on our planet. Since the dawn of *Homo sapiens*, humans have coexisted with insects, as well as with a number of other groups of organisms. This review seeks to summarize their key role in the functioning of present-day human society. In a global context, they are the pollinators of Earth's ecosystems, providing an ecosystem service that is impossible to calculate in monetary terms. Insects have numerous roles and applications beyond their basic function, which is fundamental to terrestrial life on our planet. The products of their vital activity have various direct and indirect properties, effects, and applications. They produce food, such as honey, and can also serve as food sources for animals and humans. Additionally, they are used to make textiles, varnishes, and dyestuffs. Insects create by-products that are extremely useful in medicine and cosmetics. Among insect species, some are effective agents for biological pest control. And finally, a number of them are experimental model species in experimental science. Humans and insects have formed lasting relationships and dependencies that have endured for millennia throughout history. This unique group of animals should remain a focal point for a wide range of future studies.

Keywords: insects, food and feed, medical use, pollination, industry, biocontrol.

Introduction

Insects (Arthropoda: Insecta) are the largest and most diverse class in the animal kingdom. Despite their enormous diversity, insects are often underrepresented in ecosystem studies, so their contribution to global ecosystem functioning is relatively less studied than that of other organisms, such as plants (Allsopp et al. 2008, Schowalter 2016, Noriega et al. 2017). Insects are key species in the provision, regulation, and dynamics of many ecosystem services (ES) (Noriega et al. 2017, Weisser & Siemann 2004, Schowalter 2013, Allsopp et al. 2008). Previous attempts to quantify the financial value of several ES provided by insects have generally not objectively assessed the contribution of these species to the functioning of economies and our quality of life (Beynon et al. 2015). Nevertheless, it has been estimated that insects provide ES worth $57 billion annually in the United States alone (Losey & Vaughan 2006), and insect pollination has been estimated to be worth between $235 and $577 billion annually globally (IPBES 2016). A realistic assessment of the contribution of natural resources and biodiversity to the provision and maintenance of ES depends on the availability of accurate information and a clear understanding of the processes involved in the provision of these services (Haines-Young & Potschin 2010, Noriega et al. 2017). There is a general lack of knowledge about the functional roles played by most insect species in nature (Hortal et al. 2015, Allsopp et al. 2008, Noriega et al. 2017). This is particularly important when assessing the value of ES for insects. As a result, we often lack a comprehensive understanding of the role of insects in many ecosystem processes that underlie ES. Despite the rapid technological development of agriculture and animal husbandry, insect farming worldwide is still largely carried out manually and by small farms (Kenis et al. 2018, Francuski & Beukeboom 2020). Insects are chiefly raised for the following purposes: 1. Production of industrial food products, mainly honey; 2. Food for animals and humans; 3. For medical and cosmetic purposes, 4. In waste management, 5. For biological control, 6. As pollinators, 7. For research purposes (Francuski & Beukeboom 2020). Their farming practices require manual labor and contribute to the development of local economies. The insect-based food and feed industry already produces tons of insects per day (van Huis 2016). Still, the diversity of species and their production is expected to increase even more rapidly. The European honey bee, *Apis mellifera* L. (Hymenoptera: Apidae), plays a significant role in the food industry with an annual production of about 1.2 million tons of honey (FAO 2009), and its role in pollination is part of the basic irreplaceable ecosystem services that nature provides to humans (Brittain et al. 2013). This article aims to review the practical role of insects in various key processes related to the functioning of human societies and to assess their contribution in terms of numbers, biomass, productivity, and biodiversity.

Insects and insect-derived products as a food source

Honey - the most essential product of insect activity

The honey bee *Apis mellifera*, with its production of honey and propolis, as well as its pollinator activity, is the most important insect species in this regard. Honey is a complex nutritional sweetener, composed mainly of carbohydrates (60–85%) and water (12–23%). It also contains small amounts of other compounds, such as organic acids, minerals, vitamins, enzymes, proteins, amino acids, volatile compounds, and several bioactive substances (phenols and flavonoids), as well as pollen grains (Almeida-Muradian et al. 2013, Cano et al. 2001, White 1979). Honey is commonly consumed both directly from nature and as an industrial food product. It is increasingly finding a place in human and veterinary medicine (Joseph et al. 2007, Nigussie et al. 2012).

The biological and nutritional properties of honey are decisive for consumer choice, as well as for trends in its commercialization as food. It contains 26 amino acids, comprising proline, glutamic acid, alanine, phenylalanine, tyrosine, leucine, isoleucine, lysine, methionine, histidine, arginine, aspartic acid, tryptophan, serine, valine, methionine, and threonine (Hermosin et al. 2003, Sáenz-Lain & Gómez-Ferreras 2000, Machado De-Melo et al. 2018), and carries enzymes, organic acids, vitamins, minerals, phenols, and antioxidants (Antony et al. 2000, McKibben & Engeseth 2002). Honey has antimicrobial properties (Paulus et al. 2012, Mundo et al. 2004, Bogdanov 2015) and antiparasitic properties (Sajid & Azim 2012), as well as probiotic and prebiotic properties (Abdellah & Abderrahim 2014). Honey, as a result of a bioaccumulative process, is used as a marker to identify environmental pollution (Jones 1987, Kačániová et al. 2009, Machado De-Melo et al. 2018) and to characterize the level of pollution in soil, water, plants, and air (Fodor & Molnar 1993). In general, more than 90% of the flavonoids in honey come mainly from propolis (such as pinobanksin, pinocembrin, and chrysin) (Ferreres et al. 1992, Martos et al. 1997). Propolis-derived flavonoids are relatively lipophilic and are found in honey in varying amounts, depending on the degree of propolis and beeswax present in the hive (Ferreres et al. 1994, Martos et al. 2000). The volatile and semi-volatile compounds in honey determine the organoleptic characteristics that influence consumers' choices of the final product. The aroma and taste of honey are related to volatile substances (Piana et al. 2004), as well as to the presence of sugars, organic acids, amino acids, tannins, and phenols (White 1979). More than 600 low molecular weight compounds have been identified in it at very low concentrations, as complex mixtures of different chemical substances - monoterpenes, terpenes, terpenoids, norisoprenoids, phenolic compounds, benzene derivatives, alcohols, ketones, aldehydes, esters, fatty acids, hydrocarbons, and cyclic compounds (Alissandrakis et al. 2003, Castro-Vázquez et al. 2003, Machado De-Melo et al. 2018). Pigments determine the color of honey. Of these, the most important are polyphenols, carotenoids, xanthophylls, and anthocyanins, which can be grouped into water-soluble and fat-soluble pigments. Other compounds that can contribute to the color of honey include sugars, minerals, and amino acids (Ortiz-Valbuena et al. 1996, Sabatini 2007, Sáenz-Lain & Gómez-Ferreras 2000). Lipid compounds in honey are present in small amounts (about 0.04%), including glycerides, sterols, phospholipids, and various acids such as palmitic, oleic, lauric, aromatic, stearic, and linoleic (Sáenz-Lain & Gómez-Ferreras 2000, White 1979). They originate from plants visited by foraging bees and are primarily found in wax residues (Sabatini 2007). In human nutrition, honey is an excellent source of energy. One hundred grams of honey provides about 1283 kJ of energy (306 kcal). Twenty grams of honey is the typical amount per serving or tablespoon, providing approximately 256.6 kJ (61.2 kcal), which represents around 3% of the daily energy needs (Bogdanov et al. 2008, Machado De-Melo et al. 2018). The main components of honey are simple carbohydrates, including fructose and glucose, which are readily absorbed into the bloodstream after rapid absorption, providing energy to humans without the need for prior digestion (Ajibola et al. 2012). Blasa et al. (2006) argue that honey is a good food for people of all ages. It helps improve health in older people (Alvarez-Suarez et al. 2009). It enhances the performance of athletes, maintaining muscle without the need for additional, more expensive stimulants to achieve optimal sports performance. Therefore, honey has been described as an effective source of carbohydrates for athletes (Ajibola et al. 2012, Earnest et al. 2000, Kreider et al. 2002). The benefits of honey as a protective agent against liver damage, radiation, inflammation, emotional stress, and other pathologies associated with oxidative stress have also been discussed (Bogdanov 2015, Boukraa 2014). Recent studies have highlighted that, due to its antioxidant activity, honey may play an interesting role in the management of oxidative stress-related chronic diseases (Boukraa 2014, Erejuwa et al. 2011, 2012). An antihypertensive activity of honey has also been reported. Hypertension is one of the most important cardiovascular risk factors (Poulter 2003, Machado De-Melo et al. 2018), as the continuous increase in blood pressure leads to changes in the myocardium and coronary vasculature, resulting in left ventricular hypertrophy with cardiac dysfunctions such as arrhythmia, congestive heart failure, etc. (Standridge 2005). Cardiovascular diseases are the leading cause of death worldwide (Erejuwa et al. 2012). Recent studies have shown that honey and its derivatives may help reduce the risk of hypertension (Hiwatashi et al. 2010). Fresh honey is reported to contain probiotic *Bifidus* and *Lactobacillus* bacterial species (Olofsson & Vasquez 2008), which are beneficial for human health. Prebiotics are substances that can potentially stimulate the activity of the intestinal flora, altering its composition and providing energy for beneficial microbial species within the intestinal microbiome (Abdellah & Abderrahim 2014). The possible prebiotic effects of honey have been attributed to oligosaccharides, whose actions are similar to fructooligosaccharides (Sanz et al. 2005, Yun 1996). Panose has been described as the most active oligosaccharide. The mechanism of action of oligosaccharides in honey appears to be a synergistic effect, leading to an increase in lactobacilli and bifidobacteria (Ustunol 2000, Ustunol & Gandhi 2001). Honey has potent anti-inflammatory activity (Postmes 2001). Similarly to hypertension, inflammation is considered one of the main causes of cardiovascular risk and other diseases (Willerson & Ridker 2004). Reactive oxygen species are a crucial factor in inflammation (Singer & Clark 1999), as free radicals induce the production of pro-inflammatory cytokines (Feldmann & Steinman 2005, Tracey et al. 2008). Honey has been shown to reduce inflammation in several experiments conducted with laboratory animals (Bogdanov 2015, Owoyele et al. 2014). Honey administration to rats with intestinal disorders was an effective treatment for inflammatory colitis, possibly due to the prevention of free radical production, which researchers suggest may also be indirectly related to its antimicrobial activity (Kassim et al. 2010) showing that in rats, both honey and its components can suppress edema, exerting inhibitory properties against pro-inflammatory factors. In experiments with rabbits, a reduction in inflammation was observed after the administration of honey, likely due to its induction of neutrophil infiltration and myeloperoxidase activity (Kassim et al. 2012). Honey has emerged as a valuable bio-indicator due to its ability to reflect environmental conditions and the presence of contaminants in the ecosystems where bees forage. This unique property arises because honey is a natural product derived from nectar and pollen collected by bees, which interact with various environmental elements during their foraging activities. Honey can serve as an important bio-indicator of radioactive contamination, heavy metal contamination, and pesticide residues (Machado De-Melo et al. 2018). Bees collect nectar, pollen, and other substances from wide areas, which allows honey to provide a comprehensive overview of contaminants. Its non-invasive collection makes honey an ethical and sustainable choice for environmental monitoring. Additionally, analyzing honey is cost-effective and logistically simpler than conducting extensive soil, air, or water samplings.

Insects as nutritional alternatives for humans and animals

Insects are an emerging and sustainable alternative to traditional protein sources for both humans and animals (Table 1). Rich in high-quality protein, essential amino acids, and beneficial fats, insects rival conventional meats in nutritional value while having a smaller environmental footprint. They require significantly less land, water, and feed compared to livestock. Orthopteran species (*Acheta domesticus*, *Gryllus assimilis*, *Gryllus bimaculatus*, *Teleogryllus testaceus* and Coleopterans (*Rhynchophorus ferrugineus*) are raised on several continents as pet food or for human consumption (Francuski & Beukeboom 2020). In this regard, the mealworm beetle, *Tenebrio molitor*, is crucially important, as it can be easily raised and supports large-scale production capacity (Grau et al. 2017). Mealworms have a high content of protein (13.68–22.32 g/100 g product) and fat (8.90–19.94 g/100 g product) and also provide significant amounts of polyunsaturated fatty acids (Nowak et al. 2016). Mealworms are also categorized as a source of zinc and are high in magnesium but contain low levels of calcium (Nowak et al. 2016). Additionally, mealworms can be identified as a source of niacin and are rich in pyridoxine, riboflavin, folate, and vitamin B12 (Nowak et al. 2016). The nutritional profile of mealworms has been compared to that of conventional meats, revealing that mealworm larvae have a significantly higher nutritional value than beef and chicken, and are not substantially less nutritionally balanced (Payne et al. 2016). They also provide a good source of all essential amino acids (Rumpold & Schlüter 2013). The optimal growth temperature for *Tenebrio* larvae is 25°C–27.5°C, resulting in a development period of approximately 80 days, encompassing 15–17 larval stages (Park et al. 2012, 2014). Individual food consumption and larval weight depend on larval density; i.e., increasing density from 12 to 96 larvae per square decimeter reduces biomass produced per gram of food by approximately 22% (Morales-Ramos & Rojas 2015). Female reproductive capacity decreases with increasing density and age of adults; the imago has the highest reproductive capacity 2–3 weeks after eclosion (the emergence of an adult from the pupal stage) (Morales-Ramos et al. 2012). Larvae and pupae of another species, the black soldier fly, *Hermetia illucens*, are a significant source of protein for animal consumption and as pet food. The application of black soldier fly larvae (BSFL) for organic waste treatment has garnered attention among researchers (Rehman et al. 2023, Kim et al. 2021). The resource insect black soldier fly (BSF), *Hermetia illucens*, can efficiently convert animal manure (bird or cattle), along with other organic wastes, and produce biomass from its larvae rich in protein and fat, which can be used directly or after drying as animal feed (Liu et al. 2017, Shorstkii et al. 2020, Rehman et al. 2023). Furthermore, larval biomass can be used to separate proteins and fats, which can be utilized to produce biodiesel and larval proteins for use as feed for other animals (Rehman et al. 2023). The manure residue resulting from BSFL growth can be utilized as a universal fertilizer (Ma et al. 2018, Mazza et al. 2020). Thus, BSFL can be used in solving organic waste pollution. At the same time, BSFL can alleviate the shortage of proteins and fats used in animal feed (Rehman et al. 2023). Its cultivation has promising prospects due to its ease of cultivation, low cultivation costs, high efficiency, high added value, and successful utilization of animal manure and other organic waste generated by the food industry (Rehman et al. 2023). Species such as *Musca domestica*, *T. molitor*, *Zophobas atratus*, and *Gromphadorhina portentosa* also have valuable applications for cultivation to produce food for other animals (Francuski & Beukeboom 2020).

Insects as biofactories: Industrial products and applications

The world of insects offers a fascinating realm of industrial applications, producing a remarkable array of industrially valuable materials (Table 1). From the fine threads of silk spun by the domesticated silkworm (*Bombyx mori*) to the vibrant carmine dye derived from cochineal insects (*Dactylopius coccus*) and the secretion of shellac by lac insects (*Kerria lacca*), these small organisms demonstrate extraordinary utility in diverse fields (Francuski & Beukeboom 2020). In addition to their historical roles in textiles and dyes, insects now find applications in modern biotechnology, with advancements enabling the production of eco-friendly materials and renewable energy. These insect-derived products exemplify the intricate relationship between nature and industry, displaying how even the smallest organisms can have a profound impact on human technology, commerce, and scientific research.

<u>The Silkworm - a pioneer in biotechnology and textile production</u>

The silkworm (*Bombyx mori*) is a small insect that plays a significant role in the production of silk. It is the primary economic resource for more than 30 million families, primarily in Asian countries such as China, India, Vietnam, and Thailand. The silkworm, which traditionally produces abundant amounts of silk, can be considered an ideal laboratory tool. *B. mori* possesses excellent characteristics as an experimental animal; it can be raised and bred under complete human control and is an efficient organism for research in various scientific fields. The silkworm is a well-studied insect model system due to its well-characterized mutations affecting morphology, development, behavior, and economic importance. The physical mapping of chromosomal mutants in the silkworm is also well characterized, offering excellent opportunities for understanding basic concepts in cytological and molecular studies.

Table. 1*. List of insect species and taxa widely used for various purposes by human societies (according to Dyck et al. 2021, Francuski & Beukeboom 2020, Wade & Hoelle 2020, Lamsal et al. 2019, Tang et al. 2019, Halloran et al. 2018, Ortiz et al. 2016, Sánchez-Muros et al. 2014, Morales & Wolff 2010, Frankie & Thorp 2009, Costa-Neto & Dunkel 2016)

Food (According to different data, from 1500 to 2300 insect species were reported as edible)
Blattodea: *Macrotermes* sp. **Orthoptera:** *Nomadacris septemfasciata, Acheta domesticus, Gryllodes sigillatus, Teleogryllus testaceus, Teleogryllus mitratus, Locusta migratoria, Schistocerca americana, Schistocerca gregaria, Gryllus bimaculatus, Oxya japonica, Phymateus viridipes brunneri, Ruspolia differens, Ruspolia nitidula, Acanthacris ruficornis, Locustana pardalina, Gynanisa maja, Anacridium burri, Brachytrupes membranaceus, Acrida acuminate, Zonocerus spp.* **Hemiptera:** *Aspongopus viduatus, Euschistus egglestoni, Hoplophorion monogramma, Pachylis gigas, Umbonia reclinata, Krizousacorixa azteca* **Coleoptera:** *Tenebrio molitor, Zophobas atratus, Zophobas morio, Alphitobius diaperinus, Protaetia brevitarsis, Allomyrina dichotoma, Oryctes boas, Ceroplesis burgeoni* **Lepidoptera:** *Galleria mellonella, Achroia grisella, Anaphe panda, Carebara vidua, Chaoborus edulis, Bombyx mori, Cirina forda, Urota sinope, Imbrasia belina, Striphnopteryx edulis, Bunaea alcinoë, Imbrasia ertli, Bunaea caffraria, Heniocha dyops, Heniocha marnois, Anaphe panda, Cirina butyrospermi, Imbrasia epimethea, Agrius convolvuli* **Hymenoptera:** *Apis mellifera, Carebara vidua, Carebara lignata*
Feed
Ephemeroptera: *Ameletus* sp., *Attenella delantala*, *Baetis* sp., *Caenis* sp., *Cinygmula* sp., *Drunella coloradensis, Drunella grandis, Ecdyonurus venosus, Ephemera sp., Ephemerella* sp., *Heptagenia* sp., *Ironodes* sp., *Isonycia* sp., *Paraleptophe* sp., *Rhithrogena* sp., *Tricorythodes* sp.; **Odonata:** *Aeschna multicolor, Anax sp., Anomalagrion hastatum, Argia sp., Ictinogomphus sp.* **Orthoptera:** *Acheta doméstica, Boopedon flaviventris, Melanoplus mexicanus, Schistocerca sp., Sphenarium histrio, Sphenarium purpurascens, Trimerotropis pallidipennis, Zonocerus variegatus, Gryllus bimaculatus, Gryllus testaceus, Callipogon barbatum, Brachytrupes. portentosus* **Plecoptera:** *Hesperopteria pacifica, Isogenoides* sp., *Isoperia* sp., *Pteronarcella* sp. **Blattodea:** *Periplaneta americana, Gromphadorhina portentosa, Termes* sp., *Macrotermes bellicosus* **Hemiptera:** *Atizies taxcoensis, Euschistus egglestoni, Meimuna opalifera, Pachilis gigas, Tessaratoma papillosa*, *Corixidae* spp,, *Abedus sp., Edessa montezumae, Euchistus strennus, Pachilis gigas, Notonecta* sp. **Megaloptera:** *Sialis* sp. **Coleoptera:** *Tenebrio molitor, Cetonia aurata, Pachnoda marginata, Copris nevinsoni, Holotrichia sp., Zophobas morio, Analeptes trifasciata, Aplagiognatus spinosus, Arophalus rusticus, Callipogon barbatum, Chalcophora sp., Macrodactylus lineaticollis, Melolontha sp., Metamasius spinolae, Oileus rimador, Oryctes boas, Pachymerus nucleorum,Passalus punctiger, Paxilus leachei, Phyllophaga sp., Rhantus atricolor, Rhynchophorus palmarum, Rhynchophorus phoenicis, Scyphophorus acupunctatus, Sprataegus aloeus, Trichoderes pini, Berosus sp., Lara avara, Psephenus* sp., *Tropisternus* sp.; **Hymenoptera:** *Apis mellifera, Liometopum apiculatum, Mischocytarus sp., Myrmecosistus melliger, Pogonomyrmex barbatus, Polybia occidentalis, Polistes canadensis, Polistes sagittarius, Vespa basalis, Vespula sp., Oecophylla smaragdina*; **Trichoptera:** *Allocosmoecus* sp., *Clistoronia magnifica, Dicosmoecus gilvipes, Hesperophylax* sp., *Hydatophylax* sp., *Hydropsyche* sp., *Lepidostoma* sp., *Namanyia* sp., *Neophylax* sp., *Oncosmoesus* sp, *Parapsyche* sp., *Pseudostenophylax* sp., *Psychoglypha subboreallis, Ryacophila* sp., *Ecclisomylia* sp., *Glossosma* sp., *Heteroplectron californicum* **Lepidoptera:** *Aegiale luesperiaris, Anaphe infracta, Anaphe recticulata, Anaphe venata, Bombyx mori, Catasticta teutila, Cirina forda, Comadia redtembacheri, Cossus redtenbachi, Eucheira sopcialis, Heliothis zea, Galleria mellonella, Lanifera cyclades, Ostrinia nubilalis, Samia ricinii, Phasus triangularis*; **Diptera:** *Copestylum anna, Drosophila melanogaster, Ephydra hians, Eristalis sp., Hermetia illucens, Musca domestica, Agathon* sp., *Lucilia sericata, Atherix variegate*
Industrial products
Lepidoptera: *B. mori*; **Hemiptera:** *Dactylopius coccus, Kerria lacca, K. yunnanensis, K. chinensis, K. nepalensis*
Waste management
Orthoptera: *Conocephalus* sp.; **Coleoptera:** *Stilbus apicalis*; **Hymenoptera:** *Paratrechina* sp., *Dorymyrmex* sp., *Neivamyrmex* sp.; **Diptera:** *M. domestica, H. illucens, Ornidia obesa, Desmometopa sp., Stomoxys calcitrans, Ophyra aenescens, Drosophila* sp., *Fannia canicularis, Coproica* sp., *Coboldia fuscipes, Physiphora* sp., *Themira* sp., *Curtonotum* sp.
Medical and cosmetic use
Blatodea: *P. americana*; **Orthoptera:** *A. domestica, Sphenarium purpurescens*; **Hemiptera:** *Edessa cordifera, Euschistus crenator*; **Lepidoptera:** *B. mori, Catopsilia crocale, Hyalophora cecropia, Lonomia obliqua, Prioneris thestylis*; **Coleoptera:** *Allomyrina dichotoma, Lytta vesicatoria,* **Hymenoptera:** *A. mellifera, Anoplius samariensis, Anterhynchium flavomarginatum micado, Polybia occidentalis nigratella, Pseudagenia (Batozonellus) maculifrons, Tetragonisca angustula*; **Diptera:** *Lucilia sericata, Drosophyla melanogaster, Phaenicia sericata, Sarcophaga peregrina*
Pollination (Major pollinators belong to 4 insect orders)
Hymenoptera (bees, ants, and wasps). Bees are most important – superfamily Apoidea (20,000 – 30,000 species), for example: *A. mellifera, Bombus terrestris* (L.), *Bombus occidentalis, Megachile rotundata, L. sericata, Blastophaga psenes, Osmia* sp., *Nomia melanderi*, **Coleoptera** (beetles), **Lepidoptera** (butterflies and moths), **Diptera** (flies)
Research
Diptera: *D. melanogaster*; **Lepidoptera:** *B. mori, Galleria mellonella;* **Coleoptera:** *Tribolium castaneum, Dermestes maculatus*
Biological control – predators
Neuroptera: *Chrysoperla carnea;* **Hemiptera:** *Anthocoris nemoralis, Macrolophus pygmaeus, Orius laevigatus*; **Coleoptera:** *Adalia bipunctata, Harmonia axyridis, Cryptolaemus montrouzieri, Delphastus catalinae*
Biological control –parasitoids
Hymenoptera: *Aphelinus abdominalis, Eretmocerus eremicus, Encarsia formosa, Aphidius colemani, Dacnusa sibirica, Diglyphus isaea, Trichogramma evanescens, Anagyrus pseudococci, Muscidifurax raptorellus*
Biocontrol – sterilization techniques against agricultural insect pests
Diptera: *Cochliomyia hominivorax, Ceratitis capitata, Bactrocera cucurbitae, Anastrepha ludens,* **Lepidoptera:** *Cydia pomonella, Pectinophora gossypiella*

* The list in the table does not include all known species in the relevant section

The implications of physiological studies on the silkworm have found their application in the pharmaceutical and medical fields. The silkworm is an excellent laboratory subject for conducting various molecular, immunological, and toxicological studies. It is the most genetically elucidated insect after *Drosophila melanogaster*. Apart from this, an upcoming field of development is the use of transgenic silkworms for the production of life-saving drugs in the pharmaceutical industry, which deserves special attention. The silkworm can now be manipulated to produce a vaccine against hepatitis B. Researchers at the Indian Institute of Science (IISC) in Bangalore have successfully induced silkworms to produce an antigen for hepatitis B, a blood-borne infection whose increasing incidence is a cause for concern in the country. Silk and silk fabric are the products of a series of production processes, from the cultivation of mulberry trees as food for the domesticated silkworm *B. mori* (an agricultural-based activity) to the processing of cocoons, an industrial activity that is deeply ingrained in the fabric of many rural areas. During the caterpillar stage, the larva wraps itself in a liquid protein secreted by two large glands. This secreted protein hardens when exposed to air. The resulting thread is bound together by a second secretion, sericin, which forms a hard shell or cocoon. Under natural conditions, the moth eventually bores a hole through the cocoon. The production of cocoons is the primary raw material for silk production, an agricultural activity. The cocoons are then taken for silk extraction. To develop the silk, the larva is killed in the cocoon by steam or hot air in the chrysalis stage before its metamorphosis. The prolonged heat treatment softens the hardened sericin, allowing the thread to be developed. The silk thread is a continuous thread of great strength, measuring 500-1500 meters in length. Single threads are too thin to be used; therefore, several threads are combined to produce raw silk, a process known as "silk reeling". Raw silk undergoes a series of industrial operations, namely twisting, warping, dyeing, printing, weaving, finishing, etc., to produce silk fabric for the market. This caterpillar is the basis of the silk industry, which provides a livelihood to 6 million people in India at various stages of the production process (Savithri et al. 2013).

<u>Cochineal insects - ancient origins of a modern dye</u>

The insect *Dactylopius coccus* (cochineal) is known as a source of dyestuffs. The red color obtained from *Dactylopius coccus* was discovered in ancient times in present-day Mexico (Chen et al. 2008, Bashir et al. 2022). Since the 16th century, the dye derived from this insect has been one of the most essential and basic dyes for the industry (Chen et al. 2011a, Bashir et al. 2022). Ancient North American tribes used animal-based dyes extracted from cochineal as a source of dye and lac pigment. Cochineal use has also been documented in the Peruvian Paracas culture as early as 700 BC (Köhler et al. 2009, Chen et al. 2011b). Cochineal-based coloring has been used in cultural heritage sites, such as textiles and paintings, since ancient times (Wang et al. 2022). Carmine is a chelate of carminic acid, which is a stable red dye. It is used to color foods and beverages and is also found in beauty products and pharmaceuticals (Chen & Feng 2009, Bashir et al. 2022). Carmine, derived from cochineal, has good stability in the presence of light, sulfur dioxide, heat, and water, and is stable to oxidation (Shamim et al. 2014). The Aztec, Inca, and Mayan peoples used a dye derived from the cochineal insect as both a paint and a natural dye (Koyama 1999, Zhang & Li 2013, Bashir et al. 2022). This animal-derived dye is one of the sources that provide natural color (Li 2018, Bashir et al. 2022). Carminic acid belongs to the class of anthraquinones, a group of some of the oldest dyes, which have been described in mummy wrappings dating back thousands of years (Gu et al. 2019). The cochineal insects produce the carminic acid molecule to protect themselves from predators (Haritos et al. 2012, Bashir et al. 2022). Since the 16th century, this source of dye has been utilized as a commercial product worldwide (Kayukawa et al. 2007, Bashir et al. 2022). Cochineals belong to the family Coccoidea of the order Homoptera. These insects are up to one centimeter long (Wang et al. 2016). Carminic acid can be used for spectrophotometric and quantitative analysis of various elements. In particular, this compound has been used as a reagent for the presence of the element boron (B), a group IIIA metalloid (Bousquet et al. 2012). Due to the presence of phenolic groups in carminic acid, it is a somewhat acidic molecule. The color of the solution depends on the pH (Lowe et al. 2017).

<u>Lac insects and shellac - from resin to industrial utility</u>

Some species of hemipteran scale insects from the genus *Kerria* (*K. chinensis*, *K. yunnanensis*, *K. lacca*, *K. ruralis*, *K. sindica*, *K. nepalensis*, and *K. pusana*) can produce a secretion known as shellac, which is also produced industrially (Wang et al. 2019, Bashir et al. 2022). Lac insects extract resin from the tree species *Croton lacciferus* growing in China, India, and Thailand, which they use as a host plant (Shah et al. 2015, Bashir et al. 2022), and over 400 other different host plant species have been recorded to date (Sharma 2017). Lac insects feed by sucking the phloem sap of host plants (Sharma et al. 2006). These species are very selective in their choice of host trees. They remain attached to the host tree throughout their lives, except for the male adult (Sharma 2018, Bashir et al. 2022). Polyterpene esters and hydroxyl fatty acids, as well as cyclic organic esters, are significant components of lac resin (Chen 2005). The biochemical pathways and molecular mechanisms underlying the production and secretion of shellac remain unclear. However, Wang et al. (2019) identified 28 putative genes involved in the production and secretion of this resinous product, including genes involved in fatty acid synthesis (which may produce hydroxyl fatty acids), terpenoid biosynthesis (which may be involved in the production of sesquiterpene acids), and UDP-driven glycosylation (which is indirectly or directly involved in the accumulation of activated sugars). Another study identified more than ten genes that may be involved in the biosynthesis of the lac dye pathway (Shamim et al. 2016). Lac is the umbrella term for the dried resinous substance secreted by insects (Talukder & Das 2020, Bashir et al. 2022). The composition of lac depends on the insect species, environmental conditions, and the host tree (Wang et al. 2019). In general, lac has three main components: dyes, resins, and shellac wax (Kaushik et al. 2018). Lac dye consists of an anthraquinone derivative, while shellac wax is a mixture of higher alcohol esters, acids, and hydrocarbons. Lately, lac and related products have been considered very valuable due to their properties, including biodegradability (Sharma &

Ramani 1999, Bashir et al. 2022).

Insect-mediated biological pest control

Biological control utilizes natural enemies to manage pest populations, with insects serving as key agents in this approach. More than 2,000 insect species have been used globally for biological control purposes against various pests in the past 120 years, demonstrating the widespread adoption of this eco-friendly approach (Francuski & Beukeboom 2020) (Table 1). The implementation of biological control strategies can be classified into three main categories: classical (importation), inductive (augmentation), and inoculative (conservation), each tailored to specific pest management scenarios. The orders Hymenoptera and Coleoptera are predominantly used, particularly in commercial applications (van Lenteren 2012). Parasitoid wasps (Hymenoptera) from the families Aphelinidae, Trichogrammatidae, and Braconidae are widely reared for the control of crucial agricultural insect pests in many countries (Wang et al. 2019). Representatives of the so-called flower bugs (Hemiptera: Anthocoridae), specifically the genera *Orius* and *Anthocoris,* are mass-produced as predators that prey on a wide range of arthropods, including spider mites, thrips, aphids, and insect eggs and larvae (Francuski & Beukeboom 2020). Other insect species, such as *Aphelinus abdominalis* (Dalman), *Eretmocerus eremicus*, *Encarsia formosa*, *Aphidius colemani*, *Dacnusa sibirica*, *Diglyphus isaea*, *Trichogramma evanescens*, *Anagyrus pseudococci*, and *Muscidifurax raptorellus*, are suitable as biological control agents for various species of aphids, mealybugs, whiteflies, leaf-mining flies, moths, etc. (Francuski & Beukeboom 2020). Sánchez-Muros et al. (2014) elaborated a comprehensive list of insects that had been commercially available in the EPPO region and North America as biological control agents. It consists of more than 160 species, mainly from the orders Hemiptera, Coleoptera, Hymenoptera, Lepidoptera, and Diptera. The implementation of insect-based biological control contributes significantly to integrated pest management strategies, offering an alternative or complement to chemical pest control methods in agriculture.

Insect-derived compounds in contemporary medicine and cosmetics

Insects and their products have long been celebrated for their remarkable contributions to human health and wellness, offering a fascinating interface between nature and science. From the healing properties of honey and propolis to the rejuvenating effects of royal jelly, these bioactive substances highlight unparalleled versatility in medicine and cosmetics.

Extracts from species like *Periplaneta americana* (L.) demonstrate therapeutic potential by aiding in the immune function and gastrointestinal health of patients with sepsis, a systemic inflammatory response syndrome (Zhang et al. 2016), while *Lucilia sericata* (Meigen) presents innovative applications in wound care and dermatology. The most common insect products used for medicinal and cosmetic purposes are those obtained as a result of the vital activity of bees: honey, propolis, wax, and royal jelly. Honey is produced by forager bees, which collect flower nectar and process it through repeated digestion and regurgitation. The acidic pH of the stomach, combined with the enzymatic activities of invertase, diastase, and amylase, results in a supersaturated aqueous solution composed of approximately 80% sugars, primarily fructose and glucose, with small amounts of sucrose, maltose, and other complex sugars. Most nitrogen is present in the form of amino acids and peptides. Proline is the most abundant amino acid, followed by glutamic acid, alanine, phenylalanine, tyrosine, leucine, isoleucine, and other minor ones. Honey also contains some protein, typically 0.1–1.5% in the Western honeybee *A. mellifera*, and 0.1–3.0% in the Asian honey bee *Apis cerana*. The most abundant peptides are defensin-1 and royal jelly protein (MRJP) isoforms, while the main enzymes include glucose oxidase, diastase (amylase), α-glucosidase, catalase, and acid phosphatase (Kubota et al. 2004, Di Girolamo et al. 2012, Chua et al. 2015). Data on the honey proteome are limited; however, it can be argued that each honey species has its peptide pattern, consisting of ubiquitous components and a variable set of minor elements, possibly including plant-derived peptides. Above, the medicinal properties of honey were mentioned – antioxidant (Gheldof et al. 2002, Petretto et al. 2015), antimicrobial (Brudzynski et al. 2011), antiparasitic (Mohammed et al. 2015), anti-inflammatory (Candiracci et al. 2012), and antidiabetic (Erejuwa et al. 2012). Honey has long been known for its ability to assist in superficial wound healing (Molan 2006, Vandamme et al. 2013).

Propolis is a resinous substance that bees produce for food by collecting resin from buds and other plant tissues and then mixing it with wax and pollen to obtain a malleable, compact substance that they use as a material for repairing hives and as a disinfectant (Sun et al. 2015). The chemical composition of propolis varies depending on its geographical and floral origin. Raw propolis typically contains more than 300 different compounds, consisting mainly of triterpenes (50% w/w), waxes (25–30%), and volatile mono- and sesquiterpenes (8–12%), which give propolis its typical resinous odor, and phenols (5–10%) (Huang et al. 2014). Propolis has been shown to exhibit antioxidant, antimicrobial, and antiviral activity (Viuda-Martos et al. 2008, Noronha et al. 2014, Bankova et al. 2014), as well as immunomodulatory, anti-inflammatory, and anticancer properties (Orsi et al. 2000, Armutcu et al. 2015). Royal jelly is a secretion from the honey bee hypopharynx and mandibular salivary glands. It is a white-yellowish, gelatinous, acidic colloid containing about 67% water (w/w), 16% sugar, 12.5% protein and amino acids, and 5% fat, with significant variability between different sources. Royal jelly also contains small amounts of enzymes, vitamins, phenols, and minerals (Melliou & Chinou 2005). Proteins are the most abundant fraction of dry matter, consisting of more than 80% of the soluble glycoproteins, called major royal jelly proteins (MRJPs), of which nine types have been described. Royal jelly possesses healing properties characteristic of honey and propolis, and it also has a positive influence on metabolic syndrome (Fan et al. 2016). Additionally, it exhibits neuromodulatory (Terada et al. 2011) and rejuvenating effects (Detienne et al. 2014).

Fly larvae are also used in medicine for healing wounds. Several studies have examined the use of *Lucilia sericata* maggots in treating patients with wounds. Čičková et al. (2013) investigated the growth and survival of *L. sericata* maggots used to debride traumatic, ischemic, diabetic, and venous ulcers in patients. They found that the survival of maggots after a 48-h cycle of Maggot debridement therapy (MDT) ranged between 63.6% and 82.7%. At the same time, maggots in venous ulcers had, on average, 9–19% higher mortality than maggots within traumatic, ischemic, and diabetic ulcers. It was shown that larvae in venous ulcers were significantly smaller after 48 h of treatment, but not after 72 h, compared to the other wound types.

The effect of salivary gland extract of *L. sericata* maggots on human dermal fibroblast proliferation within a collagen/hyaluronan membrane was studied in vitro using transmission electron microscopy (Polakovicova et al. 2015). These authors observed an increase in cell metabolism and protein production, and they suspected that this increase corresponded with the formation of microfibrils, which are primarily used for the proper production of the extracellular matrix.

A review describing the immunomodulation impact of maggot body components on the cellular and molecular levels of the wound healing process was also published by Bohova et al. (2012).

Insects as pollinators

Pollination by insects is a cornerstone of both natural ecosystems and agricultural production, representing one of the most critical ecosystem services provided by biodiversity. Insects such as *A. mellifera*, *Bombus terrestris*, *Megachile rotundata*, and *L. sericata* are key in this process (Francuski & Beukeboom 2020) (Table 1). Insect pollination is not only a key ecosystem function but also makes a significant contribution to the production of many crops worldwide. Of the approximately 300 crops (Richards 1993), more than 80% are pollinated by insects (Williams 1996). Insects are responsible for 80–85% of all commercial hectares pollinated (Williams 1996), with fruits, vegetables, oilseeds, legumes, and fodder crops (Richards 2001) accounting for approximately one-third of global food production (Buchmann & Nabhan 1996, Allen-Wardell et al. 1998), pollinated primarily by *Apis mellifera L.* (honey bees) (Free 1993). The majority of the world's staple foods are wind-pollinated, self-pollinated, or propagated vegetatively. There is a bias in the values attributed to insect pollination, which often come from high-value per unit crops (i.e., fruits, nuts, hybrid seeds, and intermediate products for the livestock and dairy industries) (Ghazoul 2005, Richards 1993, 2001). Some authors, therefore, argue that global food security would not be threatened if insect pollinators declined or disappeared; nevertheless, this ignores the diverse diets on which humans rely (Klein et al. 2007). Modern commercial crop production is increasingly dependent on managed pollinators (e.g., the introduction of honeybee colonies into orchards or fields to improve crop production) and less on wild insects living on the periphery of crop fields (Richards 1993). The honeybee is considered the most important commercial pollinator, and although other species of bees are also used for commercial pollination (alkali bees (*Nomia*), mason bees (*Osmia*), leafcutter bees (*Megachile*), bumblebees (*Bombus*)), at least 90% of the farming crop pollination is done by honeybees (McGregor 1976, Williams 1996). Honeybees are excellent pollinators, with commercial pollination being the most critical derivative value of commercial beekeeping worldwide (Morse & Calderone 2000). Despite the leading role of bees as pollinators in agriculture, over 20,000 insect species are contributing to pollination in nature, including other Apidae species (e.g., bumblebees, *Bombus*), chafer beetles, butterflies, hawk-moths (Sphingidae), and other Lepidopteran species, hoverflies (Syrphidae), and others (Hall & Martins 2020).

Insects as model organisms: contributions to modern science

Insects have emerged as invaluable model organisms in scientific research, facilitating significant advancements across various disciplines, including genetics, immunology, and ecology. Their short life cycles, ease of maintenance, and well-characterized biology make them particularly suitable for investigating complex biological processes. Species such as *Drosophila melanogaster* and *Galleria mellonella* provide critical insights into host-pathogen interactions, developmental biology, and the evolution of immune responses. The physiological and genetic similarities between insects and higher organisms enable researchers to explore mechanisms that are frequently conserved across species. Furthermore, insects offer ethical and cost-effective alternatives to vertebrate models, enabling large-scale experiments with minimal resources.

Drosophila melanogaster has been widely used in genetics, embryology, and developmental biology. *Bombyx mori*, *Galleria mellonella*, *Tribolium castaneum*, and *Dermestes maculatus* are the most commonly used species for research purposes (Francuski & Beukeboom 2020). The caterpillar larva of the large wax moth, *Galleria mellonella* (Lepidoptera: Pyralidae), is essential as a suitable host species for the mass rearing of parasitic, predatory insects and entomopathogenic nematodes (Killiny 2018). *Galleria mellonella* larvae have been utilized as a host and model system for various fungal and bacterial pathogens due to their limited innate immune system (Tsai et al. 2016) and ease of handling and rearing. Multiple organisms can be injected into the hemolymph of *Galleria*, where they can be maintained in vivo for up to 10 days and then isolated for purification or enumeration (Killiny 2018). However, in most virulence studies involving *G. mellonella*, pathogens have been injected to determine their LD_{50} and/or to monitor the production of antimicrobial peptides (AMPs), such as defensins and lysozyme (Bergin et al. 2006, Ramarao et al. 2012, Killiny 2018). The health of larvae after infection with various agents has been assessed by measuring activity, cocoon formation, melanization, and survival rates (Champion et al. 2016, Killiny 2018). *G. mellonella* has been used as a host model to study a variety of bacteria, including gram-positive bacteria such as *Enterococcus faecalis*, *Enterococcus faecium*, *Staphylococcus aureus*, *Streptococcus pyogenes*, *S. pneumoniae*, *Listeria monocytogenes*, and Gram-negative bacteria such as *Escherichia coli*, *Pseudomonas aeruginosa*, and *Klebsiella pneumoniae* (Tsai et al. 2016, Killiny 2018). In addition, *G. mellonella* larvae have been used to study several pathogenic fungi, such as *Candida albicans* and *Aspergillus fumigatus* (Harding et al. 2013), and serve as a model host for some trans-kingdom pathogens, including *Fusarium oxysporum* and *Pseudomonas aeruginosa* (Navarro-Velasco et al. 2011). The model species *G. mellonella* has also been used to evaluate the efficacy of bacteriophage therapy for treating pathogenic infections (Seed & Dennis 2009). It has demonstrated the ability to initiate a protective response against infection, making *G. mellonella* an excellent model species (Fuchs et al. 2010, Killiny 2018). Although many studies have been conducted to investigate the components of hemolymph about the innate immune response, the biology of *G. mellonella* is not yet well understood. The immune system of *G. mellonella* comprises both cellular and humoral responses (Tsai et al. 2016). The cellular response to invading pathogens is a direct response by hemocytes that engulf and immobilize the agent by phagocytosis (Bergin et al. 2006). The humoral response consists of melanization and production of opsonins and Antimicrobial peptides (AMPs). The opsonin apolipophorin-III, which exhibits a high affinity for bacterial lipopolysaccharide in insects, shares high homology with mammalian apolipoprotein (Tsai et al. 2016). The hemolymph of *G. mellonella* contains antimicrobial peptides (galerimycin and galiomycin) that degrade the cell walls of fungal or bacterial pathogens (Bergin et al. 2006, Killiny 2018). The synthesis and deposition of melanin serve to encapsulate pathogens at the wound site in insects (Tsai et al. 2016). Its readiness for infection and its ability to initiate a defense response make *G. mellonella* an excellent model organism for studying infection (Fuchs et al. 2010, Killiny 2018).

Conclusions

It is indisputable that insects, with their diverse life cycles, development, physiology, and functioning, are vital for human existence. They, as organisms and the products of their vital activity, have been an inseparable part of the lives of humans and other animals and plants for millions of years. They are indispensable in the functioning of global and local ecosystems, and the livelihood and survival of millions of people on the planet are directly related to them. The diverse bioecological roles they play, both in the past and in the present, underscore the inevitable need for them in many of the most important aspects of modern human existence. As the most numerous group of animals closest to human existence, and with the development of sciences such as zoology, applied entomology, and ecology in the context of the need for optimal resource management, it is inevitable that insects will have an increasingly direct impact on the functioning of human societies. The fact that, as a group, insects require significantly fewer resources to produce a unit of nutrient (proteins, fats, carbohydrates) and emit significantly smaller amounts of harmful emissions into the atmosphere compared to conventional livestock farming is a great advantage in the context of future challenges facing our planet and global ecosystem. Their various roles and applications will intensify in the future, and this is already being observed with the emergence and intensive development of larger farms for raising insects for multiple purposes. Rethinking the functioning of human communities on a global level in terms of pollution, deforestation, industrialization of conventional livestock farming, and tackling hunger confronts us with issues for which finding solutions will also include the participation of insects as a resource, since they have comprehensive and diverse, although still insufficiently well-studied, effects, roles, and applications. This should be a focus in future scientific research by specialists.

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