Policy Research Journal
ISSN (E): 3006-7030 ISSN (P) : 3006-7022 Volume 3, Issue 12, 2025

INSECT GUT MICROBIOTA: DIVERSITY, FUNCTIONAL ROLES, AND EMERGING ECOLOGICAL AND APPLIED PERSPECTIVES—A REVIEW

Kashaf Farooq[1], Fakhra Anwar[*2], Shahid Mahmood[*3], Hifza Tajammal[4], Mobeen Kausar[5]

[1, *2, *3,4,5]*Department of Zoology, University of Gujrat, Gujrat 50700, Pakistan*

[*2]fakhra.anwar@uog.edu.pk, [*3]shahid.mahmood@uog.edu.pk

DOI: https://doi.org/10.5281/zenodo.20505340

Keywords
Gut microbiota, Microbial symbiosis, Metagenomics, Pests control, Pollinators

Article History
Received: 03 November 2025
Accepted: 17 December 2025
Published: 31 December 2025

Corresponding Author: *
Fakhra Anwar
Shahid Mahmood

Abstract
Insects are the species-rich and ecologically significant animals inhabiting our planet. They perform vital ecosystem services such as pollination, nutrient recycling, and are involved in food webs and agriculture. Gut microbiota, complex microbial communities residing within the digestive tracts of insects, play an important role in shaping the success of insects in their environment. This review discusses insect gut microbiota in terms of its diversity and functional attributes that can contribute to ecological and applied relevance. The insect gut is taxonomically diverse and includes bacteria, archaea, fungi, and protists. Furthermore, the anatomical division of the insect stomach into the foregut, midgut, and hindgut provides distinct environmental variables, including pH, redox potential, and digestive enzymes, which determine the organization of the gut microbial population. Recent developments in next-generation sequencing approaches like 16S rRNA amplicon sequencing, shotgun metagenomics, and metatranscriptomics have allowed researchers to study gut microbial diversity and functions with great depths. Gut microbes can confer several benefits to their host including nutrition, detoxification of host-plant toxins and pesticides, immune defense, and regulation of host development and reproduction. Ecologically, insects and their gut microbes shape host-plant relationships, insect behavior and social interactions, tolerance to abiotic stresses, and insect-microbe-plant networks involved in ecosystem functioning. Practically, gut microbiota can be exploited for biological pest control using Wolbachia-based bio pesticides and microbial symbionts. Gut microbes of pollinators can be targeted for probiotics and prebiotics to increase pollinator fitness. Microbial enzymes could be utilized for various industrial applications. Finally, this review highlights major knowledge gaps in gut microbiota including modes of inheritance, functional redundancy, and responses to environmental disturbances. Future research that combines various omics approaches with ecological experiments will be crucial for unlocking the full potential of insect gut microbiota in agriculture, conservation, and biotechnology.

Introduction

Insects are the important group of species in the whole world. There are approximately more than 10 lakh species of insects but, many have not yet been discovered (Stork, 2018). Insects are terrestrial, aquatic, and are also found in forests.

They play a major role in ecological pollination, as approximately world's 75 percentage of flowering plants and 35 percentage of food production depends on them. (Klein et al., 2007).

If insects don't exist, then our crops will be destroyed. Insects are also an important part of food web, many vertebrates like birds, reptiles, amphibians and mammals feed on them. If insect's population decrease, then whole ecosystem will be destroyed. (Hallmann et al., 2017).

Globally, the economic value of pollination is calculated about hundreds of billion dollars each year. Due to this reason, pollinating insects are considered the world's most valuable organism (Klein et al., 2007; Hallmann et al., 2017).

Besides pollination insects play vital role in nutrient cycling and disintegration. They breakdown the remains of dead and decaying plants and animals and bring back nutrients to the soil. It maintains the soil fertility and establish the balance of ecosystem (Stork, 2018).

Recent studies has reported the alarming decline in the insects population, Also a long term study shows that in 27 years more than 75% reduction is observed in flying insects biomass. This indicates that insect's conservation is urgent (Hallmann et al., 2017).

In agriculture insects play dual role, beneficial insects provide pollination and pests control for crops. Whereas, most of the insects are economic pests that damage the crops. Globally, each insect pests cause 18%-20% crop yield loss (Oliveira et al., 2014).

Insect pests not only damage the crops but also spread pathogens through affected plant. Aphids, whiteflies and leaf hoppers transmits the viral, bacterial and fungal diseases which is a threat to staple crops. That's why, its essential to understand the insect's biology and their gut microbial communities, for agricultural sustainability and food security.

Gut microbiota refer to those microorganisms that live in animal digestive system. It includes bacteria, archaea, fungi, viruses and protists (Engel & Moran, 2013).

These microorganisms are in mutual interaction with the host and influence the physiology, metabolism, immunity and behavior of the host. Earlier, gut microbes were thought to be commensals which were not much important for the host. But the development of the culture-independent molecular tools shows that the gut microbiota are essential partner for host (McFall-Ngai et al., 2013; Douglas , 2015).For example, wood feeding termites rely on hindgut microorganisms that degrade the lingo cellulose. If these microbes are removed by the antibiotics or by other methods, then termites will starve to death even food is available (Brune, 2014; Brune & Dietrich, 2015). Gut microbiota play critical role in pathogens and immune system resistance. Microbial colonization calibrates the gut immune pathways due to which host can response accurately against the harmful pathogens (Buchon et al. 2013).

Moreover, microbiota gut influences the fitness of the host, in which development rate, reproduction and behavior are included. All these effects shows the importance of the gut microbial communities in insects biology (Douglas, 2015; McFall- Ngai et al., 2013).Due to the decline in pollinators population and increase in agricultural pests management problem the study of gut microbiota has become more important (Raymann et al., 2017).

There are many types of microorganisms that are present in insect's gut microbiota, which belongs to different group of life. Mostly, bacteria, archaea, fungi and protists are present in them. Among them bacteria are the most common and most studied members, which are present in insect gut communities. Research on different insect group reveals that usually Proteobacteria, Firmicutes, Bacteriodetes, Actinobacteria and Tenericutes are included in dominant bacterial phyla. The exact alignment of bacterial communities depends on insect species, its diet, life stage and its environment where it lives (Engel and Moran, 2013; Colman et al., 2012). Some insects have very simple and specialized gut microbiome. For example, in gut of honeybee Apis mellifera a small group of 8 to 10 bacterial types is present which is also consistently present in different colonies and geographical regions (Kwong & Moran, 2016).

On the other hand, insects that feed on different type of diets like cockroaches and termites their gut have complex bacterial communities. This diversity is due to their diverse diet and presence of different microenvironments in their gut (Brune and Dietrich, 2015).

In some insects Archaea plays an important role especially, methanogenic Species which are present in hindgut of termites, cockroaches and beetles. They use hydrogen form, during the fermentation and create environment that breaks the lingo cellulose (Brune, 2014).

Earlier these were considered less important because they grow with deficiency in laboratory culture methods, but metagenomics techniques clearly show their importance (Hongoh, 2010).

In lower termites, flagellate protists that live in hindgut ferments the cellulose and are in symbiotic relationship with bacteria. This multilayered symbiosis is very important if its get disturbed then termites will die with hunger (Ohkuma, 2008; Hongoh, 2010).

Different factors change the composition gut microbiota of insects. Diet is the most important factor because bacteria communities are richer in herbivorous insects as compared to carnivorous insects. Change in diet can restructure the communities (Colman et al., 2012; Yun et al., 2014; Broderick & Lemaitre, 2012).

Host phylogeny also shape microbiota which is known as Phylosymbiosis where closely related insect species have similar gut communities especially in obligate endosymbionts that have co-evolve with their host over million years (Moran et al., 2008; Kwong & Moran, 2016). Developmental stage also affects the gut microbiota. During the metamorphosis stage in holometabolous insects, gut remodeling takes place that change microbial community between the larval and adult stages (Engel & Moran, 2013; Hammer et al., 2017).

Habitat also play important role because there are more diverse microbial communities in soil dwelling insects. Pesticides and antibiotics disturbs gut microbiota severely like in honeybees, herbicides exposure has increase the susceptibility for pathogens (Yun et al., 2014; Chandler et al., 2011; Raymann et al., 2017).

Insect gut consists of structurally three different parts, foregut, midgut and hindgut. Each part makes its own physiochemical and microenvironment where different type of microbial communities lives (Chapman, 2013; Terra and Ferreria, 1994). Foregut and hindgut are lined with the chitinious cuticle that renewed at every molt. Midgut is protected by peritrophic matrix it regulates microbe's access and maintain compartmentalization in gut (Hegedus et al., 2009). Social insects like honey bees has specialized part of foregut know as crop. It harbors lactic acid bacteria that plays significant role in food preservation and of colony health (Vásquez et al., 2012).

Midgut, the primary place of enzymatic absorption and nutrient absorption where hydrolytic enzymes and antimicrobial compounds secretion is created by a chemically hostile environment it selects the strong resident microbial communities (Buchon et al., 2013; Terra & Ferreria, 1994). Hindgut especially of termites have a high density microbial compartment where more than 10^{10} cells per milliliter microbes are present. It works like an anaerobic fermentation chamber where oxygen tolerant and strictly anaerobic microorganisms spatially stratified communities live together (Brune, 2014; Hongoh, 2010; Brune & Dietrich, 2015).

The PH of insect's gut vary dramatically in different insect's taxa. It can exceed PH 11 in Lepidoptera's midgut under highly alkaline condition. Where as in bee crop acidic condition is found in less than PH 3 (Brune et al., 1995; Vásquez et al., 2012). These extremes perform different biological functions, alkalinity solubilize the plant protein whereas acidity favors the acid tolerant symbionts and suppress the pathogens (Vásquez et al., 2012; Terra and Ferreria, 1994).Oxygen availability also produce important gradients, especially in large insects. Where steep radial oxygen profiles make aerobic, micro aerobic and anaerobic zone at hundred micrometer distance, and help in sequential anaerobic fermentation of lingo cellulose (Brune et al., 1995).

Other than that digestive enzymes like proteases, lipases and amylases along with the host- derived antimicrobial peptides and reactive oxygen species create a selective chemical environment. Where only those microorganisms can establish a stable gut population which are adapted to these conditions (Hegedus et al, 2009; Buchon et al. 2013; Ryu et al., 2008).

Classical culture dependent approaches have provided the basic information about insect gut microbiology. But their biggest limitation was the cultivation of majority of gut microorganisms in the laboratory. Estimates shows that bacteria present in complex gut communities can be recovered less than 1% by using standard cultivation methods (Dillon& Dillon, 2004; Hongoh, 2010; Engel & Moran, 2013).

Culture independent molecular methods has dramatically transform this field. These methods enable the characterization of gut communities through DNA extract. Earlier techniques like 16SrRNA clone libraries reveal the extraordinary bacterial diversity in termite guts. Whereas fluorescence in situ hybridization (FISH) has made it possible to visualize the intact gut compartments in specific taxas (Ohkuma, 2008; Hongoh, 2010; Brune & Dietrich, 2015).

High-throughput 16S rRNA sequencing provides the facility to make hundreds of profile samples of gut microbial communities at a time. Standardized pipelines like QIIME2and DADA2 makes the results reproduce able and reliable (Caporaso et al., 2010; Callahan et al., 2016).Shotgun metagenomics sequence all the DNA of community and help to discover new enzymes with biotechnological application (Warnecke et al., 2007; Colman et al., 2012).Metatranscriptomics capture those genes that actively express under real physiological conditions, that provide direct microbial activity perspective (Broderick & Lemaitre, 2012; Engel & Moran, 2013).

The integration of these multiomic tools with experimental approaches helps to understand gut microbiota in a more precise way (Broderick & Lemaitre, 2012; Callahan et al., 2016).

Functional Role of Gut Microbiota

The microbiota gut of insects consists of a variety of microorganisms, including fungi, bacteria, protozoa, and archaea that form symbiotic relationships with their hosts. Insect physiology, metabolism, and ecological adaptation all depend on these microbial ecosystems. Gut microbes play important role in digestion, food synthesis, immune modulation, detoxification activities that improve host fitness and survival in many insect species (Engel & Moran, 2013).

Insects have high nutritional value, has a 40 to 75 percentage protein content and high levels of B vitamins, unsaturated fatty acids, important amino acids, and inorganic elements (Singh et al., 2023). Caterpillars, crickets, locusts, termites, and beetles are among the insects frequently consumed in culinary traditions of various cultures (Munialo et al., 2018). Compared to livestock production, raising insects requires minor energy, water, land and emits fewer greenhouse gases. Insect proteins can be enzymatically hydrolyzed to produce bioactive peptides with antihypertensive, antibacterial, and antioxidant properties (Singh et al., 2023).

Insect powders are increasingly used in North America and Europe, often added to meat or soy-based products to enhance nutritional profiles without compromising texture (Krawczyk et al., 2024; Ronchetto et al., 2024). Insects are heterotrophic organisms, acquiring essential nutrients from their diet through diverse feeding strategies, including herbivory, carnivory, and hematophagy, each with specific structural and molecular modifications (Chapman, 2013).

Many insects benefit nutritionally from long-term relationships with microbes that digest or detoxify food or synthesize vital nutrients. Symbiotic bacteria help wood-feeding insects, such as lower termites, digest cellulose and supply critical amino acids. Microbes also provide B vitamins for blood-feeding insects and can influence host plant utilization (Dadd, 1985; Miguel-Aliaga et al., 2018).

Microorganisms may concentrate nitrogen, utilize nitrogenous waste, and synthesize essential amino acids and nitrogen fixing. For example, fungi developed by Macrotermitinae termites produces nitrogen-rich nodules for consumption. Mycetocyte symbionts in phloem-feeding aphids synthesize essential amino acids for the host (Douglas, 2006; Shigenobu et al., 2000; Tamas et al., 2002; Van Ham et al., 2003).

Similarly, the glassy-winged sharpshooter (*Homalodisca vitripennis*) hosts two bacteria with complementary metabolic capacities, producing vitamins and amino acids (McCutcheon & Moran, 2007). Microbes can also provide detoxification, as seen in attine ants cultivating Leucoagaricus fungi externally in the nest (North et al., 1997).

Gut bacteria assist in lipid and protein digestion, detoxification of secondary plant compounds, and influence insect endurance, size, and reproduction (Coon et al., 2014; Visôtto et al., 2009; Dillon & Charnley, 2002). They also contribute to pesticide resistance (Kikuchi et al., 2012).

Detoxification of enzymes, help insects metabolize plant toxins. Phase I reactions (oxidation, reduction, hydrolysis) modify plant metabolites for easier excretion (Feyereisen, 1999, 2012; Li et al., 2004, 2007). Examples include hydroxylation of abietane diterpenes by Spodoptera litura P450s and glucosylation of (S)-naringenin by *Tetranychus urticae* UDP-glycosyltransferases (Fahey et al., 2001; Xu et al., 2016).

Some kinases may detoxify plant-specific compounds via phosphorylation (Feyereisen, 2012; Xia et al., 2018). Detoxification gene families are extensive across herbivorous insects, with broad substrate specificity, and are also present in pollinators and sensory organs protecting against toxins (Berenbaum, 2002; Johnson et al., 2013; Kwong et al., 2017; Wang et al., 2018).

Gastrointestinal tract (GIT) regulates microbial, physiological, and immune processes, helping hosts resist infections and ecological stressors (Engel & Moran, 2013; Broderick & Lemaitre, 2012; Dillon & Charnley, 2002). In insects gut microbial communities interact with host immune system. It influences the production of antimicrobial peptides, pathogens resistance and immune signaling pathways (Engel & Moran, 2013; Broderick & Lemaitre, 2012; Douglas, 2015).

Microbial symbionts produce metabolites that can influence gut physiology. They can also modulate the host immune responses (Engel & Moran, 2013; Dillon & Charnley, 2002). In insects, host immune signaling senses the microbial activity and also coordinate defenses against pathogens. It contributes in gut homeostasis (Broderick & Lemaitre, 2012; Engel & Moran, 2013).

The epithelial cells of insect gut interact with both symbiotic and pathogenic microbes. The microbiota colonization provides resistance and modulate the immune responses (Engel & Moran, 2013; Dillon & Charnley, 2002; Broderick & Lemaitre, 2012).

Microbes influence host development, behavior, and immune function, and can provide evolutionary novelties for colonizing new habitats (Belkaid & Hand, 2014; Dinan & Cryan, 2017; McFall-Ngai, 2007). Microbial communities can be species-, tissue-, and stage-specific, acquired horizontally (environment or conspecifics), vertically (parent to offspring), or both (Bright & Bulgheresi, 2010; Funkhouser & Bordenstein, 2013; McFall-Ngai et al., 2013; Round & Mazmanian, 2009).

Vertical transmission ensures consistent transfer across generations and promotes host-symbiont coevolution, impacting reproductive success (Funkhouser & Bordenstein, 2013; Moran & Sloan, 2015; Russell et al., 2009; Sachs et al., 2011). Transmission occurs through gametes, embryos, egg smearing, and parent-offspring interactions (Belkaid & Hand, 2014; Zapién-Campos et al., 2017).

Microbial migration between hosts and the environment also contributes to host-microbe evolution (Leftwich et al., 2018; Martinez et al., 2014; Roughgarden, 2020; Van Vliet & Doebeli, 2013; Turnbaugh et al., 2007; Van Leeuwenhoek, 1677).

The microbiota of insect gut has great significance in defining ecological relationships among insects, plants, microorganisms, and the surrounding environment. Recent ecological research has highlighted that microbial symbionts affect insect feeding, host exploitation, adaptation to diverse environmental conditions, and interaction with the ecosystem. Those microorganisms help insects to obtain nutrients, detoxifying plant secondary metabolites, as well as adapting to various ecological niches. These kinds of relationships are key to interpreting the success of insects as ecological entities and it may provide means for sustainable pest control (Douglas, 2018; Engel & Moran, 2017).

Alkaloids, phenolics, terpenoids and glucosinolates are typical active defense compounds of the plant tissues commonly targeted by herbivorous insects. In general, only a select few insect species can feed on chemically defended plants; however, the presence of symbiotic gut microorganisms allows insects to accomplish this. Whereas gut microbiota is vital for the detoxification of plant secondary metabolites and digestion, thus enabling insects to utilize

Hammer and Bowers (2015) put to the test the idea that gut microbes are what allow insects to make a meal of chemically defended host plants. They showed these microbial symbionts will break down the plant's toxic compounds so the insect can get by on its diet. In this way, the microbes mediate herbivory (Hammer & Bowers, 2015; Zhang, Zhang, & Xu, 2023).

What an insect eats have a lot to do with the diversity and make up of its gut microbiota. Take the case of *Riptortus pedestris*, a soybean pest in China. (Shan et al., 2024) found the insect is quite selective in putting together its gut bacteria from what is available in the soil or on plant surfaces. The resulting microbes give the insect an edge in terms of growth, reproduction and adapting to its environment. You see the same thing with the fall armyworm, *Spodoptera frugiperda*. Research into this invasive species shows a strong link between diet and microbial diversity. With the help of dominant Proteobacteria, Firmicutes and Bacteroidetes to detoxify and digest, the worm can put down over 350 species of plants, which is no doubt why it has become such a nuisance to agriculture. (Shan et al., 2024).

In Drosophila melanogaster, certain bacteria such as *Lactobacillus* and Acetobacter control feeding habits and food choice by disrupting metabolic signaling pathways (Wong et al., 2017). Microbial symbionts also produce volatile compounds that affect mate choice and reproductive behavior (Engl & Kaltenpoth, 2018). Social insects like honeybees, ants, and termites rely on gut microbiota for colony stability. Raymann, Shaffer, and Moran (2017) showed that disrupting gut microbes in honeybees impaired behavior, learning, and survival. Termites transfer gut microbes through trophallaxis, which maintains colony stability (Otani et al., 2019).

Gut bacteria can influence mating preferences. Sharon et al. (2016) found that differences in microbial communities, influenced by diet, altered reproductive compatibility in fruit flies. Additionally, microbial metabolites affect the gut-brain axis, influencing locomotion, learning, and stress responses (Schretter et al., 2018).

Insect gut microbiota aids adaptation to environmental changes and stress. Factors such as temperature, habitat shifts, pesticides, nutrition, and pathogens influence survival. Gut microbes enhance metabolic plasticity, detoxification, and immune response (Douglas, 2018; Engel & Moran, 2017).

Temperature, among the most important environmental elements affect insect physiology also endurance. Zhang, Zhang, and Xu (2019) reported that gut microbes in *Plutella xylostella* adjust microbial composition under high temperatures to support host metabolism. Resistance to chemical stressors such as pesticides is also influenced by gut microbiota. In *Riptortus pedestris*, gut symbionts degrade organophosphate insecticides, providing resistance to chemical stress (Kikuchi et al., 2016). Nutritional stress is another challenge in natural ecosystems. Many insects inhabit nutrient-limited environments, and gut microbes compensate by producing essential nutrients which support growth and reproduction (Douglas, 2018).

Insects interact with plants and diverse microorganisms, forming complex ecological networks. Insect gut microbiota mediates trophic interactions, nutrient cycling, and ecosystem stability (Brune, 2018; Shan et al., 2024). When herbivorous insects feed on plants, microbial components from their gut may be transferred to plant tissues via saliva and feeding behaviors. These microbial signals can trigger plant defenses and alter plant chemical phenotypes. Frago, Dicke, and Godfray (2017) showed that herbivore gut microbes influence plant volatile emissions, attracting predators and parasitoids, and indirectly regulating food webs.

Applied perspectives and future directions

In 1924, Hertig and Wolbachia discovered the genus Wolbachia, which is a member of the phylum Alphaproteobacteria's family Rickettsaceae, in a mosquito (*Culex pipiens*). Wolbachia mainly refers to *Wolbachia pipientis*, despite the fact that there were other recognized taxa at first. To identify the various Wolbachia isolates, specific genome (DNA) sequences are targeted, (Bordenstein & Rosengaus, 2005)

Alphaproteobacterium Wolbachia is an essential component of symbiotic microorganisms worldwide (Bordenstein & Theis, 2015) (McFall-Ngai, 2008). The morphologies of several Wolbachia species, including WRi, WPip, WBm, and wMel, have been defined by genetic research (Duplouy et al., 2013).

Wolbachia has proven to be an effective biocontrol of mosquitoes in the search for novel control methods because it not only reduces vector competency but also shows a significant level of maternal transmission in a variety of species, including St. aegypti. In the specimen of embryo cytoplasm transfer from a similar mosquito species (*St. albopicta*), strong appearance of the wAlbB strain in St. aegypti was noted (Xi et al., 2005).

In insect-microbe interactions, the host, insect and the bacterial component is the symbiont. Typically, symbionts are microorganisms like fungi, bacteria, and archaea (Crotti et al., 2012). The majority of symbionts that have close relationships with their host insect (Kikuchi, 2018). The major symbiont in insects including psyllids, aphids, and tsetse flies provides protection and produces essential nutrition (Crotti et al., 2012). For example, Candidatus Portieraaley rodidarum Costa is the principal symbiont of whiteflies, *Bemisia tabaci Gennadius* (Hemiptera: Aleyrodidae). Henceforth referred to as *Portiera* sp. Similar to Portiera sp., certain significant symbionts of insects supply their whitefly hosts with vital carotenoids and amino acids (Sloan & Moran, 2012).

Buchnera aphidicola Munson et al. Erwiniaceae is another example of a significant symbiont. It is present inside bacteriocytes, the abdominal body cavity of almost all aphids and supply essential amino acids that are absent in the insects' phloem sap diet (Shigenobu et al., 2000).

Secondary symbionts, usually show less host-specific commitment and are more varied. While certain bacteria, referred to as mutualists, are helpful to their host, others, referred to as parasites or pathogens, are harmful. Insects frequently engage in mutualistic interactions, forming a variety of alliances with microbes. High-temperature tolerance, parasitoid resistance, defense against dangerous viruses, and toxin manufacturing are all made possible by symbiotic bacteria (van den Bosch & Welte, 2017).

These microorganisms contribute significantly to insect growth by improving their capacity to adapt to a variety of situations (Kikuchi, 2018). Mass-rearing insect for food has been recognized as a profitable industry, and current forecasts indicate that the market will expand by 47 percentages between these years 2019 and 2026 (van Huis et al., 2013). Production levels are predicted to reach 730,000 tons by 2030 as a result of this expansion (Halloran et al., 2018).

Literature has documented the consumption of more than 1900 insect species globally (Jongema, 2017).

Small number of species, meanwhile, are intensively mass-reared. Mass-rearing insects faces similar difficulties to traditional intensive livestock production, including high densities, high rate of pathogen, increased vulnerability to infections because of oxygen deprivation, high temperatures, and dietary inadequacies (Smetana et al., 2019; van Huis et al., 2020).

Use of antibiotics has been a way to address some of these issues, but there is a chance that some antibiotic-resistant "superbugs" will emerge and endanger the health of both humans and animals. As a result, Probiotics are described as "live microorganisms that, when given in sufficient amounts, confer a health benefit on the host." has become more popular (Food and Agriculture Organization & World Health Organization, 2002).

It is now clear that every organism from humans to invertebrates, including insects—is connected to a microbial ecosystem that ranges from parasitic to mutualistic. Researchers have recently focused on the gut microbiota in particular because of its connection to the health of its host; numerous studies suggest that taking use of these microbes could increase animal productivity while preserving their health and well-being (Engel & Moran, 2013; Douglas, 2015).

The behavior and evolution of many insect species are significantly influenced by interactions between insects and their microbiome (Engel P & Moran N A, 2013; Sharon G et al., 2010).

Number of bacteria can alter the behavior of their hosts in order to spread more widely. For instance, Wolbachia can alter its hosts' preferences for mating when it functions as a symbiont, and the presence of foreign gut bacteria or a lack of microbiota can alter insects' eating habits by altering their sense of smell (Engel P & Moran N A, 2013). Certain microbes in mass-reared insects have been linked to growth, conversion, and reproduction (Douglas A E, 2015).

In this circumstances, insect diets play a crucial role in supplying nutrients to both insects and microbes. Prebiotics are described as selectively fermented ingredients that allow specific changes in the gastrointestinal microbiota that confers benefits upon host wellbeing and health. These nutrients can be highlighted within its composition (Gibson G R & Roberfroid M B, 1995).

Each organism has a microbial ecosystem that could be beneficial to its health. The discovery of probiotics made it possible to investigate how giving helpful microbes to insects affects their health. The impact of the microorganisms is specifically evaluated in terms of enhancing growth and reproduction as well as lowering the incidence of illnesses under stressful rearing circumstances. Probiotics are defined worldwide by the World Health Organization as "alive microorganisms, provide the host with a health benefit when given in sufficient quantities. (FAO & WHO, 2002). However, there are still situations where this definition is ambiguous, leading to debate and misunderstanding. Microorganisms that are supplemented to insects are distinguished from commensal intestinal bacteria that may provide the insect with health benefits (Savio C et al., 2022).

The latter are sometimes mistakenly referred to as probiotics, although this necessitates their isolation, characterization, and subsequent validation of their health-promoting benefits (Savio C et al., 2022). When researchers found that human milk included a unique growth-promoting component that supported growth of the probiotics (Tissier) in the early 1950s, the idea of prebiotics was born (Tissier H, 1900).

Gibson and Roberfroid later gave these components names called prebiotics, which are characterized as "no digestible food ingredients that try to improve host health by stimulating the growth and activity of one or a limited number of bacterial species already resident in the colon." In other words, these are the proteins that support the growth of the probiotic microbes in the gut (Gibson G R, 2004).

Most of these nutrients consist of inulin, oligofructose (produced from inulin), fructooligosaccharides (FOS) synthesized from sucrose, oligosaccharides containing galactose and xylose, resistant starch (RS), pectin, and other fermentable fibers. (Roberfroid M B, 2007).

Probiotics and prebiotics were soon neatly integrated into a single synergistic box called symbiotic (Gibson G R & Roberfroid M B, 1995; Swanson K S et al., 2020).

Insects raised in large quantities are particularly vulnerable to illnesses brought on by organisms from various phyla of bacteria, viruses, fungi, Protista, and nematode (Savio C et al., 2022). Therefore, one of the main objectives of both businesses and researchers is to find a way to stop these illnesses and improve the growth and reproductive capabilities of insects raised for food and feed (Savio C et al., 2022). Heat shock/thermal therapy, biological control, RNA interference, breeding of tolerant strains, mechanical pest management, differential breeding, and daily commitment to hygiene habits were some of these techniques. Because probiotics can improve host performance and boost immune responses to pathogens, they have also been thought of as a potential means of lessening the effects of illnesses (Maciel-Vergara G et al., 2020; Savio C et al., 2022).

Most known probiotic bacteria are Lactic Acid Bacteria that have high immune system response in humans (Savio C et al., 2022). The Lactobacillus genus has demonstrated antibacterial effects and immune-regulating effects when the pathogens Pseudomonas aeruginosa (Gessard) and *Nosema* spp. infect the microbiota of the silkworm Bombyx mori and the honeybee *Apis mellifera* (L.) (Hymenoptera: Apidae), respectively (Savio C et al., 2022; Upfold J K et al., 2022).

Observations of *Galleria mellonella* have demonstrated the antibacterial properties of *Lactobacillus reuteri* and *Lactobacillus rhamnosus* against *Staphylococcus aureus*, *Escherichia coli*, *Candida albicans*, and *Pneumonia aeruginosa*. (Savio C et al., 2022; Upfold J K et al., 2022; Mugo-Kamiri L et al., 2022).

Alongside small-molecule RNA interference methods and supplements, probiotic strains have been evaluated for their effectiveness against Nosema ceranae in honeybees, aiming to decrease spore burden and viability while enhancing survival and performance. (Upfold J K et al., 2022).

Lactobacillus and *Bifidobacteria* affected the pathogens at the genus level, however when honeybees were given *Lactobacillus rhamnosus* and sucrose to lessen the effect of *N. ceranae*, increased mortality rates and decreased phenol oxidase production were noted (Upfold J K et al., 2022; Savio C et al., 2022; Mugo-Kamiri L et al., 2022).

Studies on *Drosophila melanogaster* and *Galleria mellonella*, respectively, infected with diaporthe FY and *Candida albicans*, have demonstrated the beneficial benefits of *Lactobacillus* spp. on fungal-infected hosts (Savio C et al., 2022; Upfold J K et al., 2022).

Other genera, such as Enterococcus, have been researched for their potential to overcome the prevalence of bacterial diseases. *E. mundtii* positively influenced the immune responses of *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) to *Bacillus thuringiensis* infections (Savio C et al., 2022).

Regarding viral illnesses, it is still unclear how probiotics activate either general or insect-specific immune responses (Upfold J K et al., 2022). Even though endosymbionts are not considered probiotics, it is important to note that the occurrence of Wolbachia and Spiroplasma, which enhance protection against viral infections in T. molitor and G. mellonella, is responsible for the majority of the good outcomes (Upfold J K et al., 2022; Mugo-Kamiri L et al., 2022).

It's significant to note, nevertheless, that certain bacterial species that were isolated from shrimp have demonstrated antiviral efficacy in plaque assay and have improved fitness performance in shrimp who have contracted the white spot syndrome virus. This illuminate's potential method for examining insect microbiome for the same (Savio C et al., 2022; Upfold J K et al., 2022).

The World Gastroenterology Organization states that the genera Lactobacillus, Saccharomyces, Streptococcus, and Bacillus are most often investigated probiotics for insects raised for food and feed (Savio C et al., 2022). Some of the seven core microbes that are most frequently utilized as probiotics. Enterococcus frequently serves as a common symbiont of the insect stomach, particularly in Lepidoptera, it is an underrepresented category. This might be partly because Enterococcus species contain both probiotic and harmful strains (Upfold J K et al., 2022; Mugo-Kamiri L et al., 2022).

However, Grau et al. reported an instance of its possible application as a probiotic when they extracted an E. mundtii strain from the feces of Ephestia kuehniella (Zeller) (Lepidoptera: Pyralidae), which showed antimicrobial effects on several Gram-positive and Gram-negative bacteria and improved survival rates in *Tribolium castaneum* beetles after infection with Bacillus thuringiensis (Savio C et al., 2022)

Conclusion

Gut microbiota of insects is among the most diverse and important microbial systems on Earth. This review tells us that the communities of bacteria, archaea, fungi and protists that live in the guts of insects are not just sitting there. Insect guts and the communities of bacteria, archaea, fungi and protists that live in them actually do a lot of things to help the insects they live in. The way the insect gut is set up and the special chemicals in it create homes for the bacteria, archaea, fungi and protists that live there. This helps a lot of types of bacteria, archaea, fungi and protists to live in the insect gut and do different things to help the insect. The communities of bacteria, archaea, fungi and protists that live in insect guts are very important for the insects. They help the insects get the nutrients they need. They also help get rid of things that the insects might eat. The communities of bacteria, archaea, fungi and protists that live in insect guts help keep the insects healthy and help them grow and have babies. Insect guts and the communities of bacteria, archaea, fungi and protists that live in them also help the insects interact with the plants and the environment around them. This affects how insects eat plants and help plants make seeds. It also has an impact on the decomposition of dead plants and animals and how nutrients are moved around in the environment. Insect guts and the group of bacteria, archaea, fungi and protists that live in them are very important for people too. We can use the bacteria, archaea, fungi and protists that live in insect guts to help control insects that spread disease. We can also use them to help get rid of pests that eat crops. Insect guts and the communities of bacteria, archaea, fungi and protists that live in them can even be used to help make foods and fuels. The groups of bacteria, fungus, protists, and archaea that inhabit insect guts are still mostly unknown to us. We do not know how the insects get the bacteria, archaea, fungi and protists that alive in their guts. We do not know what happens if some of the bacteria, archaea, fungi and protists that live in the insect gut die. We also do not know how the communities of bacteria, archaea, fungi and protists that alive in insect guts will be impacted by climate change and things that people do. We need to do research on the communities of bacteria, archaea, fungi and protists that live in insect guts. We need to use tools to study the bacteria, archaea, fungi and protists that alive in insect guts. We also need to do experiments to see how the communities of bacteria, archaea, fungi and protists that live in insect guts affect the insects and the environment. Insect guts and the communities includes bacteria, archaea, fungi and protists that are alive in them are very important for people and, for the environment. We need to take care of them so that we can have food and a healthy environment.

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