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Pyrethroids have become a barrier to the daily existence of molluscs (Review)

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ABSTRACT

Molluscs are significant aquatic organisms, which serve as bioindicator species. They are crucial for maintaining ecological balance as secondary consumers. Molluscs are threatened by pesticides such as pyrethroid insecticides. Pyrethroids are increasingly utilized to control insects in agriculture and gardening. It contaminates aquatic bodies through rainwater runoff and drainage-sewage systems. The current review will focus on the issue of increasing pyrethroid use and its biological effects on molluscs. Due to their highly lipophilic nature, pyrethroids pose a significant risk to these organisms by affecting their metabolites, producing reactive oxygen species, and influencing neurotransmitter actions. The threats to the molluscs and eventually to the concerned aquatic ecosystem warrant significant discussion and attention.

Introduction

The global population is increasing, leading to a higher demand for food. Pesticides help increase crop yields and reduce losses due to pests. As cities expand, agricultural land decreases, making it necessary to maximize crop yields on available land (Saroop and Tamchos, 2024). Changes in temperature and precipitation patterns alter pest dynamics, leading to increased pest pressure and pesticide use. Overuse of traditional pesticides has led to the development of resistant pest populations, making pyrethroids and other alternative pesticides more attractive. The Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO) define a pesticide from an ethical point of view. The pest has been defined, by FAO and WHO as “any species, strain or biotype of plant, animal or pathogenic agent injurious to plants and plant products, materials or environments and includes vectors of parasites or pathogens of human and animal disease and animals causing public health nuisance” (FAO and WHO 2014).

It’s important to note that while pesticides can provide short-term benefits, their overuse and misuse can have negative environmental and health consequences. It’s essential to promote sustainable agricultural practices and Integrated Pest Management (IPM) techniques to minimize pesticide use. Since the 1980s, these pyrethroid insecticides have been widely used because of their high efficacy and limited toxicity in comparison to organophosphorus and carbamic esters (Yoo et al., 2016). Pyrethroid pesticides are currently among the top three categories of pesticides (Xiao et al., 2012). It can alter aquatic food webs by affecting predator-prey dynamics, nutrient cycling, and energy transfer. Different aquatic species exhibit varying levels of sensitivity to pyrethroids, which can lead to community-level impacts. Pyrethroids interact with other environmental stressors, such as climate change, habitat destruction, and other pollutants, to exacerbate impacts. It can alter the composition and function of aquatic microbiomes, with potential cascading effects on ecosystem health. They affect the exchange of nutrients, energy, and organisms between aquatic and terrestrial ecosystems (Akkaş, 2009). They also can induce epigenetic changes and transgenerational effects, influencing the health and fitness of future generations (Manna et al., 2020). Pyrethroids can cause subtle changes in behaviour, physiology, and ecology, leading to long-term population declines. Pyrethroids are highly hazardous to aquatic organisms including molluscs, amphibian tadpoles, and fish, as they are highly active insecticides with LC values over 1000 micrograms per litre (Breistøl et al., 2015). Synthetic pyrethroids, used at the lowest rates, are most harmful to aquatic animals, with similar effects on species in field

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aquatic ecosystems after agricultural usage. The aim of this review is to explore the problems related to pyrethroid exposure in aquatic molluscs by tracking changes in behaviour, physiology, and cellular level alterations. We are trying to figure out how pyrethroids work in molluscs and how antioxidants protect against these types of pyrethroids.

Nature and Physico-chemical properties of Pyrethroids

Pyrethroids are a type of synthetic insecticide linked to natural pyrethrum, which is produced from chrysanthemum flowers (*Chrysanthemum cinerariaefolium* and *Chrysanthemum coccineum*). Pyrethrum, derived from the granulated heads of *Chrysanthemum* flowers (Hill, 1989). They are widely used for various pest control purposes due to their effectiveness and relatively low toxicity to humans and animals (Saha and Dutta, 2024). They are utilized to manage insect pests in gardens, horticulture, forestry, and agriculture and are employed as clothing repellents to keep mosquitoes away. These are used in warehouses and food storage facilities to protect stored products like grains, rice, and other commodities from infestation by pests such as beetles and moths, which can damage the products and lead to food waste. Pyrethroids are essential in public health pest management, particularly in vector control programs to combat mosquito-borne diseases (malaria, dengue, and Zika). They are used in insecticide-treated bed nets, indoor residual sprays, and fogging operations. Permethrin, a light-stable compound for outdoor usage, was first marketed internationally in the late 1970s to combat insect pests on crops. Over the next decades, the number of photostable insecticides has increased dramatically (Hill, 1989). Pyrethroids are classified as agricultural (alpha-, medium-toxic) or urban (non-alpha-, low-toxic) based on their molecular structure. Pyrethroids are very adsorbent to particulate matter due to their high lipophilicity and low water solubility. Due to their lipophilic nature, pyrethroid's tendency to dissolve in fats rather than in water and are readily absorbed by tissues and cell membranes. Because of this property makes it highly effective pesticide. Stereoisomers forms are frequently combined to create pyrethroids, which have different degrees of toxicity (Liu et al., 2005). Type I and type II synthetic pyrethroids are distinguished from one another and produce different poisoning symptoms. The alpha-cyano group found in type II pyrethroids has the ability to block ion channels, including as sodium, chloride, and calcium channels (Burr, 2004). For instance, the pentenone ring is frequently replaced with a phenoxy-benzyl group, the isobutene group with a vinyl- or phenyl-based halogenated ring, and the cyano group with a benzylic carbon. The first and second structural changes lessen the molecule's susceptibility to oxidation while increasing its photostability. The ester bond's resistance to hydrolysis is strengthened by the third alteration. Photostable synthetic pyrethroids display water solubilities ranging from 1 to 10 pg/L and octanol/water partition coefficients of 10^4 to 10^7 (Coats et al.,1989). Several aquatic and marine species, particularly fish and mollusc, are severely harmed by them (Coats et al., 1989). The activity of pyrethroids depends on their steric conformation and chemical makeup. Structural modifications can affect the activity of the pyrethroid by affecting detoxifying rates and the three-dimensional connection with receptors. High-activity compounds often have a (R) configuration at the cyclopentane ring's C-1 position. The toxicity of 16 cis isomers is greater than that of trans (Narahashi, 1984). Pyrethroids are typically composed of Cyclopropane carboxylic acid groups are linked to aromatic alcohols by a central ester (or ether) linkage. Changes in pyrethroid structure can enhance insecticidal efficacy and photostability, but may also affect non-target species (Soderlund et al., 2002). Pyrethroids are synergistically combined with organic chemicals like piperonyl butoxide, piperonyl sulfoxide, and sesamex to improve insecticide activity. These chemical compounds boost pesticide efficacy of pyrethroids. According to the Agency for Substances and Disease Registry (2003), commercial pyrethroids often include extremely hazardous inactive chemicals. Pyrethroid insecticides are more effective at targeting many insect pest species like dipteran, lepidopteran larvae, aphids, whiteflies, mites etc. compared to others insects like cockroaches, bed bugs which may have some physiological traits like thicker

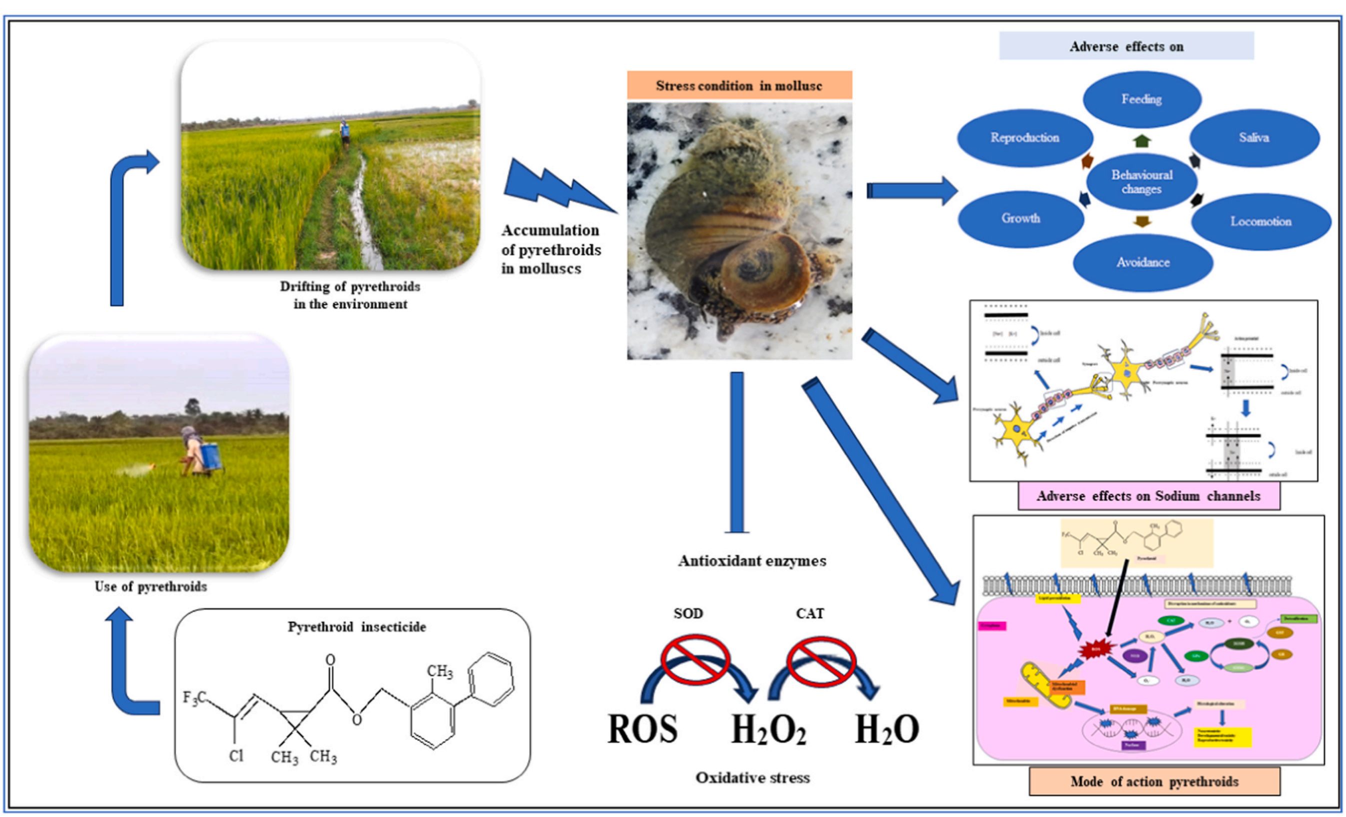


Fig. i. The abstract is graphically represented.

exoskeleton (Cai et al. 2024) and some specific enzymes like carboxylesterases (Gajendiran and Abraham 2018). The effectiveness is found less in vertebrate than invertebrates due to the presence of more diverse and efficient set of cytochromes P450 enzymes, enabling them to metabolize and detoxify pyrethroids more effectively (Chandor-Proust et al. 2013). The effectiveness of pyrethroid is often evaluated using specific endpoints that measure their impact on target organisms and environmental persistence. The endpoints include Lethal Concentration (LC_{50}) or Lethal Dose (LD_{50}), the concentration of the pesticide required to kill 50 % of the target population. Pyrethroids can exhibit moderate to high toxicity in water due to their hydrophobic nature, leading to bioaccumulation (Wang et al. 2019). Reported LC50 values for aquatic molluscs can range from 1 μg/L to 1 mg/L depending on the compound. However, in case of terrestrial molluscs, LD50 values fall in the range of 50–200 mg/kg body **(**Palmquist et al. 2012**)**. Organophosphates, organochlorines, and carbamates have an LD_{50} ratio in rat and insect is less than 100 mg/kg, but pyrethroids have an LD_{50} ratio of more than 2000 mg/kg (Katsuda, 1999). These are extremely toxic to fish and other invertebrate species also. In case of fish, 96hrs LC_{50} values are 7.2–803 nmol/L range however in molluscs it is found approx. 1000 nmol/L (Breistøl et al., 2015). According to research by Haya (1989), fish may kill by impacts on the nervous system, pulmonary areas, and urinary ion regulation, which might result in acute death symptoms. Pyrethroids can affect normal insect neuronal activity by altering the kinetics of voltage-sensitive sodium channels. This causes temporary influx in sodium ion permeability of the neuronal membrane, which is responsible for nerve activity (Bloomquist, 1993). The parent molecule undergoes biotransformation via esterase at its core ester link monooxygenases that are reliant on cytochrome P450 (Casida and Quistad 1998). The effect of the initial hydrolytic or oxidative attack varies by pyrethroid component and isomer. Following ester cleavage, primary alcohol molecules, such as 3-phenoxybenzyl alcohol, are further oxidised to carboxylic acids via the aldehyde reaction. Cyano-substituted alcohols lose cyanide non-enzymatically to produce aldehyde (Soderlund et al., 2002). Certain ester fragmentation byproducts can become hydroxylated, and around of the hydroxylated ester intermediates may hydrolyze, resulting in hydroxylated ester fragmented byproducts. The early outcomes of hydrolytic assault undergo pairing with amino acids, sugars, or sulphates before excretion (Soderlund and Bloomquist, 1990). Pyrethroids have estrogenic and anti-progestogenic properties, as evidenced by epidemiological, clinical, and laboratory research. Thus, they are classed as endocrine-disrupting substances (Garey and Wolff, 1998). The primary structure of Class I pyrethroids is cyclopropane carboxyl esters. These consist of allethrin, bifenthrin, permethrin, resmethrin, and tetramethrin. Choreoathetosis and salivation are produced by class II pyrethroids, which include the cyano group. Pyrethroid effectiveness and selectivity for mollusc species depend on characteristics such as form and essential structural traits, particularly the chirality with cis/trans stereochemical composition throughout the cyclopropane circle, an ester, along with additional physical aspects (Khambay, 2002). Pyrethroids are toxic to aquatic animals, particularly molluscs, crustaceans, insects, and fish (larvae and juveniles) (Ranatunga et al., 2023). Pyrethroids are excitotoxic to axons because they impede the voltage-gated sodium pathways in axonal membranes are closed, prohibiting neurons since repolarizing and depolarizing the membrane, thereby paralysing the organism. Pyrethroids can be improved by combining them by synergist piperonyl butoxide, an established inhibitor of microsomal P450 enzymes involved in pyrethroid metabolism (Fig. ii).

Different types of commonly used pyrethroids

Permethrin

Permethrin is an ester that belongs to the cyclopropane carboxylate family. Cyclopropane-carboxylate ester is generated by esterifying alcohol groups in the form of phenoxybenzyl alcohol and replacing the cyclopropane ring using 2,2-dichloro vinyl as well as gem-dimethyl

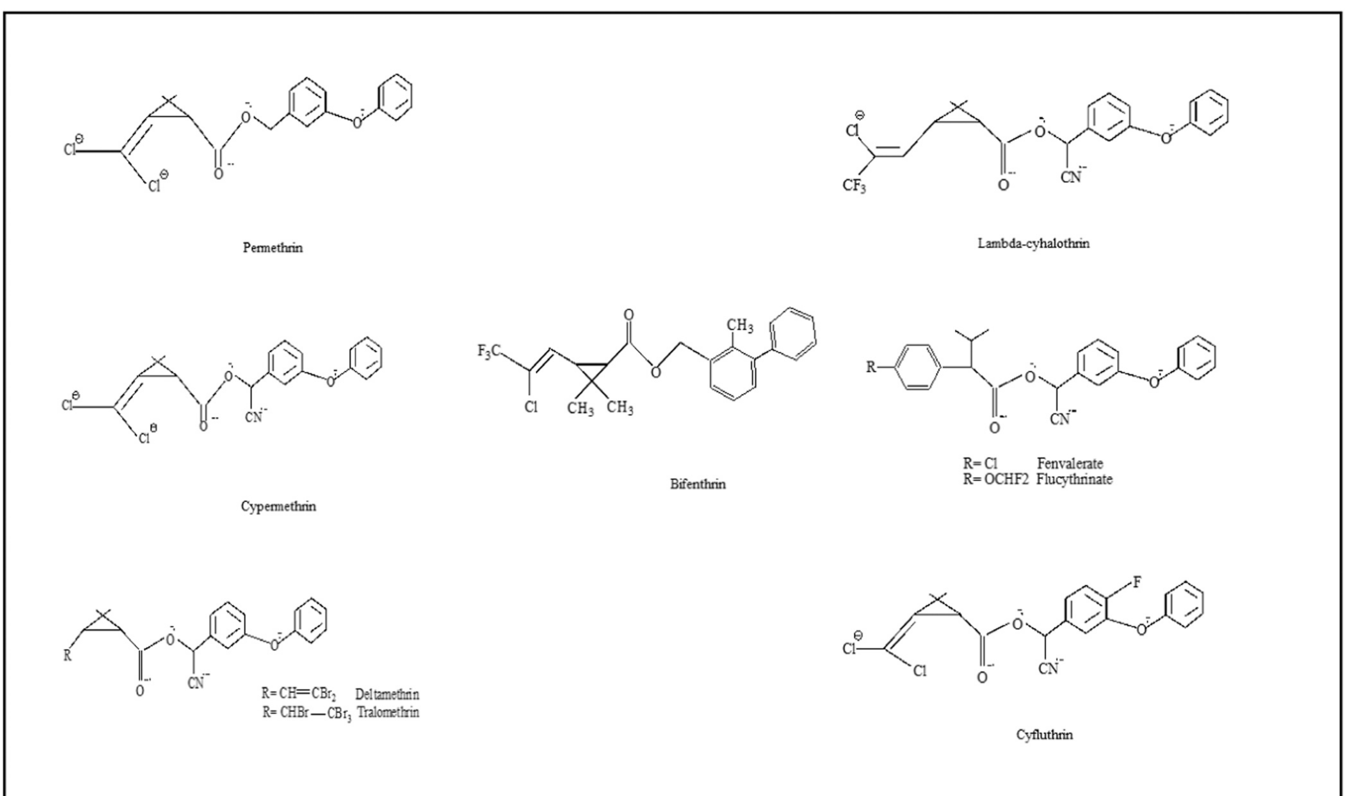


Fig. ii. Some of the commonly used pyrethroid insecticides on the market (Stereochemistry not shown).

groups. Permethrin is functionally comparable to 3-(2,2-dichloro vinyl)-2 and 2-dimethyl cyclopropane carboxylic acids. It is soluble in water, 6.00 × 10ˆ-3 mg/L (pH 7, 20 °C); cis-isomers 0.20 mg/L (25 °C); trans-isomers 0.13 mg/L (25 °C). and also, in xylene and hexane > 1000, methanol 258 (all in g/kg at 25 °C). It has a Kow value of 6.50 and 96-h LC50 values > 1000 μg/litre in molluscs.

Cypermethrin

Cypermethrin is a carboxylic compound produced through the chemical combination of 3-(2,2-dichloro vinyl)-2,2-dimethyl cyclopropane carboxylic acid using the hydroxy (3-phenoxyphenyl) acetonitrile as an alcoholic hydroxy group. It is classed as a pyrethroid derivative insect repellant, agrochemical, along molluscicide. It contains a chlorinated hydrocarbon molecule, thus a propenonitrile, an aromatic ether, among others, as well as a cyclopropane carboxylate ester compound. It is functionally equivalent to 3-(2,2-dichloro vinyl)-2,2-dimethyl cyclopropane carboxylic acid. It is soluble in water, 0.01 mg/l at 25 °C, also, in acetone 620, dichloromethane 550, cyclohexane 515, ethylacetate 440, chlorobenzene 420, acetophenone 390, o-xylene 350, hexane 7 (all in g/l, 25 °C). In maize oil 19–20, ethylene glycol < 1 (both in g/kg at 20 °C). It has a Kow value of 6.94 and shows the toxicity to molluscs 400 and 800 mg/l.

Fenvalerate

Fenvalerate is a carboxylic derivative derived from the proper condensation of 2-(4-chlorophenyl)-3-methylbutyric acid in cyano(3-phenoxyphenyl) methanol. This insecticide and molluscicide contain pyrethroid esters. The compound consists of an aromatic carboxylic ester and a monochlorobenzene derivative. It is functionally identical to 2-(4-chlorophenyl)-3-methylbutyric acid. Pyrethroids inhibit the sodium channel's closure, causing the sodium tail impulse with a delayed sodium inflow at the conclusion of hypolarization. Evidently, the pyrethroid particle maintains the activation gate accessible. Pyrethroids having an alpha-cyano group (such as fenvalerate) produce longer sodium tail flows than other pyrethroids. It is soluble in water, 2.4 × 10ˆ-2 mg/L at 22 °C (seawater) and also soluble at 20 °C (g/L): acetone > 450; chloroform > 450; methanol > 450; hexane 77. It has a Kow value of 6.2 and 96-h LC_{50} values > 1000 $\mu g\ l^{-1}$ in molluscs.

Deltamethrin

Deltamethrin is a cyclopropane-carboxylate ester formed via proper condensation of 3-(2,2-dibromo vinyl)-2,2-dimethyl cyclopropane carboxylic acid with cyano (3-phenoxy phenyl) methanol. It is the active ingredient in the insecticide tralomethrin. This compound acts as a pyrethroid ester insecticide, pesticide, phosphoprotein phosphatase inhibitor, calcium channel agonist, and antifeedant. It contains an aromatic ether, an organobromine molecule, a nitrile, and a cyclopropane-carboxylate ester. It acts similarly to cis-3-(2,2-dibromo vinyl)-2,2-dimethyl cyclopropane carboxylic acid. It is soluble in water, < 0.002 mg/L at 25 °C, soluble in cyclohexane 750, dichloromethane 700, acetone 500, benzene 450, dimethylsulfoxide 450, xylene 250, isopropanol 6 (all in g/L at 20 °C). It has a Kow value of 6.2.

Flucythrinate

Flucythrinate is one type of insecticide that has a wide spectrum. The IUPAC name of flucythrinate is [cyano-(3-phenoxyphenyl) methyl]2-[4-(difluoromethoxy) phenyl]-3-methylbutanoateis. It is a new synthetic pyrethroid with potent insecticidal effects. This herbicide has a non-systemic action and affects the skin and gastrointestinal regions. It is efficient at controlling Lepidoptera, Homoptera, and Coleoptera in a variety of crops, fruits, vegetables, ornamentals, and flowers. It is soluble in water, 0.06 mg/L at 25 °C and soluble in acetone > 820, xylene 1810, n- propanol > 780, corn oil > 560, cottonseed oil > 300, soya bean oil > 300, hexane 90 (all in g/L, 21 °C). It has a Kow value of 6.2.

Bifenthrin

Bifenthrin is a carboxylic ester formed by the formal synthesis of cis-3-(2-chloro-3,3,3-trifluoroprop-1-enyl)-2,2-dimethyl cyclopropane carboxylic acid with [(2-methyl-1,1′-biphenyl)-3-yl] methanol. It serves as both a pyrethroid derivative and an acaricide. It contains organochlorine, organofluorides, and cyclopropane-carboxylate esters. It is functionally similar to cis-chrysanthemic acid. It is soluble in water, < 1.0 μg/L /< 1.0 × 10ˆ-3 mg/L/ at 20 °C. It has a Kow value of 6.0.

Cyfluthrin

Cyfluthrin is a carboxylic ester formed by the chemical condensation of 3-(2,2-dichloroethenyl)-2,2-dimethyl cyclopropane carboxylic acid with (4-fluoro-3-phenoxyphenyl)(hydroxy)acetonitrile. The composition contains organochlorine, organofluorine, nitrile, aromatic ether, and cyclopropanecarboxylate ester. It serves as both a pyrethroid-derived insecticide and an agrochemical. It functions similarly to a 3-(2,2-dichloro vinyl)-2,2-dimethyl cyclopropane carboxylic acid. Its primary agricultural use has been to control chewing and sucking insects in cotton, turf, ornamentals, hops, cereal, corn, deciduous fruit, peanuts, potatoes, and vegetables. Cyfluthrin is also used to preserve public health and control structural pests. It is soluble in water, 3.0 × 10–3 mg/L at 20 °C and also soluble in dichloromethane > 1000 g/L. It has a Kow value of 5.95.

Lambda-cyhalothrin

Lambda-cyhalothrin is a 1:1 combination of two stereoisomers (S). -α-cyano-3-phenoxybenzyl-(*Z*)-(1 R, 3 R). −3-(2-chloro-3,3,3-trifluoroprop-1-enyl)-2,2-dimethyl cyclopropanecarboxylate, (R) -α-cyano-3-phenoxybenzyl-(*Z*)-(1S, 3S). −3-(2-chloro-3, 3-trifluoroprop-1-enyl) −2,2-dimethylcyclopropanecarboxylate. It was first discovered by Robson and Crosby in 1984. It was introduced into the market by ICI Chemicals (now Syngenta) in Central America and the Far East in 1985. Warrior, Scimitar, Karate, Demand, Icon, and Matador all use lambda-cyhalothrin as an active component. According to CDPR, 2006, agricultural usage of lambda-cyhalothrin was around 30,000 lbs per year from 2000 to 2003 but climbed to over 40,000 lbs per year between 2004 and 2006 in California. Karate, one type of lambda-cyhalothrin, serves as an insecticide that acts both on the skin and in the gastrointestinal system, providing repellent characteristics. It is a new pyrethroid insecticide that is now known as Syngenta. These neurotoxic agents damage nerves by targeting the central nervous system. It is mostly absorbed via the gastrointestinal system by the absorption of dust and finely sprayed mist, and slightly through unaffected skin. It is soluble in water, 5.0 × 10–3 mg/L, temp not specified, and soluble in acetone, dichloromethane, methanol, diethyl ether, ethyl acetate, hexane, toluene, all > 500 g/L (20 °C). It has a Kow value of 6.8.

Uses of pyrethroids

Synthetic pyrethroid insecticides are often employed in agriculture, mosquito control, and the treatment of ectoparasitic diseases (Ansari et al., 2011). Every year, farmers use more than one million metric tonnes of fertiliser and insecticides, which compromises surface water and groundwater (Cruzeiro et al., 2016; Rodrigues et al., 2018). Pesticide concentrations in the environment are continually increasing. Before World War II, only 30 pesticides were recognised. Pesticide consumption peaked globally at more than 1.8 billion metric tonnes per year between 1960 and 1980 (Renault, 2011). In the U.S., pyrethroid usage is also significant but has been somewhat constrained by increasing regulatory scrutiny regarding environmental impacts,

Table I
Pearson Correlation Matrix for Pyrethroids (Source: Ncbi.nlm.nih.gov and PubChem).

Pyrethroid	Molecular Weight (g/mol)	LogP	Solubility (mg/L)	Vapor Pressure (mmHg)	Toxicity (LD50)	Half-life (days)
Permethrin	391.3	6.1	0.006	1.5 × 10^−9	500	12
Cypermethrin	416.3	6.6	0.004	2.0 × 10^−10	250	15
Deltamethrin	505.2	6.2	0.002	5.0 × 10^−11	50	5
Fenvalerate	419.9	6.2	0.005	6.0 × 10^−10	250	9
Bifenthrin	422.9	6.7	0.001	3.5 × 10^−9	55	7
Cyfluthrin	434.9	6.5	0.0025	1.7 × 10^−10	40	8
Flucythrinate	462.5	6.3	0.003	8.0 × 10^−11	100	11
Lambda-cyhalothrin	449.9	7.0	0.001	9.5 × 10^−10	56	13

especially in water bodies. Pyrethroids are widely used on crops like corn, cotton, and vegetables, with annual usage estimated in the thousands of tons. Pyrethroid usage in the European Union is more restricted due to environmental regulations. They are still used in some agriculture but are tightly controlled to limit their impact on aquatic life (Sylvestre et al., 2022). The Ministry of Environmental Protection forecasts that Poland might have up to 60,000 metric tonnes of insecticide waste (Joanna et al., 2019). The most popular pesticide class is pyrethroids. Their excessive use raises the risk of water pollution. Farmers of India specifically in Madurai and Tamil Nadu, frequently use this herbicide to improve their agricultural and aquaculture practices. China is the world's largest producer and user of pesticides, and synthetic pyrethroids have been identified as widespread Environmental pollutants utilised in agriculture and animal production (Tang et al., 2018). These toxic substances are employed by insecticides, which are popular soy-growing zones in Brazil (Hunt et al., 2016). These synthetic insecticides, specifically cypermethrin insecticides, are employed by way of an agricultural pesticide in paddy farming in the Philippines massively (Elfman et al., 2011). Pyrethroids are utilised for monitoring public health to reduce pests, including roaches, mosquitoes, ticks, and flies, that can spread diseases (Weston et al., 2005). The current pyrethroid formulations are oil-based emulsifiable concentrations. The emulsifiable composition retains pyrethroids in liquid longer than technical chemicals. Piperonyl butoxide is widely used in pyrethroid preparations to increase the adverse impact of the active component. Piperonyl butoxide inhibits enzymes that detoxify pyrethroids (Werner and Moran, 2008). Permethrin, cypermethrin, fenvalerate, and deltamethrin were previously thoroughly investigated, but there is less information on more contemporary products such as flucythrinate, bifenthrin, cyfluthrin, and lambda-cyhalothrin (Table-II). The Food and Agriculture Organization of the United Nations (FAO) reports that the greatest usage of synthetic insecticides occurs in Asia and Europe. Turkey, Pakistan, India, and the Ukraine all have higher consumption values than other countries (FAO, 2021). Although pyrethroids are used globally, there is a lack of comprehensive information regarding their usage and detection in many other countries, especially in well-known developing nations that are unlikely to have environmental regulations and monitoring programs. There is currently a lot of information about the aquatic toxicity of many synthetic pyrethroids available in the scientific literature. Pyrethroids are utilised for monitoring public health to reduce pests, including roaches, mosquitoes, ticks, and flies, that can spread diseases (Weston et al., 2005).

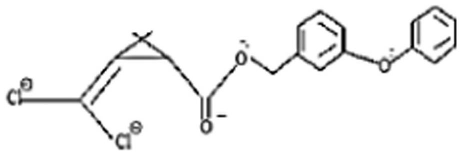
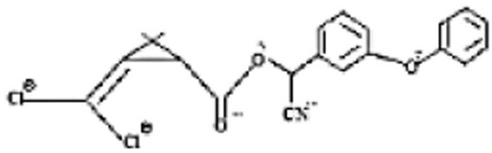
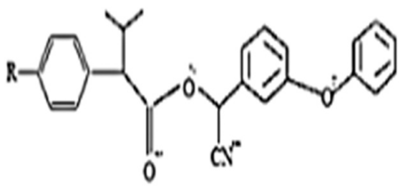
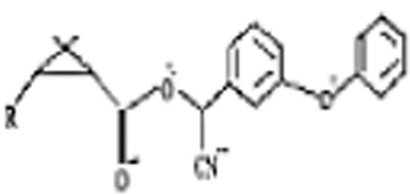
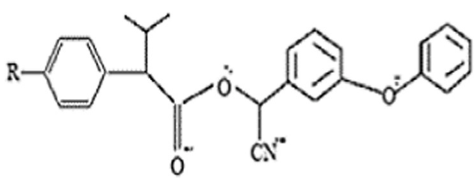
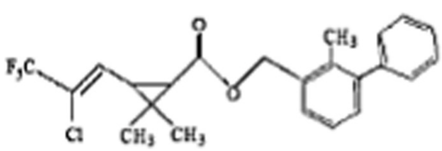
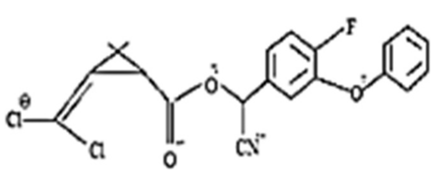
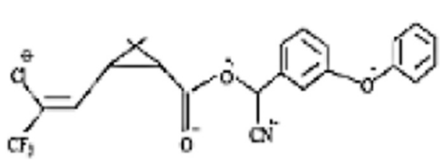
Pyrethroids contamination and prevention

Pyrethroids applied in agricultural, urban, and residential areas can be carried into water bodies through runoff, especially after heavy rains. Pyrethroids are relatively persistent and can accumulate in various environmental matrices like air, water and soil. They are relatively hydrophobic, so they tend to adsorb strongly to soil particles, particularly those with higher organic content. Their persistence in soil can vary depending on environmental factors like pH, organic matter, and microbial activity. pyrethroids can remain in the soil from several weeks to months, with half-lives often ranging from 1 to 4 months. In aquatic environments, pyrethroids generally have low water solubility and tend to adsorb onto suspended particles or settle into sediments. Although their concentrations in water are often low, they can pose risks to aquatic organisms due to their high toxicity to fish and invertebrates. The persistence of pyrethroids in water bodies is generally lower compared to soil, as they are more readily degraded by hydrolysis, photodegradation, and microbial activity. Pyrethroids can enter the air through spray applications or volatilization from treated surfaces. However, because they are semi-volatile, pyrethroids are often present in the air in lower concentrations. Their persistence in the atmosphere is generally short, as they break down more rapidly under sunlight and through photolytic reactions. Although pyrethroids break down relatively quickly in sunlight and soil, they can persist in water bodies by binding strongly to organic matter and sediments at the bottom of rivers, lakes, and streams, which makes them more available to bottom-dwelling organisms and increases the risk of bioaccumulation (Reddy and Osborne, 2022). The use of pyrethroids is increasingly concerning for aquatic ecosystems because these compounds, while effective as insecticides, are highly toxic to aquatic life, particularly fish and invertebrates. Pyrethroids do not discriminate between pest and non-pest species, so they can affect a wide range of non-target aquatic organisms, including species that are ecologically beneficial or endangered. The disruption of these populations can impact entire aquatic ecosystems, as affected species may play critical roles in nutrient cycling, water filtration, and food webs (Edwards, 2013; Nowell et al., 2014). To reduce the usage of pesticides, promote integrated pest management tactics that combine cultural, biological, and crop rotation strategies (Syversen and Bechmann, 2004). Evaluation of environmental contamination, quantification, and assessment of the potential risks, and recommendations of possible mitigation strategies are also important. The following tactics should be used to prevent pyrethroid contamination in water bodies. A general decrease in the amount of pyrethroids used might be one of the most promising alternative management strategies. Alternatively, active mitigation techniques, such as establishing vegetated buffer strips and/or sediment check dams on minor rivers to reduce sediment flow, or growing cover crops during the fallow winter rainy season (DeMars et al., 2021). Educate users on proper application techniques, timing, and dosage to reduce runoff and drift. Raise awareness among farmers, homeowners, and the general public about pyrethroid risks and prevention strategies.

Effects of pyrethroids

Pyrethroid insecticides are less environmentally harmful than typical pesticides, although they can still enter the food chain. They are very poisonous to aquatic organisms and may have long-term negative consequences for aquatic ecosystems (Zhao, 2014). Pyrethroids can be transferred through the food web, affecting species that consume contaminated prey. It can alter species interactions, leading to changes in community composition and ecosystem function. Prolonged exposure to pyrethroids can drive evolutionary changes in species populations, leading to adaptations or changes in population dynamics. These differences highlight the complexity of assessing pyrethroid toxicity in aquatic ecosystems and the need for species-specific research to

Table II
About some commonly used pyrethroids and their uses (Source: Ncbi.nlm.nih.gov and PubChem).

Pyrethroids	Structure	Commercial Brand name	Uses
Permethrin		Nix, Elimite, and Acticin.	Permethrin is a medicine used to control and treat scabies and pediculosis. It belongs to the synthetic neurotoxic pyrethroid family of medicines. It kills eggs, lice, and mites by inhibiting sodium transport across arthropod neural membranes, resulting in depolarisation.
Cypermethrin		Rallis Alpha 10 EC, Ralothrin 5 EC, Rallis Cyper 10 EC, Ralothrin 10 EC	Cypermethrin is utilised for agricultural purposes to manage ectoparasites that infect cattle, sheep, and poultry.
Fenvalerate		Sumicidin, Pydrin, Tatafen	Fenvalerate is a powerful pesticide that works against a wide range of pests, including those that are resistant to organochlorine, organophosphorus, and carbamate pesticides.
Deltamethrin		Butox, Butoflin, Cislin, Crackdown, Decis and K-Othrine.	Deltamethrin (Butox®, MSD) has been effectively used to protect agricultural animals in control programmes against a variety of arthropods with significant vector-borne or nuisance potential, including midges, ticks, flies, and fleas.
Flucythrinate		Aastar(TM), CyBolt(TM), Cythrin(TM), Funchiong jujr (TM), Pay-Off(TM)	It is used to eradicate insects in apples, cabbage, field corn, head lettuce, pears, along with cotton. Flucythrinate is a dark-colored liquid with a thick consistency.
Bifenthrin		Talster, Marker (Bifenthrin 10 % EC).	On a wide scale, bifenthrin is frequently employed to combat invasive red fire ants.
Cyfluthrin		Solomon® Beta-Cyfluthrin + Imidacloprid 300 OD.	Cyfluthrin is used to treat pests such as ants, silverfish, cockroaches, termites, weevils, fleas, mosquitoes, and flies.
Lamda-cyhalothrin		Reeva 2.5 EC, Reeva 5 EC, Trekker, Sentry	Lambda-cyhalothrin is an artificial pyrethroid pesticide that is widely used in agricultural, household pest management, food safety, and disease vector control.

understand their impacts (Tang et al., 2018). Pyrethroids, due to their lipophilicity, are difficult to remove from an organism. Long-term, low-dose pyrethroid exposure can damage the neurological, immunological, cardiovascular, and genetic systems and promote chronic illnesses, which can result in teratogenicity, carcinogenicity, and mutagenicity (Ma, 2009). The global prevalence of pyrethroid insecticides in sediments and their detrimental effects on aquatic invertebrates were examined by Li et al. (2017).

Impacts of pyrethroids on molluscs

Molluscs are highly diverse, with thousands of species in various environments. They contribute to nutrient cycling by breaking down organic matter, which helps in recycling nutrients back into the ecosystem. This process supports the growth of other aquatic organisms. They serve as a crucial food source for many aquatic animals, including fish, birds, and other invertebrates. Their abundance affects the structure and dynamics of food webs (Chahauri et al., 2023). Many molluscs, such as certain gastropods (e.g., carnivorous snails) and cephalopods (e.g., octopuses and squids), feed on primary consumers like small fish, crustaceans, and other invertebrates. By preying on these organisms, they help control their populations and maintain ecological balance. As secondary consumers, molluscs transfer energy from primary consumers (herbivores) to higher trophic levels (tertiary consumers), such as larger fish and marine mammals. This energy flow is crucial for the functioning of food webs. Some molluscs, particularly bivalves, engage in bioturbation—disturbing and mixing sediment as they feed. This process enhances nutrient availability in the sediment and can improve habitat quality for other organisms. Molluscs are valuable bioindicator species in biomonitoring systems as they can bioaccumulate pollutants such as heavy metals (like lead, cadmium, and mercury), organic pollutants (like pesticides), and hydrocarbons in their tissues. This accumulation occurs because they filter large volumes of water, allowing pollutants in the water to concentrate in their bodies over time. They are also sensitive to changes in pH, salinity, temperature, and nutrient levels. Their population, growth rate, shell formation, and overall health can be affected by these changes, providing early signs of ecosystem stress or imbalance. Molluscs absorb pyrethroids primarily through filter feeding and respiratory surfaces, with sediment contact and adsorption on external surfaces playing secondary roles. Their inability to actively detect and avoid pyrethroids makes them particularly vulnerable to exposure in contaminated environments. This passive absorption and the lipophilic nature of pyrethroids lead to bioaccumulation, posing significant risks to mollusc health and survival. Several types of pesticides pose significant threats to molluscs, especially organophosphate, carbamate, pyrethroids, organochlorine etc. Within these pyrethroids are highly toxic to invertebrates, including molluscs. It can cause developmental issues, reproductive failures, and lethality even at low concentrations. They often bind to sediments in aquatic environments, prolonging their presence and effects (Amiard-Triquet and Amiard, 2012). They are highly toxic to aquatic molluscs, causing mortality, physiological stress, and behavioural changes (Werner and Moran, 2008). It can also affect mollusc reproduction, development, and growth, leading to population declines. It disrupts their nervous systems, altering behaviour, feeding patterns, and predator avoidance. It causes tremors, paralysis, and even death by upsetting nerve systems. Suffocation and hypoxia may result from breathing difficulties (Liu et al., 2024). Additionally, it modifies the social relationships of snails, including mating, aggregation, and communication. For their profound and highly toxic effects, pyrethroids are sometimes considered as nightmare for aquatic mollusc.

Behavioural changes

Environmental stress can have a significant impact on behaviour and survival (Byrne and O'halloran, 2001; Naskar et al., 2023a). Behaviour offers a unique perspective that connects the relationship between an organism's physiology, ecology, and environment (Little and Brewer, 2001). Ecotoxicology research indicates that observing behaviour can provide a sensitive way for monitoring sub-lethal toxicity (Dutta et al., 2014). Behaviour helps organisms adapt to changing environments by responding to both internal and external stimuli (Naskar et al., 2023b). Behavioural changes are a holistic reaction (Dutta et al., 2018). Alterations in reactions can lead to decreased wellness and survival, leading to negative repercussions for populations (Sanyal et al., 2024). Cypermethrin exposure causes mussels to reduce valve opening, display intermittent adductions, and respond to rapid and repetitive adductions, short and prolonged closures, and full and continuous closures for 400 and 800 mg/l Cypermethrin (Ait Ayad et al., 2011). Cypermethrin decreased the closure of valves in a time-dependent way. Exposure to Cypermethrin increased over time, leading to a faster onset of substantial effects. Cypermethrin concentrations increase valve closure times, comparable with how the pyrethroid deltamethrin decreases filtering function in *Anodonta cygnea* (Kontreczky et al. 1997). According to a study on the effects of deltamethrin and malathion on *Helisoma duryi* snails, these pesticides reduced the egg-laying capacity of the treated snails as compared to the control snails. The treated snails reduced their egg-laying capacity by up to 92.83 % as compared to the control snails (Bakry et al., 2011). The study found that deltamethrin and malathion significantly kill *H. duryi* snails, with LC50 values of 1.76 and 4.82 ppm, respectively (Bakry et al., 2011). Pyrethroid insecticides appear to be potentially harmful to non-target aquatic invertebrates as well as having a negative impact on their survival and reproductive success (Ray et al., 2013). Under stress from pyrethroid contamination, molluscs may display altered feeding habits, decreased activity during feeding, or avoidance of food sources (Ray et al., 2013). Burrowing, concealing, or seeking cover more frequently or for longer periods of time. Sluggishness, trembling, erratic gait, or changed patterns of migration are commonly found. In bivalves, pyrethroids can cause prolonged or incomplete shell closure. Avoiding areas with high pyrethroid concentrations or changing habitat use. In snails, it can cause tentacle retraction or reduced tentacle activity (Kontreczky et al. 1997). These behavioural changes can serve as indicators of pyrethroid stress in molluscs, allowing for early detection and potential mitigation of contamination effects.

Effects on external defence system

Molluscs have strong calcareous shells or valves that provide major protection against infections and toxic substances. In the case of shell-less molluscs, the thick exterior cuticle covering known as the mantle or pallium is thought to serve a key physiological function in preventing toxin and disease entry (Gökoğlu and Gökoğlu, 2021). On the other hand, molluscs have soft body walls made up of cuticles, epidermis, and muscle, each of which is assumed to play an active role in innate immunological protection against environmental infections and poisons (Newton and Smolowitz, 2018). The valves of mussels are kept closed to prevent unwanted agents from entering contaminated aquatic environments. In addition to providing outward protection, the mucus generated by the interior viscera adds another layer of protection against infections and toxic substances. The mucus functions as a protective barrier, prohibiting toxins from directly contacting epithelia. Mucus release is a key detoxification and evasion strategy in invertebrates. Toxic substances become caught within their mucus, resulting in their removal. The production of mucus is regarded as an exterior physiochemical barrier in mollusca. It is essential for aquatic organisms' immunological defence (Weng et al., 2022). Pollution of aquatic environments by these pyrethroids frequently causes breakdowns in the physicochemical barriers of the exterior body surface, allowing poisonous chemicals to enter the viscera of nontarget molluscs. Physiochemical barriers prevent the introduction of exogenous, harmful chemicals (Meftaul et al., 2020). Köprücü and Seker, 2008 found that the synthetic pyrethroid deltamethrin was extremely harmful to *Unio elongatulus eucirrus* at concentrations of 8.99, 8.09, 7.30, and 6.60 mg/L over 24, 48, 72, and 96 hours, correspondingly. The LC50 values of cypermethrin on *Unio eucirrus* were 96.50, 77.96, and 59.20 μg/l after 48 hours, 72 hours, and 96 hours, respectively (Koprucu et al., 2010). An investigation suggested that evaluated cypermethrin cytotoxicity within the snail, *Chilina parchappii*, reported about 96-hour LC50 as 44.59 mg/L (San Juan et al., 2020). Once *Lymnaea acuminata* was treated with sublethal doses of cypermethrin such as 4.0 mg/L, 8.0 mg/L, and 12.0 mg/L, individuals demonstrated improved oviposition, resulting in higher egg production (Tripathi and Singh, 2004). According to **Joana et al. (2019)**, the toxic effects of these insecticides on mussels differ in terms of their effect on normal behaviour, such as shell opening, activity, and movement, in addition to the early beginning of mortality (Fig.-iii).

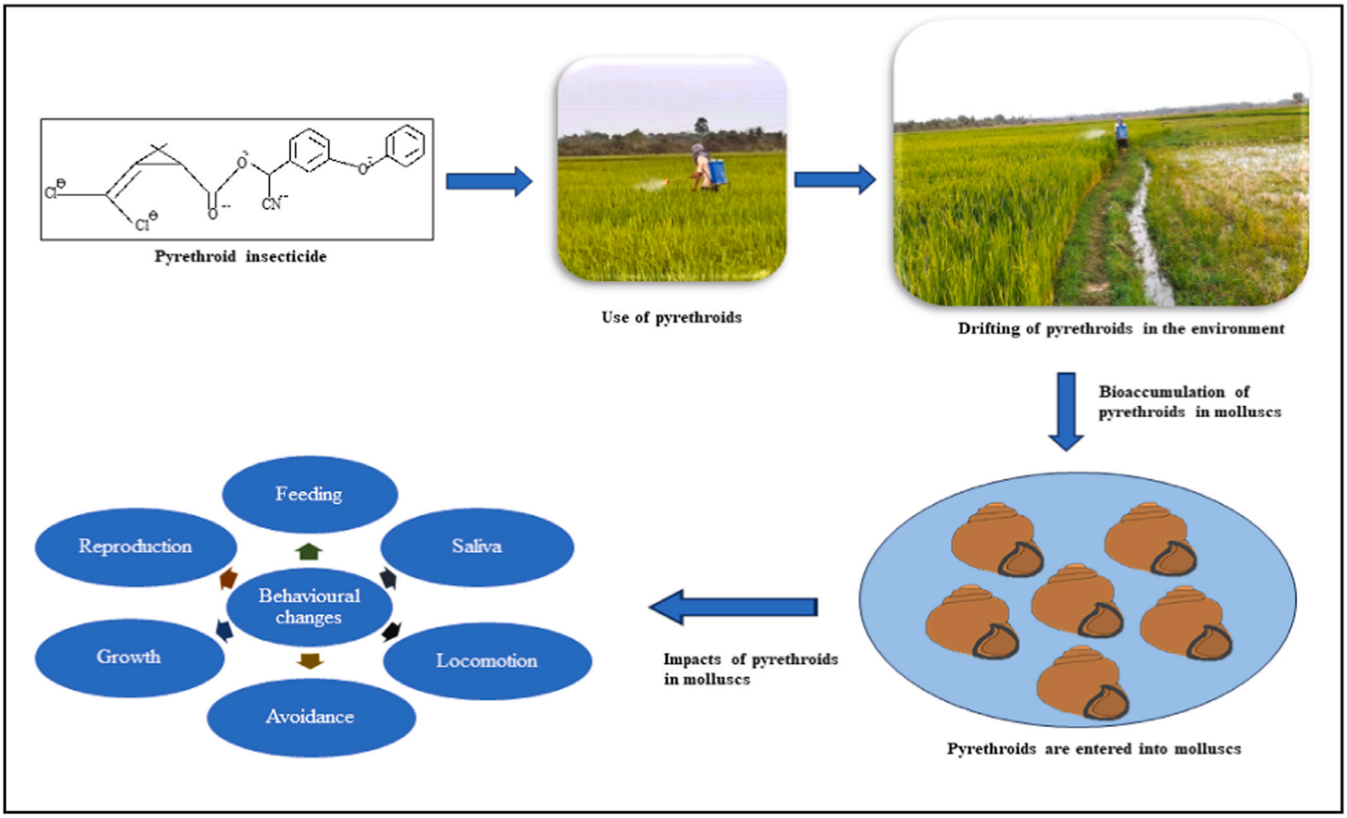


Fig. iii. Drifting of pyrethroids in aquatic environments shows negative impacts on behavioural alterations of molluscs.

Effects on physiology of molluscs

According to Bakry et al. 2011 the effects of deltamethrin and malathion on *Helisoma duryi* has revealed considerable decreases in the albumin level of the hemolymph which indicate injury to the hepatic parenchyma. They increased glucose levels in snail hemolymph, which led to a considerable reduction in oxygen consumption during anaerobic respiration. Glycogen is the main source of serum glucose and is the most significant anaerobic energy source among anoxic-tolerant molluscs (Rawi et al., 1995). Pesticides can cause hypoxic or anoxic conditions, leading to enhanced glycogenolysis and elevated blood glucose levels. To replenish energy, the snail increases glycolysis, reducing glycogen content and increasing glucose levels in the hemolymph. They also found that the glycolytic enzyme activity of lactate dehydrogenase, succinate dehydrogenase, ornithine aminotransferase, and arginase was reduced in snail tissues after exposure to deltamethrin and malathion. Aboul-Zahab and El-Ansary (1992) reported that succinate dehydrogenase exhibited the lowest activity and this could be attributed to either inflated or damaged mitochondrial membranes, or to lower levels of Cristal that led to enzyme leakage. Arginase and ornithine aminotransferase enzyme activity is significantly reduced in snails exposed to insecticides. The ability of cells to get rid of endogenous harmful chemicals like ammonia, which is converted into urea, may be impacted by decreased enzyme activity (Bakry et al., 2011). Based on their detrimental effects on the immunological characteristics of the host animal, scientists categorized pyrethroids, cypermethrin, and fenvalerate as immunotoxins after observing their hazardous effects on freshwater molluscan invertebrates (Ray et al., 2013).

Effects of cellular defence system

The molluscan defence mechanism relies on circulating hemocytes in the bloodstream. Hemocytes migrate throughout tissues in reaction to external substances, including infections. The major defensive mechanism involves phagocytosis, encapsulation, and the release of numerous cytotoxic chemicals (Carballal et al., 1997). Multicellular organisms often feature mobile phagocytic cells capable of recognising and eliminating externally harmful compounds. Phagocytosis is a recognised immune response and a diagnostic of water pollution (Oliver and Fisher, 1999). Fenvalerate administration dramatically reduced phagocytic indices in *B. bengalensis*, with a dose-dependent response. In molluscs, phenoloxidase is regarded as a vital defence enzyme. It plays a crucial role in the intracellular antibacterial defence system of oysters (Munoz et al., 2006). To produce active phenoloxidase, a prophenoloxidase activating system is activated by PAMPs such as lipopolysaccharide, peptidoglycan, laminarin, and β-1,3-glucan (Cerenius and Söderhäll, 2004). Exposing *B. bengalensis* to fenvalerate affected its phenoloxidase activity. Fenvalerate therapy dramatically lowered hemocyte phagocytic indices in a dose-dependent manner. Male *B. bengalensis* showed a 56.6 ± 3.73 reduction in their phagocytic response as compared to the control sample when exposed to 3 ppm fenvalerate after 15 days of in vivo exposure (Mukherjee and Mandal, 2023).

Mechanism of action of pyrethroids and the role of antioxidants

Over time, molluscs accumulate pyrethroids in their fatty tissues, where the chemicals are stored instead of being easily metabolized or excreted. Even if pyrethroid levels in the water are relatively low, this slow accumulation results in large internal concentrations that have the potential to become hazardous. Pyrethroids can be the reason for serious damage to cells, which is caused by free oxidative radicals. Pyrethroid exposure in molluscs causes widespread metabolic disruption by increasing oxidative stress, depleting energy stores, altering amino acid and neurotransmitter levels, and accumulating toxic metabolites in fatty tissues. Pyrethroids are metabolized in the body through a series of enzymatic processes that primarily take place in the liver but can also occur in other tissues, such as the kidneys and intestines. These metabolic processes can lead to the formation of reactive oxygen species (ROS) and other toxic intermediates, which can contribute to oxidative stress and potential cellular damage. The primary enzymes involved in the metabolism of pyrethroids are cytochrome P450 enzymes (CYPs), carboxylesterases, and, to a lesser extent, esterases and oxidases. The oxidative reactions carried out by P450 enzymes can produce toxic intermediates, such as epoxides or hydroxylated derivatives, which may be unstable and react with cellular components. During the P450-mediated oxidation of pyrethroids, electrons are transferred to molecular oxygen, which can produce superoxide (O_2^-), hydroxyl radicals (•OH), and hydrogen peroxide (H_2O_2) if the oxygen is only partially reduced. These ROS are by-products of oxidative metabolism, particularly when excess pyrethroid exposure overwhelms the metabolic capacity, leading to leakage of ROS (San Juan et al., 2020). These ROS can act as molecular cutters, which means they can damage DNA and proteins. Aquatic organisms, such as molluscs, have the ability to reduce the action of ROS. But when these particles produce more ROS in the body, the antioxidants fail or cannot control the normal cellular functions in aquatic organisms. Cypermethrin can cause ROS formation, resulting in DNA damage, lipid peroxidation, and protein carbonylation, altering normal cellular processes (Shashikumar and Rajini, 2010). Organisms have both enzymatic and non-enzymatic antioxidant defence mechanisms to neutralise ROS, including H_2O_2, superoxide (O_2^-), and hydroxyl radical ($OH^\cdot$), produced during aerobic metabolism. Enzymatic defences such as superoxide dismutase (SOD) and catalase (CAT) breakdown O_2^- and H_2O_2 to create less harmful metabolites (Livingstone, 2001). Organisms can respond to increased ROS generation from xenobiotic exposure by increasing antioxidant enzyme activity in their cells. Enzyme activity is increased by transcriptional and post-translational control, promoting a defensive strategy (Regoli and Giuliani, 2014). SOD and CAT activity are widely used as indicators of pollution contamination in aquatic systems (Monserrat et al., 2007). Glutathione peroxidases and peroxiredoxins are part of the antioxidant mechanism and serve the same function as CAT. Cypermethrin exposure increased SOD and CAT activity in the digestive gland of the freshwater mussel *Unio gibbus* (Khazri et al., 2015). According to Regoli and Giuliani (2014), increased ROS levels may inhibit the alternating tendency of CAT activity. Superoxide radicals are thought to be the primary cause of CAT inhibition, resulting in high levels of H_2O_2 and reduced SOD activity (Wei et al., 2015). According to scientists, ROS can interfere with protein synthesis while impacting the functioning of enzymes. While SOD and CAT represent the first defence walls versus ROS, many researchers indicate that their responses differ significantly (Fig.-iv). The digestive gland is the primary location of phase I and II detoxification in molluscs. When enzymes in phase I fail to protect cells, Glutathion-S-Tranferase (GST) increases its activity (Sellami et al., 2015). Its primary function is to detoxify electrophiles, when pesticide metabolites combine with reduced glutathione to promote their excretion (Livingstone, 2001). Xenobiotics can trigger GST activity through transcription or stress-activated signalling pathways (Richardson et al., 2009). Some data indicate that GST has a role in cytomethrin conversion in aquatic organisms (Xu and Huang, 2017). According to Mahmoud et al. (2012), permethrin increased CAT activity in the digestive gland of the sea gastropod *Hexaplex trunculus* at varying doses but lowered it at higher concentrations. The pyrethroid elicited comparable reactions in *P. canaliculata*, but there was no concentration- or time-dependent linear responses in lipid peroxidation. Cypermethrin had a short- and

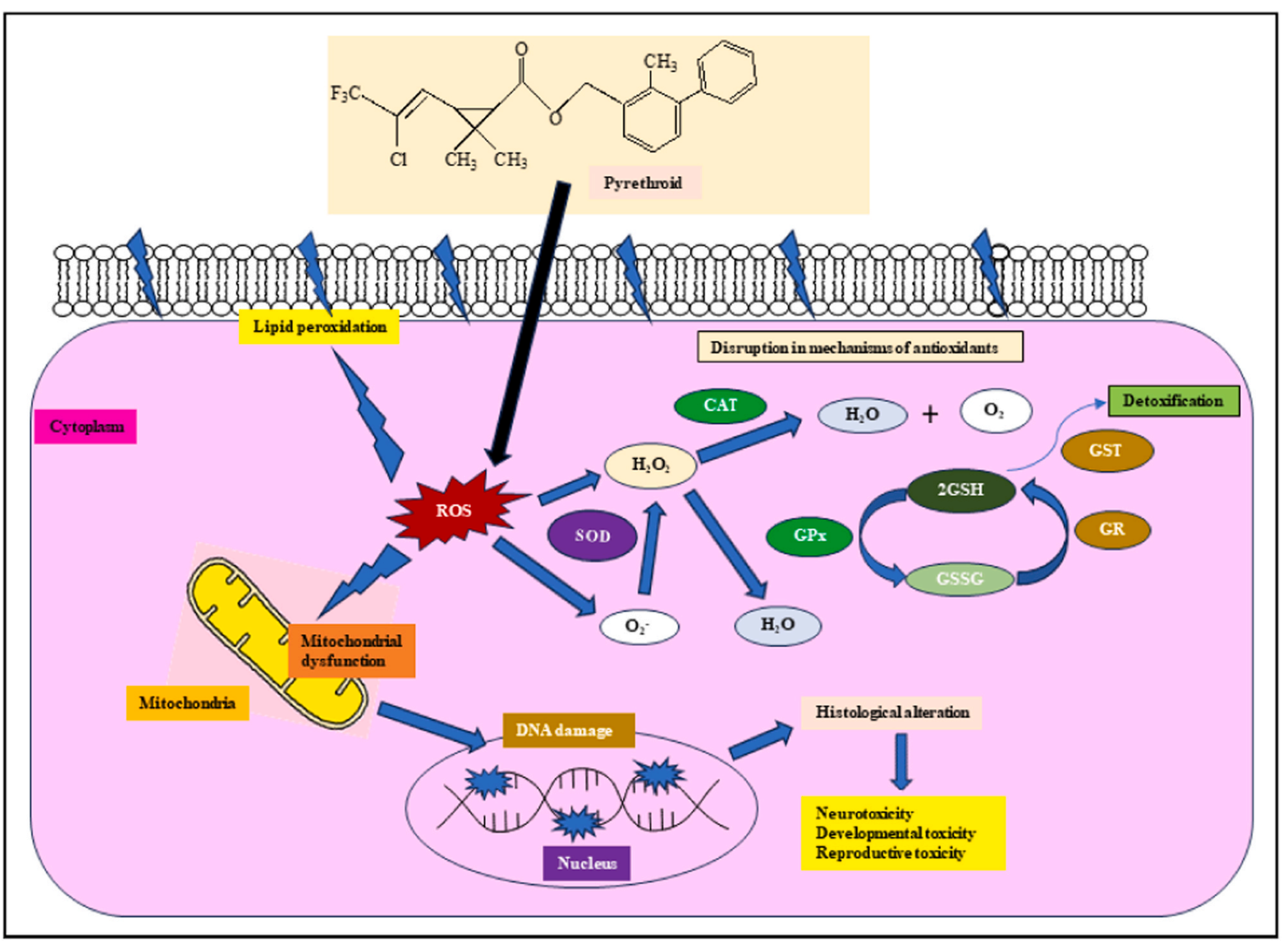


Fig. iv. Mode of action of pyrethroids and the role of antioxidants in aquatic molluscs.

long-term influence on lipid oxidation in *P. canaliculata* gills, resulting in significantly elevated TBAR levels. However, in clams *R. decussatus* and *V. decussate*, the digestive gland was shown to be more vulnerable to pyrethroid toxicity than the gills (Sellami et al., 2014; Sellami et al., 2015). The digestive gland, which detoxifies pesticides and produces large levels of ROS, may be responsible for these tissue-specific reactions (Sellami et al., 2015). The gill acts as a location for gas exchange and ion control, including catabolic waste elimination. subsequently also serves as a primary point of entry for dissolved toxicants from the surrounding water (Wei and Yang, 2015). This organ is sensitive to ROS damage, as seen in *P. canaliculata.* Cypermethrin and other xenobiotics can cause lipid peroxidation, which affects membrane fluidity and biomolecule integrity (Wei and Yang, 2015). Lipid peroxidation products, such as aldehydes and ketones, may accelerate the oxidation of proteins. Amino acid oxidation through glycation and glycoxidation processes can also produce these moieties (Dalle-Donne et al., 2003). According to Ahirrao and Phand (2015), cytomethrin exposure in *Bellamya bengalensis* causes a significant decrease in the concentration of ascorbic acid in reproductive phases. ROS induces lipid peroxidation (LPO) and elevates calcium levels (Ca++), which leads to both genotoxicity and cell death in affected species (Ullah et al., 2018). Cypermethrin administration boosted antioxidant enzyme activity in the gills and digestive glands of *U. gibbus*, a freshwater mussel (Khazri et al., 2015).

Effects of pyrethroids to nervous system

Pyrethroids have a significant impact on neurotransmitter actions in molluscs, primarily due to their interference with voltage-gated sodium channels, which are essential for proper nerve signal transmission. Whenever this gate opens, it stimulates the nerve and shuts to end the communication. Channels are passageways that allow ions to enter the axon and produce stimulation. When nerve cells possess accessible channels, they discharge repeatedly, leading to paralysis (Shafer and Meyer, 2004). Pyrethroids bind to this gate and prevent it from closing which results in stimulation and convulsions of the nervous system in infected molluscs (Fig.- v).

The prolonged nerve activity disrupts the balance of inhibitory neurotransmitters like gamma-aminobutyric acid (GABA) and also causes irregular release of acetylcholine, leading to poor control over muscular function, and affecting activities like movement, feeding, and respiration. Molluscs may exhibit uncoordinated or weakened movements, making them more vulnerable to predation and less able to perform necessary functions for survival (Ali, 2012). Pyrethroids are divided into Type I and Type II, depending on their poisoning symptoms. Type II pyrethroids differ from Type I by having an α-cyano group in their chemical structure. Unlike Type I pyrethroids, which primarily disrupt sodium channel activity in the central nervous system, Type II pyrethroids may interfere with chloride and calcium channels, both of which are essential for nerve function (Burr and Ray, 2004). Pyrethroids are easily absorbed by cellular membranes and tissues due to their lipophilicity. Lambda-cyhalothrin enters the mollusc muscle, interrupting nerve transmission within minutes. This causes discontinuation of feeding, loss of muscle control, paralysis, and death. The reaction that occurs in the sodium channel is not the sole mode of action postulated for pyrethroids. Their impact on the central nervous system has prompted several researchers to propose activities such as antagonising GABA-mediated suppression, modulating nicotinic cholinergic transmission, increasing noradrenaline release, or acting on calcium ions (Reis et al., 2009; Brown, 2020). Because neurotransmitter-specific pharmacological treatments provide only little or no protection against poisoning, it is doubtful that one of these consequences is the predominant mode of action of pyrethroids, and most of the discharge of neurotransmitters is a result of increased salt entry.

Discussion and conclusion

With rising population and food demand, pesticides and insecticides are increasingly used to protect plants and enhance productivity (FAO

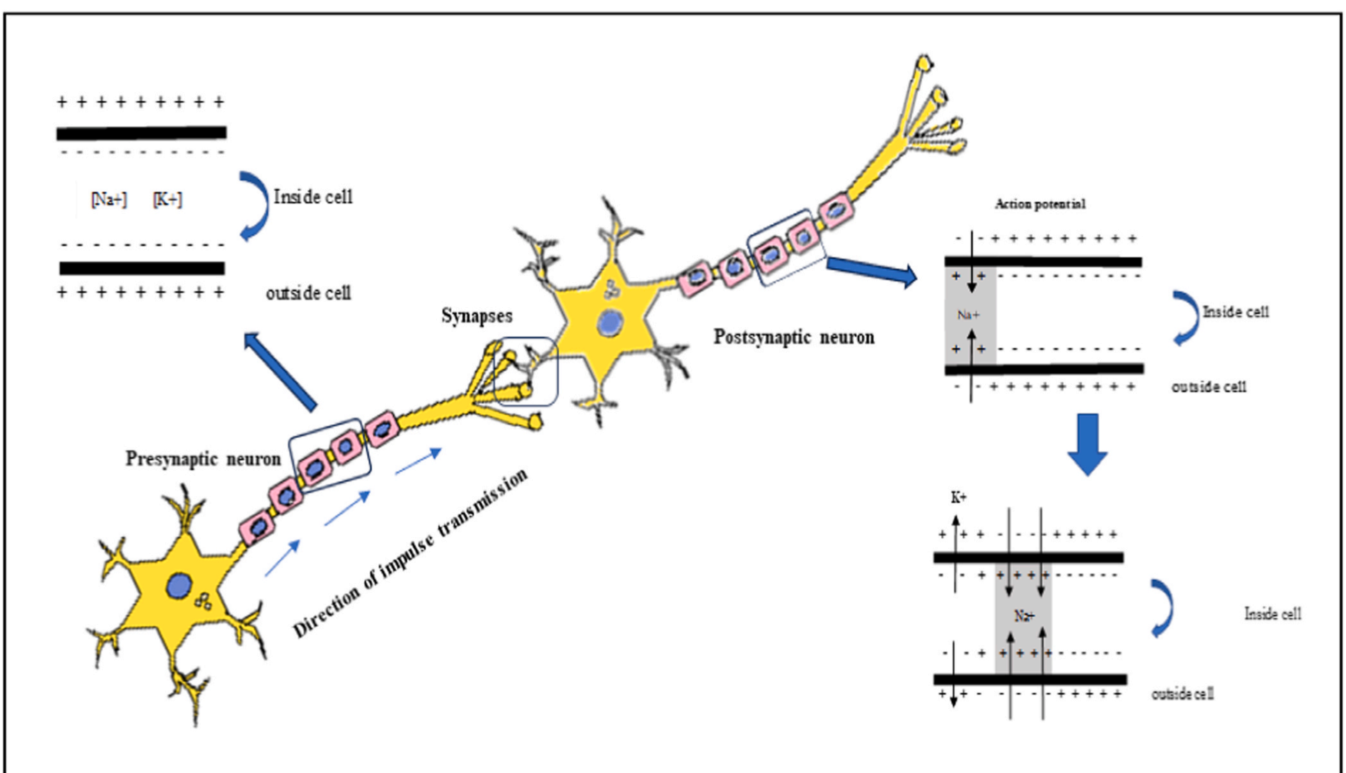


Fig. v. Mode of action of pyrethroid insecticides on sodium gated channel.

2002). The widespread utilisation of these pyrethroids is projected to continue globally. According to research findings, pyrethroids pose a significant environmental threat to aquatic molluscs worldwide (Zhao, 2014). Researchers are mostly focused on larger water bodies, such as rivers, to evaluate the impacts of pyrethroids on aquatic life, whereas smaller ponds and streams are being overlooked. Because they are often considered more significant due to their larger size, greater water volume, and role in shaping landscapes (Vaughan et al., 2009). These are more visible and accessible, making it easier for researchers to study them. Research funding often prioritizes projects focused on larger, more conspicuous water bodies, neglecting smaller Studying smaller water bodies can be more difficult due to their smaller size, greater heterogeneity, and potential inaccessibility. It often lacks standardized monitoring and data collection, making it harder to compare and synthesize data across different studies. However, smaller water bodies like ponds and streams are crucial components of aquatic ecosystems, providing unique habitats and supporting diverse biota. Neglecting these systems can lead to an incomplete understanding of freshwater ecosystems and their responses to environmental changes. Pest management strategies should focus on preventing pyrethroid contamination of discharge and drift in waterbodies. The negative impacts of pyrethroids on nontargeted molluscs become a significant issue to be concerned about. The response to the rationale underlying reviewing the effects of pyrethroids on molluscs is very useful information. It can exert multifaceted effects on molluscs, primarily through neurotoxicity and oxidative stress, cascading into reproductive, behavioural, immune, and growth impairments. It primarily affects the nervous system of molluscs by interfering with the function of sodium channels. It also increases the release of neurotransmitters resulting in disrupting normal nerve function (Sharma et al., 2020). Also, it can produce reactive oxygen species (ROS) that damage neurons oxidatively, which damages DNA and activates cytochrome c, Bax, Bid, Bak, Caspase-3, 8, and 9, and other regulators of the apoptotic cascade (Martinez et al., 2018). Additionally, in vitro, pyrethroid exposure reduces the activity of antioxidant enzymes such glutathione peroxidase (GPx), reduced glutathione (GSH), and CAT in a dose- and time-dependent manner (Wang et al., 2016). By changing the structure of gonadotrophs and the hypothalamic Na^{+}, Cl^{-}, and Ca^{2+} channels, it can cause disruption of the hypothalamus–pituitary–gonadal axis circuit. GnRH levels fall as a result, and the pituitary gland releases less LH and FSH, which further lowers the secretion of progesterone and oestrogen (Ngang and Okafor, 2004). So, Pyrethroids compromise multiple physiological systems in molluscs, particularly reproduction, behaviour, and growth, with downstream ecological consequences These impacts highlight the ecological risk of pyrethroid contamination in aquatic environments, necessitating stringent regulatory measures to mitigate their adverse effects. Approximately 550 million years ago, an earliest group of invertebrates called molluscs began to develop. Their ability to successfully adapt to a variety of environmental situations, both favourable and unfavourable, accounts for their extensive dispersion and continuous survival. Molluscs, including species like clams, mussels, and snails, are important members of aquatic food webs. They serve as primary food sources for various fish, birds, and other wildlife, making them essential for the survival of numerous predator species. Mollusc populations contribute to species diversity within ecosystems. Declines in its populations can lead to weakened ecosystems that are more vulnerable to disruptions, such as pollution, climate change, and invasive species. The constant release of novel xenobiotics into the environment over the past few decades has raised concerns about aquatic creatures' ecotoxicological health. The newly used insecticides called pyrethroids in India's agriculture sector require particular ecotoxicological consideration. Snail physiological changes cause reduced egg production and increased death rates in pyrethroid-affected snails (Bakry et al., 2011). Several behavioural alterations may indicate stress due to the hazardous environment (Ray et al., 2013). Behavioural alterations of molluscs reveal a distinct reaction to water contamination by various pyrethroids. More research is needed to use bioindicative signals from bivalves under contamination stress to better understand the interaction of pyrethroids in freshwater environments. To further assess the environmental impact of pyrethroids, it may be beneficial to analyse other biomarkers beyond oxidative stress. Previous findings provided by researchers clearly reveal that long-term exposure to pyrethroids can interfere with physiological functioning in molluscs (Rawi et al., 1995). More molecular research and understanding of molluscs are needed to efficiently implement the effects of pyrethroid insecticides. It can reveal the precise mechanisms by which pyrethroids interact with mollusc biology, leading to toxicity. It can identify specific biomarkers for pyrethroid exposure, allowing for earlier detection and monitoring. These studies can explore how pyrethroids interact with mollusc genes, influencing toxicity and adaptation (Valavanidis et al., 2006). Understanding the molecular mechanisms underlying pyrethroid tolerance can inform strategies for managing pesticide resistance (Nowell et al., 2014). Molecular research can uncover differences in pyrethroid sensitivity among mollusc species, informing conservation efforts. It can investigate epigenetic changes induced by pyrethroids, with implications for long-term effects and heritability. When determining the risk of pyrethroid exposure to aquatic creatures, toxicity criteria offer a baseline. Risk management decisions are guided by standards, which specify the threshold at which unfavourable impacts are expected to occur. It permits the comparison of pyrethroid sensitivity in various species, revealing populations that are more susceptible. It also provides information for the creation of water quality recommendations, guaranteeing the preservation of aquatic life. Regulation frameworks are supported by toxicity standards, which make enforcement and compliance monitoring easier. Environmental monitoring programs are guided by standards, which detect exceedances and initiate corrective action. By establishing toxicity standards, regulatory agencies and researchers can better evaluate the biological threats of pyrethroids to aquatic organisms, ultimately protecting aquatic ecosystems and promoting environmental sustainability. When determining the risk of pyrethroid exposure to aquatic creatures, toxicity criteria offer a baseline. Risk management decisions are guided by standards, which specify the threshold at which unfavourable impacts are expected to occur. It permits the comparison of pyrethroid sensitivity in various species, revealing populations that are more susceptible. 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The impacts of various stressors on organisms, including prolonged toxic effects and interspecies interactions, are not widely recognised. The combined effects of pyrethroids and other stressors, such as temperature, pH, and other pollutants, ought to be observed in aquatic animals. More study is needed to determine the influence of pyrethroids on aquatic organisms. It is necessary to conduct long-term exposure studies to evaluate the impact of pyrethroids on aquatic creatures. It is necessary to conduct research on the effects of low-dose pyrethroid exposure, which is more indicative of real-world situations. It is also necessary to carry out studies on a larger variety -of aquatic species in order to comprehend the differing pyrethroid sensitivity. The potential for pyrethroids to bioaccumulate and biomagnify in aquatic food webs should be thoroughly investigated through appropriate research. By addressing these research gaps, we can gain a more comprehensive understanding of the influence of pyrethroids on aquatic organisms and develop effective strategies to minimize their impacts.

Ethical approval

Not applicable

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None

CRediT authorship contribution statement

Dutta Dr. Sangita Maiti: Visualization, Validation, Supervision, Conceptualization. **Saha Raja:** Writing – review & editing, Writing – original draft, Visualization, Validation, Conceptualization.

Declaration of Competing Interest

The writers say they have no competing interests.

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Code availability

No software is used for writing this manuscript.

Author's contribution

Author Raja Saha prepares the manuscript under the guidance of the corresponding author Dr. Sangita Maiti Dutta.

Data Availability

Data will be made available on request. Every dataset that was examined for this study is openly accessible to the public.

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