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Report on the future of insects and ecosystems: Research and Management for sustainability

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Abstract- The importance of insects in an ecosystem is well-established by different researchers. Due to the anthropogenic interventions, the relationship between insects and ecosystems mainly in agro-horticultural areas came under threat. Chemical fertilizers and insecticides have an impact on the life-table parameters of insects both pests and other non-pest insects. The objectives of this article are to focus on the core areas of research and management for the sustainability of integrated pest management. The causes of the diversity threat of insects were habitat loss, climate change, pollution, pesticides, invasive species, and overexploitation. The future of insect management depends on IPM strategies, biological control, genetic control, precision agriculture, sustainable farming practices, and citizen science. Fruitful utilization of recent technologies like RNA interference, autonomous robots, gene editing, nanotechnology, artificial intelligence (AI), and drones are game-changers in the management of insects and ecosystems.

Key words: Horticulture, Fertilizers, Pest insects, Integrated pest management, nanotechnology, AI

INTRODUCTION

A popular quote is - "*If all mankind were to disappear, the world would regenerate back to the rich state of equilibrium that existed ten thousand years ago. If insects were to vanish, the environment would collapse into chaos*."

(E. O. Wilson, 2007)

1. OVERVIEW OF THE IMPORTANCE OF INSECTS IN THE ECOSYSTEM

A class of animal kingdoms called Insecta carries most animal species on this earth.[1] It is cosmopolitan and is important because of its biodiversity, ecological practices, influence on pollination, and effects on human health and other natural resources. Their adaptation to the surrounding is commendable. The ecological factors like temperature, mean rainfall, humidity, food plants, and other minor factors.

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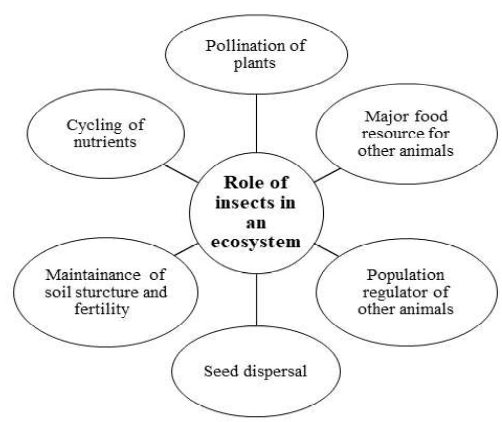

Fig. 1- Roles of insects in an ecosystem.

Moths, butterflies, bees and beetles are the most common pollinators. Insectivorous animals are belonging to different phyla of animal kingdom. Insects feed on both animals and plants. Insects participate in the dispersal of seeds of many plants.

This article covers analytical reports and reviews published recently on the subject concerned. It included **(a)** reviews of existing recent works of literature, **(b)** results from experimental studies, and **(c)** priorities for future research and design best practices for them.

1.1 What are the current issues with insect diversity?

The goal of this chapter is to document the harmonious interaction between insects and their ecosystem, the types of threats they face, and their impact on their diversity and ecosystem. What steps do researchers take to protect them for sustainable management practices?

1.2 Threats to insect diversity and ecosystem health

Insects are considered maintainers of the health of an ecosystem. About 58% of the earth's animals' biodiversity is insect diversity.[1] They serve as pollinators, food sources for many animals and some insectivorous plants, and decomposers of biological wastes. However, insects face different threats like biological, physical, chemical, environmental, natural, and fabricated threats for survival. It really affects their biodiversity and the functions of an ecosystem like energy flow, food pyramids, and ecological productions. Some of the major threats that the insect population faces nowadays are described under the following points:

(a) Habitat destruction and fragmentation: Several pieces of research clearly depicted the threat to the insect population by continuous habitat destruction and fragmentation. Manufactured activities like urbanization, deforestation, and agro-horticulture have led to the destruction and fragmentation of the natural habitat of insects. To meet the demand for the shelter of the increasing human population, forests, grasslands, and agricultural fields are fabricated and new infrastructural development may completely morph the area. Deforestation for agricultural, road infrastructure, and shelter purposes not only destructed the natural habitat of animals and plants but also the insects.

(b) Climate change: Climatic factors like temperature, rainfall, and humidity are important for the survival of insects. They vary from one place to another because of the different ecosystems and topography. Fabricated industries, burning of fossil fuels, and household items can alter the temperature of a place. It can lead to the loss of host plants, change of soil nature, and loss of animals in a food web. It may lead to the community-level cascade of decline and extinction of species.[2]

(c) Invasive Species: A non-native species of plants or animals introduced in an ecosystem for the purpose of economic growth purpose but become harmful to the environment, the economy, and human health is called invasive species. There are many examples reported by the scientists listed in Table 1.

Table 1- A list of invasive animals and plants and their effect on the insects and their ecosystem.

S.N.	Invasive animal/ plant	Effect
1.	Emerald Ash Borer	This beetle attacks and kills ash trees and also damage the local insects and the ecosystem.[3]
2.	Asian Longhorned Beetle	This beetle attacks hardwood trees and therefore, negative impact on both insects and the ecosystem. [3]
3.	Japanese Knotweed	A type of plant that outcompetes native plant, therefore, shows a negative impact on the insect population and local ecosystem. [4]
4.	Zebra Mussel	Shows a negative impact on both the aquatic ecosystems and insect population.

(d) Light pollution: Although the major factors, which affect insects in wider aspects, are habitat loss, use of insecticides, and climatic stress but artificial lighting at night (ALAN) has also a role. ALAN is created by different sources like buildings, streetlights that illuminate roads and highways, industrial sites, cultural programmes, markets malls, and other infrastructures. Still, spare research works have been done to correlate the effect of artificial lighting at night on the life-table parameters of insects and other nocturnal animals.[5] But the work done by many researchers have observed the effect of such illuminations on the nocturnally active insects like moths.[6,7] It affected the vital behaviours of insects that included feeding, migration, defence, and reproduction. Stewart (2021)[5] reported that 'white' LEDs with major short wavelength mimic daylight. It is well known that nowadays these LEDs are profusely used for ALAN. Owens reported that communication abilities like warming signals or courtship signals of bioluminescent taxa became obscured in ALAN. Whereas, the ultraviolet and blue radiations attract moths.[6]

(e) Overexploitation: The utilization of a natural resource in a manner where it loses sustainability is called the overexploitation of that resource. The resource can be a living or non-living material. In the case of insects, overexploitation can lead to significant damage to their population, diversity, and species richness of an ecosystem. There are many examples reported by scientists. A few of them are Wild Honey Bee, Lac Worm, Silk Worm, and Beetles. Due to commercialization, the Wild Honey Bee population has been depleted in recent years. It threw a negative impact on the pollination of plants. Beetle wings are collected for making decorative items. It created the overexploitation of the beetle population. Green Jewel Beetle (*Chrysophora chrysochlora*) population is declining therefore, the bird population feeding on them also declined.[7] Many colourful butterflies have been illegally exported to foreign countries for decoration like Southern Birdwing (*Triodes minos*). It declined the pollination of the plants.[8]

(f) Insecticides: Farmers control insects profusely and use various types of insecticides. Mostly synthetic types were used like organophosphates, Lindane organochlorines, carbamates, Cyclodiene, Pyrethroids, etc. They killed insects by damaging the nervous system, respiratory system, and digestive system. There are non-specific insecticides that also affected mammals, birds, microbes, and other beneficial insects. Insecticides are widely used to control pests and insects that harm crops, animals, and human health. However, the use of insecticides has raised concerns about their impact on human and ecosystem health. This report will provide an analysis of the impact of insecticides on human and ecosystem health. Impact on Human Health: Insecticides can have significant impacts on human health. Exposure to insecticides can cause acute or chronic poisoning, which can result in nausea, headaches, dizziness, seizures, and even death. Long-term exposure to insecticides has been linked to chronic health effects such as cancer, reproductive problems, neurological disorders, and developmental abnormalities. Pregnant women and children are particularly vulnerable to the harmful effects of insecticides. Exposure to insecticides during pregnancy can lead to birth defects, developmental disorders, and low birth weight. Children who are exposed to insecticides are at increased risk of developing behavioral problems, cognitive impairments, and respiratory illnesses. Impact on Ecosystem: Insecticides can also have significant impacts on ecosystem health. The widespread use of insecticides can disrupt ecosystems by killing off non-target organisms such as pollinators and natural enemies of pests. This disruption can lead to imbalances in the ecosystem, which can have cascading effects on other species and ecological processes. Insecticides can also contaminate soil, water, and air, leading to long-term environmental damage. Contaminated water and soil can affect plant growth and aquatic life, and contaminated air can affect the respiratory health of humans and animals. The use of insecticides can have significant impacts on human and ecosystem health. The harmful effects of insecticides on human health include acute and chronic poisoning, reproductive problems, neurological disorders, and developmental abnormalities. Insecticides can also disrupt ecosystems by killing off non-target organisms and contaminating soil, water, and air. To mitigate these impacts, it is important to minimize the use of insecticides and adopt alternative methods of pest control such as integrated pest management.

2. THE NEED FOR RESEARCH AND MANAGEMENT

About 80% of the animals found on earth are insects; their number and diversity reflect their intensity. Common people do not have much goodwill towards insects because many diseases are insect-borne. Almost all people have to deal with mosquitoes, flies, cockroaches, etc., for which many types of insecticides have to be used for prevention. Killing them generally gives happiness to people. In the same way, farmers also have negative feelings about insects because they harm their crops, as a result of which different types of chemical pesticides are available in the market and farmers buy them and use them in large quantities so that their crops can be saved. Stay and earn the benefit of a good yield. Lack of correct information, lack of training, and lack of effective pest management can be clearly felt. The reality is that about 35% of the world's food grains are produced only with the help of insects because it is the main polymer. Organic wastes are also eliminated by decomposing them. It is a source of food for many types of animals. For us, silk honey is also an important source of dyes, medicines, etc. It is necessary to understand the importance of insects and there should be a continuous effort to make them accessible to the common people. Globally, it is reported a decline in insect diversity and richness.

3. UNDERSTANDING INSECT DIVERSITY AND ECOSYSTEM FUNCTIONALITY

3.1 Methods for studying insect communities

Trapping and collection of insects are important for the proper study of their life cycle, host plants, host-pest interaction, the impact of climate change, and the effects of the insecticides applied on them. There are many methods used to collect them detailed as follows:

a. Sweep netting: this method is used to sweep flying or hopping insects by using the net in the field. Examples belonging to different orders are Coleoptera (beetles), Hymenoptera (bees and wasps), Diptera (flies), Lepidoptera (butterflies and moths), and Orthoptera (grasshoppers and crickets).

b. Pitfall trapping: Small holes are made and then cups or traps are placed there to catch insects that fall in. It is also used to collect samples of ground-dwelling insects. Insects of different orders are trapped by this method: Dilopoda (millipedes), Gryllidae (crickets), Araneae (spiders), Formidae (ants), and Carabidae (ground beetles).

c. Light trapping: It is used to trap nocturnal insects specially moths and coleoptiles. There are different types of this trap used by researchers.

d. Malaise trapping: It is made up by setting up a tent-like structure with a funnel-shaped trap. It directs flying insects into a container of alcohol or some other alternative preservatives. It is used to collect insects from different orders: Lepidoptera (butterflies and moths), Hemiptera (bugs), Hymenoptera (ants, bees, wasps), Coleoptera (beetles), and Diptera (flies).

e. Visual survey: researchers estimate the insect populations in a given area and time quickly use it.

f. Mark and recapture: Marking of insects with paint or tiny binds made by the researcher. Then they are released back into their environment. By counting marked and unmarked insects, the population size can be determined.

3.2 The Role of Insects in ecosystem services

Insect participates in different ecological services like pest control, pollination, wildlife nutrition, dung burial, and nitrogen recycling. Large animals excrete a great amount of dung may create a challenge the waste-management issues. Insects play a role in dung decomposition.[10] Dung beetles are popular decomposers that roll dung into balls. Flies and some species of moths lay their eggs in dung and their larvae feed on them. It recycles its nutrients. Some ant species collect and feed on dung. They are recycled dung.

3.3 The impact of climate change on insects and the ecosystem

The diversity of insects in an ecosystem is highly influenced by climatic factors like temperature, humidity, rainfall, light, food sources, etc.[11,12]

4. THE FUTURE OF INSECT MANAGEMENT

4.1 IPM strategies:

Integrated pest management (IPM) is considered an effective and sustainable approach to managing and regulating populations. It involves multiple tactics to control pests without making significant harm to the environment and non-target organisms. Major reaches are progressing towards the conclusion that IPM is a promising approach to managing insects and the environment. There are various alternative and traditional chemical-based pest control methods as explained below:

(a) Biological control: Natural predators, parasites and pathogens come under biological control to manage insect populations.[13] Parasitoid wasps like *Aphidius colemani* are widely used to control aphids like Green Peach Aphids in greenhouse crops. These wasps lay their eggs inside the aphid's body. Their larvae feed on the body of wasps and kill them. The use of predatory insects like Lady beetles and lacewings kills target insects in cropland. Other predatory bacteria and viruses also kill target insects.

(b) Genetic control: Genetic engineering is very helpful to control insect pests by introducing genetically modified insects.[14]

(c) Precision agriculture: Technological advancements like GPS, sensors and drones are used to gather information on cropland including crop health, pest populations and climatic conditions.

(d) Sustainable farming practices: Crop rotation, cover cropping and reduced tillage can help the farmer to get healthier soil and thus dependence on synthetic materials can be reduced.

(e) Citizen science: Common citizens are involved in scientific research with the help of digital devices like smartphones and other digital platforms. It is helping scientists to get valuable data for accurate analysis.[15]

4.2 Habitat restoration and conservation for insects:

Several reports say that due to unplanned developmental strategies in the last two hundred years damages have been made to a large extent. Different manuals of habitat restoration and conservation strategies. It includes the following steps:

(a) Restoration of a degraded landscape can help butterflies to regain status. A study in the Western Ghats region of India reported that the restored forest contained higher diversity of butterflies than the degraded forests. It was due to the increased host plants and microhabitats. Nature Conservation Foundation (NCF) Rajanikanth *et al.*, (2020)[16] also reported dragonfly conservation in the Western Ghats. This place is also known for the natural habitat for fireflies called bioluminescent insects.

(b) Restoration of grassland benefited the restoration of the population diversity of grasshoppers. A report published in 2019 said that grasslands in the Deccan Plateau region of India helped grasshopper populations to regain their richness.

(c) Agroforestry also emerged as a suitable place for different types of pollinators. In Tamil Nadu, it played a key role in increasing the diversity and abundance of pollinators. Das *et al.*, (2020)[17] reported the positive impact of the restoration of nectar plants on the population of butterflies.

(d) Restoration of wetlands in the Himalayan foothills of India is one of the best examples that depicted the benefit for the dragonflies' populations.

(e) For the diversity of beetles, the conservation of the Thar Desert in India was reported in 2016. Sengupta *et al.*, (2020)[18] reported the conservation of dung beetles in a tropical montane forest in the Southern Western Ghats.

(f) Conservation of tillage practices also found suitable for the increasing diversity of soil insects.

(g) Nilgiri Biosphere Reserve was announced World Heritage Site by UNESCO for butterfly conservation.[19]

(h) The Himalayan region is known as a natural habitat for many species of bees like the Himalayan honeybee and Giant honeybee. It was reported by *Apis* Himalayan Foundation (AHF) working for the conservation of bee habitats.

4.3 The use of technology for insect management:

(a) RNA interference: RNAi is a unique technology that is used to make a specific gene silent. In the pest control system, it can be used to silent target genes of pests and therefore, can control their population of them. One of the examples is controlling Diamondback moths. Researchers have developed an RNAi-based approach to control diamondback moths. They have identified a specific gene called V-ATPase that is essential for the moths' survival. By using RNAi to silence this gene, the researchers were able to significantly reduce the survival rate of the diamondback moths. The RNAi molecules were delivered to the moths by incorporating them into a transgenic broccoli plant, which the moths fed on.

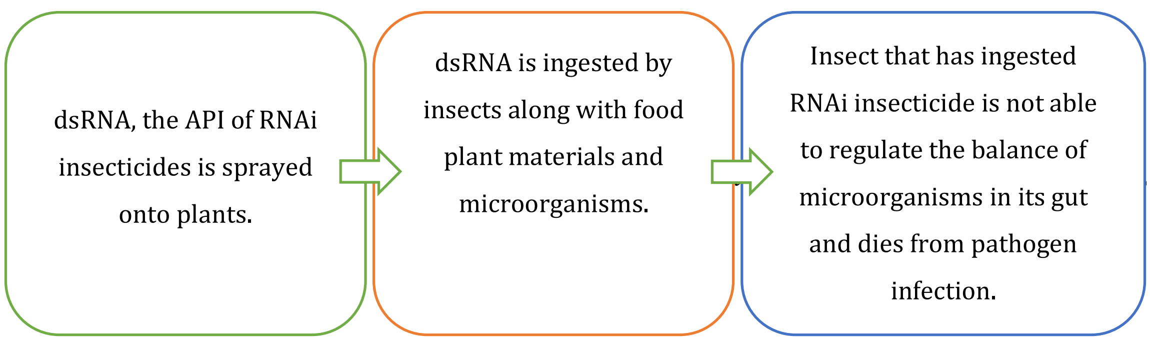

Figure 2: Scheme of the mechanism of RNAi action on controlling insect pests. The active pharmacological ingredient of RNAi insecticides is a double-stranded (ds) RNA. It is developed by the application of the RNAi mechanism. The sequence of the dsRNA is articulated specifically to make pair with a sequence within an essential gene or the survival of the pest. This assigned dsRNA is delivered to the insect midgut through diet. Once this dsRNA reached the cell, it starts the processing of its own RNAi pathway into a guide RNA (gRNA)- ssRNA. It disrupts the expression of the target gene and therefore insect dies.

(b) Autonomous robots: Robotics is a branch of engineering and technology that includes the conception, design, manufacture, and operation of specified robots. It works as an intelligent machine. It is very helpful in certain tasks of agriculture applications. A project H2020-funded Green Patrol worked on the detection and control of insect pests. It was very helpful to identify the insect pests in real-time. Chung *et al.*, (2014)[20] reported about an autonomous robot called Cabbot sampled adult whiteflies (*Bemisia tabaci*) on the host plant paprika plant (*Capsicum annuum*). It saved time in identifying and collecting insects on the host plants.

(c) Gene editing: Gene editing is one of the new biotechnological processes in which the specific nucleotide sequences of an mRNA or DNA are edited purposely. One of them is known for its result and it is CRISPR-Cas9. It is used to develop a crop that is more resistant to pests. It is related to different categories of genes of insect pests.

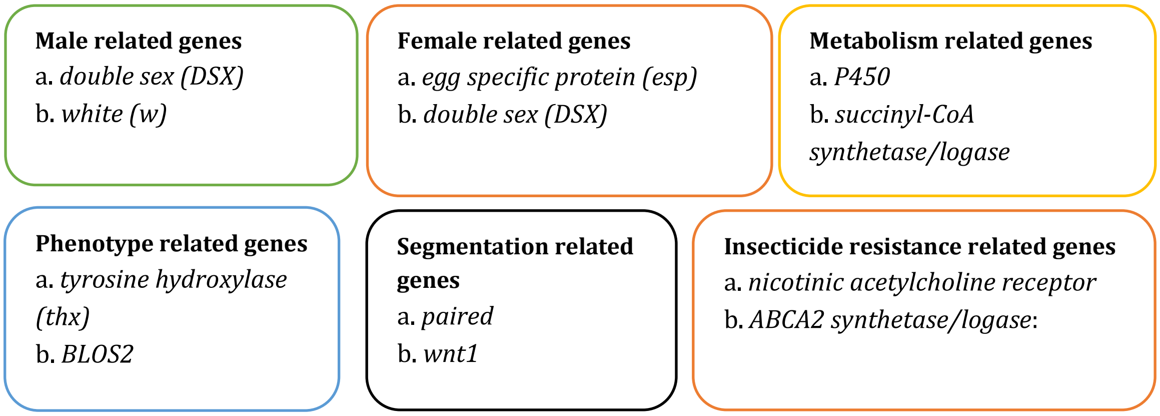

Figure 3: Various genes targeted by CASPER/Cos9 for insect pest control. It includes different categories of genes like male, and female, metabolism, phenotype, segmentation, and insecticide resistance-related genes.

(d) Nanotechnology: Nanotechnology has evolved as a potential tool to manage insect pests for their control more effectively and efficiently. Several researchers were helping the narrative to establish that nanoparticles can be an alternative method to control pests. Silver nanoparticles have been shown significant as insecticides that controlled mosquitoes, aphids, and termites. The research established the killing of bed bugs by the application of silver nanoparticles. Silver nanoparticles made from lemongrass oil were found effective to repel mosquitoes. Nano-sensors are also applied in cropland to detect the presence of pest larvae like the fall armyworm larvae were detected by the researchers in maize and other crops. Tomato plants were protected against whitefly infestation by the application of silicon dioxide nanoparticles. However, more research is needed to fully understand the effects of nanoparticles on pests, the environment, and non-targeted animals.

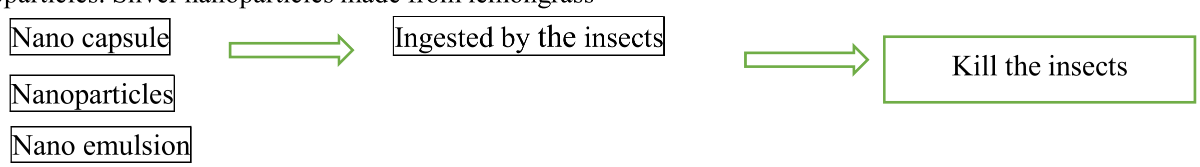

Fig. 4: The pest that leads to death can ingest different forms of insecticidal nanoparticles.

(e) Artificial intelligence (AI): AI is considered a technology of interest that can serve insect pest management more accurately without a great expense. Image AI is helping in the identification and control of insect pests. Singh *et al.*, (2019)[21] used AI to detect and classify tomato leaf diseases caused by insect pests effectively. It is also used in pest forecasting and early warning based on machine learning. It was reported by Lu *et al.*, (2019)[22] in China to control cotton bollworms.

(f) Drones: Drones are playing important role in insect pest management. They are used for surveying, monitoring, and spraying insecticides. They are well-equipped with cameras that can give accurate results in surveying the crop field. Drones can be equipped with sprayers or dispensers to deliver precise amounts of insecticides or other treatments directly to pest hotspots. This reduces the number of chemicals used and minimizes environmental impact. Drones can also be used to create detailed maps and models of crop fields, allowing farmers to identify areas of high pest activity and track changes over time. This information can be used to optimize pest control strategies and improve crop yields.

5. CHALLENGES AND OPPORTUNITIES FOR RESEARCH AND MANAGEMENT

5.1 Addressing knowledge gaps in Entomology

There are many fields in entomology specially related to insect pest management where extensive research work is required. Several scientists are working on different models of integrated pest management. Some of the knowledge gaps are belonging to Insect-pest interaction, Insect microbiomes, Insect conservation, Insecticide resistance, Insect social behaviour, Insect evolution, and

Insect genetics. Applications of Artificial intelligence and Robotics are a new field of research where machine learning and big data are helping researchers and farmers to get results that are more accurate.

5.2 Building Partnerships between Scientists, Policymakers, and Stakeholders

Making policies for effective and sustainable farming to fulfill the demand of the people as well as to maintain the ecosystem services and environmentally friendly practices are complicated. It needs active participation and strong scientific communication of stakeholders, scientists, and policymakers to build up effective science communication and evidence-based policies for the betterment of farmers and the environment. It can also point out the identification of shared goals, research questions, and objectives for the betterment of the community under a time frame. Sharing of data and research findings can also develop trust and accurate interpretation of a problem. These collaborative inputs may help in designing and implementing the research projects.

CONCLUSION

One of the major priority threats in the 21st century is to fulfill the need of hunger of more than eight billion human beings without altering the natural processes. The need for sustainable insect management practices to maintain a healthy ecosystem, enhance food security, and prevention of the spread of diseases. Various recent research outcomes have been discussed to address the challenges, the development of new technologies, the development of integrated pest management strategies, adoption of holistic approaches by taking care of environmental, economical, and social factors that influence the insect population. In this article, the author discussed the potential positive outcomes of ecosystem conservation and management in the field of providing quality food, clean water, and air, protecting against climate change, and mitigating climate change. Continuous research, engagement with social communities and stakeholders, and collaboration with different government and non-government institutions are required for effective integrated pest management.

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