# Integrating Botanical Molluscicides into One Health Strategies for Fasciolosis Control: Current Advances, Challenges and Future Directions

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**ABSTRACT:** Fasciolosis is a neglected parasitic disease of major veterinary and public health importance, causing substantial economic losses in livestock and posing an increasing zoonotic risk. Control strategies have traditionally relied on synthetic molluscicides to reduce or control populations of freshwater snail intermediate hosts. However, their widespread use is constrained by environmental toxicity, adverse effects on non-target organisms, and concerns regarding long-term sustainability. Botanical molluscicides have emerged as promising eco-friendly alternatives owing to their biodegradability, diverse bioactive phytochemicals, and potentially lower environmental impact. This review summarises recent advances in plant-derived molluscicides, with emphasis on their efficacy against freshwater intermediate host snails, mechanisms of action, and advantages over conventional chemical agents. The integration of botanical molluscicides into a One Health framework is discussed, highlighting their potential to reduce parasite transmission while promoting livestock productivity, human health, biodiversity conservation and environmental sustainability. Current challenges, including extract standardisation, formulation development, field validation, and regulatory implementation, are also addressed. Overall, botanical molluscicides represent a sustainable and integrated approach for fasciolosis control and offer significant potential for future parasite management programmes.
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**Short Title:** Botanical Molluscicides in One Health.

## [1] INTRODUCTION

Fasciolosis is a neglected food-borne zoonotic disease caused by *Fasciola hepatica* and *Fasciola gigantica*, digenetic trematodes that infect domestic ruminants, wildlife, and humans (Lalor et al., 2021; Singh et al., 2021a). The parasite requires freshwater lymnaeid snails as obligatory intermediate hosts, making snail populations central to disease transmission (Vázquez et al., 2023; Ngcamphalala et al., 2025). Once regarded primarily as a veterinary disease, fasciolosis is now recognised as an important public health concern because of its expanding geographical distribution, increasing human infections, and substantial socioeconomic impact. Recently, Ntivuguruzwa et al., (2026) reported its epidemiology is shaped by interactions among humans, livestock, and aquatic ecosystems, placing the disease within the One Health framework. Fasciolosis is endemic in temperate and tropical regions, particularly where livestock production depends on grazing systems and freshwater habitats support intermediate host snails (Abdullah, 2023; Huertas-López and Ferre, 2026). Infection in livestock results in reduced weight gain, decreased milk production, impaired reproduction, liver condemnation, and increased susceptibility to secondary infections, causing significant economic losses (Rashid et al., 2019; Rizwan et al., 2023). Mas-Coma et al., (2022) reported that human infection occurs mainly through the consumption of contaminated aquatic vegetation or water. Moreover, climate change, irrigation expansion, and changing agricultural practices have facilitated the spread of both *Fasciola* spp. and their intermediate hosts, increasing the complexity of disease control (Alba et al., 2021; Mas-Coma et al., 2022). Interrupting snail-mediated transmission remains one of the most effective strategies for controlling fasciolosis. Although synthetic molluscicides such as niclosamide and copper sulphate are effective, their use is constrained by environmental persistence, toxicity to non-target organisms, and sustainability concerns (Zheng et al., 2021; Oyeyemi et al., 2025). These limitations have intensified the search for environmentally compatible alternatives. Botanical molluscicides have emerged as promising candidates because they are biodegradable, renewable, and contain diverse

bioactive phytochemicals that act through multiple mechanisms against freshwater snails (Singh et al., 1996c; Radwan and Gad, 2021).

However, their wider application is hindered by variability in phytochemical composition, lack of standardised extraction methods, limited field validation, formulation instability, and regulatory constraints (Ahmad et al., 2026). Although numerous studies have reported the molluscicidal potential of individual plant species, a comprehensive synthesis integrating botanical molluscicides with phytochemistry, mechanisms of action, environmental sustainability and One Health-based fasciolosis control remains limited. Therefore, this review critically examines current advances in plant-derived molluscicides targeting freshwater snail intermediate hosts of *Fasciola* spp., discusses their mechanisms of action and role within integrated One Health strategies, and highlights key challenges and future research directions for developing safe, effective, and sustainable fasciolosis control programmes.

## [2] FASCIOLOSIS: DISEASE BURDEN AND TRANSMISSION

### [2.1] Overview of Fasciolosis

Fasciolosis is a parasitic disease caused by the liver flukes *Fasciola hepatica* and *Fasciola gigantica* (family-Fasciolidae) (Lalor et al., 2021). *Fasciola hepatica* predominates in temperate regions, whereas *F. gigantica* is more common in tropical and subtropical areas, particularly in Asia and Africa (Mas-Coma et al., 2022). Both species infect a wide range of mammalian hosts, especially cattle, buffaloes, sheep and goats, while humans acquire infection through ingestion of metacercariae on contaminated aquatic vegetation or untreated water (Li and Liu, 2024; Hassan et al., 2025). The disease transmission depends on freshwater lymnaeid snails, which serve as obligatory intermediate hosts linking the parasite to aquatic ecosystems. Consequently, climate variability, irrigation expansion, land-use changes and livestock movement have facilitated the maintenance and spread of fasciolosis in many endemic regions. Although anthelmintic drugs are potentially effective strategies for treating infected animals, reinfection remains common where infected snail populations persist, highlighting the importance of integrated control strategies that combine chemotherapy, surveillance, environmental management, and snail control (Ntivuguruzwa et al., 2026; Freire and Capozzo, 2026).

### [2.2] Life Cycle of *Fasciola* spp.

The life cycle of *Fasciola* spp. is indirect, involving a mammalian definitive host and a freshwater lymnaeid snail as the obligatory intermediate host (Figure 1). Adult flukes inhabit the bile ducts of infected mammals, where they produce eggs that are excreted in faeces (Hawash, 2020). Under suitable environmental conditions, eggs embryonate in freshwater and hatch into free-swimming miracidia, which actively penetrate susceptible freshwater snails, particularly *Lymnaea acuminata,* in many endemic regions of Asia (Erkano, 2021). Within the snail, the parasite undergoes successive developmental stages (sporocyst, redia and cercaria), producing numerous cercariae through asexual multiplication (Whitfield and Evans, 1983; Konecny, 2022) The cercariae are released into water and encyst on aquatic vegetation or other submerged surfaces as metacercariae, the infective stage for the definitive host. Recently, Shamsi (2025) noted infection occurs when livestock or humans ingest metacercariae on contaminated aquatic vegetation or in untreated water. Following excystation in the small intestine, juvenile flukes migrate through the intestinal wall and liver parenchyma before establishing themselves in the bile ducts, where they mature and begin egg production, completing the life cycle. Because development within freshwater snails is essential for parasite transmission, disrupting this stage through effective snail control remains a cornerstone of fasciolosis control.

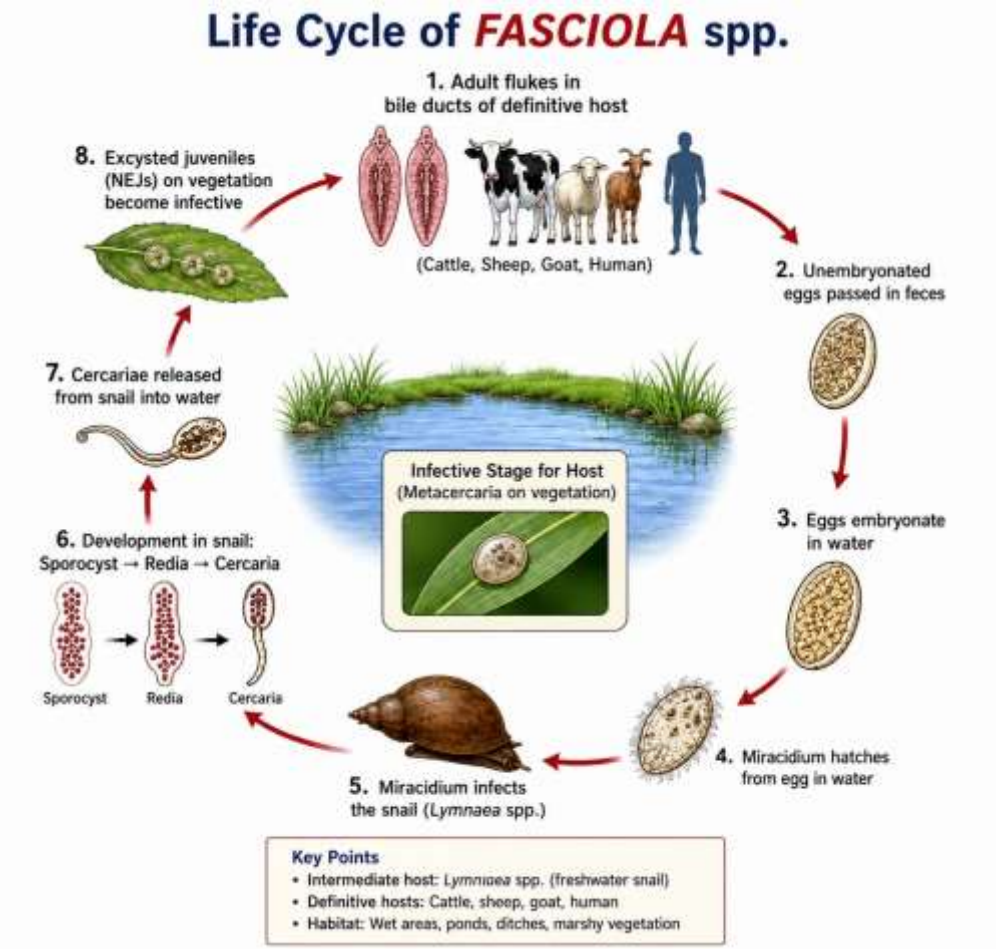


**Figure 1**. Life cycle of *Fasciola* spp. showing development within the freshwater intermediate host (*Lymnaea acuminata*) and transmission to mammalian definitive hosts.

**[2.3] Human and Veterinary Importance**

Fasciolosis is a major zoonotic disease affecting both livestock and humans, with important implications for animal health, public health and food security (Singh et al., 2021a; Abdullah, 2023). In livestock, particularly cattle, buffaloes, sheep and goats, infection with *Fasciola* spp. causes reduced weight gain, decreased milk production, impaired fertility, liver condemnation at slaughter and increased susceptibility to secondary infections (Huertas-López and Ferre, 2026). Furthermore in humans, infection is acquired by ingesting metacercariae on contaminated aquatic vegetation or in untreated water, leading to fever, abdominal pain, hepatobiliary disorders, eosinophilia and, if untreated, chronic liver damage (Christaki, 2020; Hawash, 2020; Braseth et al., 2021). The close interaction among livestock, freshwater habitats and human populations in endemic areas facilitates parasite transmission, emphasising the need for integrated control strategies within a One Health framework (Mas-Coma et al., 2023).

**[2.4] Economic Burden**

Fasciolosis imposes a substantial economic burden on livestock production and public health worldwide (Mohammed, 2026). Globally, annual economic losses amount to billions of US dollars, primarily due to reduced livestock productivity, liver condemnation, expenditures on anthelmintic treatment, veterinary care, disease surveillance and other control measures (Strydom et al., 2023; Strydom et al., 2025). In India, where livestock farming is a major component of the rural economy, fasciolosis continues to cause significant financial losses, particularly in cattle, buffalo, sheep and goat production (Garg et al., 2009; Patel et al., 2025). The disease's persistent economic impact highlights the need for sustainable preventive strategies that interrupt parasite transmission and reduce long-term losses.

## [3] FRESHWATER SNAILS AS KEY INTERMEDIATE HOSTS

### [3.1] Role of Freshwater Snails in Fasciolosis Transmission

Freshwater lymnaeid snails are indispensable intermediate hosts in the life cycle of *Fasciola* spp., supporting the development and asexual multiplication of larval stages before the release of cercariae, which subsequently encyst on aquatic vegetation as infective metacercariae (Whitfield and Evans, 1983; Vázquez et al., 2023). The presence and abundance of susceptible snail populations are therefore critical determinants of parasite transmission. Consequently, the geographical distribution and prevalence of fasciolosis closely correlate with the occurrence of suitable freshwater snail hosts (Garg et al., 2009; Chai and Jung, 2024; de Almeida et al., 2025). As an essential link in the parasite life-cycle, freshwater snails represent a key target for disease control ( Gaye et al., 2024; Shamsi, 2025). Targeting intermediate host snails remains one of the most effective approaches for interrupting parasite transmission, providing a strong rationale for the development of environmentally sustainable botanical molluscicides.

### [3.2] *Lymnaea acuminata*: The Principal Intermediate Host of *Fasciola gigantica*

Snail *Lymnaea acuminata* is the dominant intermediate host of *Fasciola gigantica* in the Indian subcontinent and plays a central role in sustaining parasite transmission in endemic regions (Singh et al., 2021c; Singh et al., 2023). In India, eastern Uttar Pradesh is recognised as a major endemic focus, with the Gorakhpur region among the most extensively investigated transmission hotspots (Singh et al., 2021b). Molecular studies have confirmed the pivotal role of *L. acuminata* in the life-cycle of *F. gigantica*. At the same time, surveys from the Gorakhpur reservoir of sub-merged areas transmission focus reported a natural fasciolid infection prevalence of 72-94% in the lymnaeid snail population. Amongst the highest recorded worldwide for a lymnaeid intermediate host (Sunita et al., 2021; Ngcamphalala et al., 2025;), likewise, fasciolosis prevalence of up to 94% has been documented in slaughtered buffaloes from the Gorakhpur region (Singh and Agarwal, 1981), and it was highlighting the strong epidemiological association between infected snail populations and livestock infection (Singh et al., 2021a; Singh et al., 2021b). These observations underscore the epidemiological significance of *L. acuminata* and justify its widespread use as an experimental model for evaluating plant-derived molluscicides.

### [3.3] Other Medically Important Freshwater Snail Species

Although *Lymnaea acuminata* is the principal intermediate host of *Fasciola gigantica* in the Indian subcontinent, several other freshwater lymnaeid snails contribute to fasciolosis transmission worldwide. Species such as *Galba truncatula*, *Pseudosuccinea columella*, *Radix natalensis* and *Lymnaea neotropica* serve as important intermediate hosts of *Fasciola* spp., with their distribution shaping regional epidemiology (Correa et al., 2010; Alba et al., 2021;Vázquez et al., 2023). The compatibility between *Fasciola* species and their snail hosts varies according to local ecological conditions and host–parasite interactions (Hurtrez-Boussès et al., 2001; Dube et al., 2023) Therefore, effective snail control programmes should be tailored to the predominant intermediate host species in each endemic region.

Table 1. Major freshwater snail species involved in the transmission of *Fasciola* spp. worldwide.

| **Snail species** | **Associated parasite** | **Major geographical distribution** | **Epidemiological significance** |
|---|---|---|---|
| *Lymnaea acuminata* | *Fasciola gigantica* *Fasciola hepatica* | Indian subcontinent | Principal intermediate host in India ( Singh et al., 2021b; Abdullah, 2023) |
| *Galba truncatula* | *Fasciola hepatica* | Europe, West Asia, North Africa | Principal intermediate host in temperate regions (Dube et al., 2023; Smith et al., 2024) |
| *Pseudosuccinea columella* | *Fasciola* spp. | America, Africa, parts of Asia | Invasive host contributing to disease spread (Ngcamphalala et al., 2022) |
| *Radix natalensis* | *Fasciola gigantica* | Sub-Saharan Africa | Important intermediate host in tropical Africa (Malatji et al., 2020) |
| *Lymnaea neotropica* | *Fasciola hepatica* | South America | Regional intermediate host associated with livestock infections (Vázquez et al., 2023) |

### [3.4] Transmission Dynamics and Ecological Factors Influencing Snail Populations

The transmission of fasciolosis is closely governed by the population dynamics of freshwater snails, which are regulated by environmental and climatic factors (Vázquez et al., 2023; Dube et al., 2023; Siama et al., 2023). Temperature, rainfall, water availability and aquatic vegetation influence snail survival, reproduction and distribution, thereby affecting the intensity and seasonality of parasite transmission (Erkano, 2021; Modabbernia et al., 2024). Jumawan et al., (2025) reported that the agricultural activities, particularly irrigation and rice cultivation, create favourable habitats that facilitate snail proliferation and increase transmission risk. Seasonal variation and climate change influence the abundance and geographical distribution of intermediate host snails, thereby altering transmission dynamics and potentially expanding fasciolosis into previously non-endemic regions. Therefore, integrating ecological surveillance with environmentally safe molluscicidal interventions is essential for sustainable disease management while minimising adverse effects on non-target aquatic organisms.

## [4] CONVENTIONAL MOLLUSCICIDES: ACHIEVEMENTS AND LIMITATIONS

Conventional chemical molluscicides have long been an integral component of fasciolosis control programmes by reducing populations of freshwater intermediate host snails (Nyandwaro, 2018; Djirmay et al., 2024; Oyeyemi et al., 2025). Among these, copper sulphate and niclosamide are the most extensively used because of their rapid and reliable molluscicidal activity against lymnaeid snails (Singh et al., 2021c; Richter et al., 2023; Djirmay et al., 2024). When combined with anthelmintic treatment and improved livestock management practices, these chemicals can effectively reduce snail abundance and interrupt parasite transmission. Despite these advantages, the long-term use of synthetic molluscicides is associated with several ecological and operational challenges (Hussein et al., 2026). Many chemical agents exhibit toxicity towards non-target aquatic organisms, including fish, amphibians and beneficial invertebrates, thereby disturbing aquatic ecosystems. (Mosta-Fa et al., 2005; Olivier et al., 2016). Moreover, rapid recolonisation of treated habitats necessitates repeated applications, increasing both operational costs and environmental contamination. The persistence of certain compounds in aquatic environments further raises concerns regarding ecological sustainability. Although documented cases of resistance to chemical molluscicides remain limited, prolonged and indiscriminate application may reduce their efficacy in some snail populations (Mokhtar et al., 2024; Mesfin and Temesgen, 2025). Collectively, these limitations have intensified the search for safer and more sustainable alternatives. In this context, plant-derived molluscicides have attracted considerable attention owing to their biodegradability, renewable availability, save hard currency, diverse bioactive phytochemicals and generally lower environmental impact, making them promising candidates for sustainable snail control (Singh et al., 2005; Kashyap et al., 2019; Kourime et al., 2025).

## [5] BOTANICAL MOLLUSCICIDES

Botanical molluscicides comprise a diverse group of plant-derived products, including crude extracts, essential oils, purified phytochemicals and their formulations, that exhibit toxic effects against freshwater snail vectors (Kloos and McCullough, 1982; Singh et la., 1996c; Singh et al., 2005; Singh et al., 2021c). Over the past few decades, numerous medicinal and aromatic plants have been evaluated for their molluscicidal potential, with varying degrees of efficacy against lymnaeid and other medically important snail species (Agarwal and Singh, 1988; Singh et al., 2021c). The activity of these botanicals is largely attributed to secondary metabolites such as terpenoids, alkaloids, flavonoids, saponins and phenolic compounds, which interfere with vital physiological processes in snails. Among the various botanical resources investigated, species belonging to the families Sapindaceae, Phytolaccaceae, Euphorbiaceae, Meliaceae, Asteraceae, Solanaceae and Fabaceae have demonstrated considerable molluscicidal activity against freshwater snails. Several plant extracts have exhibited concentration- and time-dependent toxicity, with efficacy varying according to plant species, plant part, extraction method and the phytochemical composition of the extract. In many cases, organic solvent extracts have shown greater molluscicidal potency than aqueous preparations, highlighting the importance of extraction techniques in recovering bioactive constituents. These findings have encouraged extensive screening of medicinal plants to identify environmentally compatible alternatives for snail control. Among the diverse plant taxa investigated, several medicinal plants have demonstrated remarkable molluscicidal activity and are discussed below.

**Table 2**. Representative botanical molluscicides investigated against freshwater snails.

| Plant species | Major bioactive constituents | Principal target snail(s) | Reported biological effects | Advantages/ Remarks | Relevance to fasciolosis |
|---|---|---|---|---|---|
| ***Artemisia* spp.** | Sesquiterpene lactones, flavonoids, monoterpenes, essential oils | *Lymnaea acuminata*, *Biomphalaria alexandrina*, *Oncomelania hupensis* | Snail mortality, reduced fecundity, and suppression of cercarial production | Multitarget activity; biodegradable; promising candidate for integrated snail control. (Meepagala et al., 2004; Alinsub and Bagot, 2019) | Direct relevance |
| ***Azadirachta indica*** | Azadirachtin, nimbin, salannin, nimbolide | *Lymnaea acuminata* | Mortality, reduced feeding and reproduction | Widely available; eco-friendly; relatively low non-target toxicity. (Singh et al., 1996c; Danlami et al., 2025) | Direct relevance |
| ***Jatropha curcas*** | Phorbol esters, diterpenoids | *Biomphalaria glabrata*, *Bulinus globosus*, *Biomphalaria pfeifferi* | Mortality, inhibition of feeding and reproduction | High potency; environmental safety requires further evaluation (Valdez-Ramirez et al., 2023) | Indirect/ general molluscicidal evidence |
| ***Euphorbia* spp.** | Diterpenoid, triterpenoids, flavonoids | *Lymnaea acuminata and other freshwater snails* | Rapid molluscicidal activity | Highly effective latex; formulation optimisation required. (Vasconcellos and Amorim, 2003) | Direct/ Indirect depending on study |
| ***Phytolacca dodecandra*** | Triterpenoid saponins | *Biomphalaria* spp., *Bulinus* spp. | Rapid mortality | One of the most extensively studied botanical molluscicides (Beressa et al., 2020) | Mainly schistosomiasis evidence |
| ***Sapindus mukorossi*** | Saponins | *Lymnaea acuminata* | Molluscicidal activity | Natural surfactants with membrane-disrupting properties. (Upadhyay and Singh, 2011) | Direct relevance |

**[5.1] *Artemisia* spp. as Promising Botanical Molluscicides**

The genus *Artemisia* (family Asteraceae) comprises more than 500 species of herbs and shrubs distributed across Asia, Europe, North America and parts of Africa (Sharifi-Rad et al., 2022). Owing to their long history of use in traditional medicine, *Artemisia* species have been extensively investigated for diverse pharmacological activities, including antimicrobial, antiparasitic, insecticidal and anti-inflammatory effects ( Hussain et al., 2024; Cruz-Estupiñan et al., 2025; Selim et al., 2026;). Their molluscicidal potential has recently gained increasing attention because of the abundance of bioactive secondary metabolites, particularly sesquiterpene lactones (artemisinin), monoterpenes, flavonoids, coumarins, phenolic acids, and essential oils (Anibogwu et al., 2021; Ivănescu et al., 2021, Mostafa et al., 2026; Diab et al., 2026). Experimental studies have demonstrated that extracts and essential oils from several *Artemisia* species exhibit significant toxicity against freshwater snails, including *Lymnaea acuminata*, the principal intermediate host of fasciolosis in many endemic regions (Radwan and Gad, 2021). Molluscicidal activity has been reported for different plant parts, particularly leaves and aerial tissues, using aqueous, ethanolic, methanolic and organic solvent extracts (Bisht et al., 2021). The molluscicidal effects of *Artemisia* are mediated through multiple mechanisms. Bioactive compounds like artemisinin disrupt cellular metabolism, impair neuromuscular coordination, induce oxidative stress and damage digestive and reproductive tissues, ultimately leading to reduced feeding, impaired reproduction and snail mortality (Ma et al., 2020). Such multitarget activity may also decrease the likelihood of resistance development compared with single-target synthetic molluscicides. Among the investigated species,

*Artemisia judaica* has shown pronounced molluscicidal activity against *Biomphalaria alexandrina*, accompanied by reduced snail fecundity and suppression of cercarial production (Bakry et al., 2011; Taljaard et al., 2023). Likewise, *Artemisia dubia* leaf extracts have demonstrated promising molluscicidal activity against *Oncomelania hupensis quadrasi*, indicating the potential of the genus as a source of plant-based molluscicides, (Alinsub and Bagot, 2019; Terciño et al., 2020). Collectively, these findings indicate that the molluscicidal efficacy of *Artemisia* extends beyond direct lethality by limiting reproduction and reducing transmission potential.

Despite these encouraging results, *Artemisia*'s molluscicidal performance varies by species, geographical origin, season, plant part and extraction method, leading to variability in phytochemical composition and biological activity. Furthermore, most investigations remain confined to laboratory conditions, while standardised formulations, comprehensive field evaluations and long-term ecological safety assessments remain limited. Nevertheless, the rich phytochemical diversity, broad-spectrum biological activity, biodegradable nature and multitarget mode of action make *Artemisia* one of the most promising botanical candidates for environmentally sustainable snail control and integrated fasciolosis management.

**[5.2] *Azadirachta indica* as a Promising Botanical Molluscicide**

Plant *Azadirachta indica* (family Meliaceae), commonly known as neem, is one of the most extensively studied medicinal plants with well-documented insecticidal, antiparasitic, and pesticidal properties (Juma et al., 2022). Its rich phytochemical profile, comprising limonoids (particularly azadirachtin), nimbin, salannin, nimbolide, flavonoids, tannins and saponins, has attracted considerable interest for the development of eco-friendly molluscicides (Almadiy et al., 2025). Experimental studies have demonstrated that extracts prepared from neem leaves, seeds, bark and seed kernels exhibit significant molluscicidal activity against *Lymnaea acuminata* and other freshwater snail species (Singh et al., 1996b). These bioactive compounds interfere with vital physiological processes by disrupting cellular metabolism, inducing oxidative stress, impairing neuromuscular function, and suppressing feeding and reproductive activities, ultimately leading to snail mortality. In addition to direct toxicity, neem extracts reduce oviposition and inhibit snail population growth, making them valuable for integrated snail management. However, variations in phytochemical composition, extraction methods, and limited field validation remain important challenges for large-scale application. Collectively, these characteristics make *A. indica* a promising eco-friendly botanical molluscicide for integrated snail management.

**[5.3] *Jatropha curcas*: An Emerging Plant-Based Molluscicide**

Plant *Jatropha curcas* (family Euphorbiaceae) is a drought-tolerant medicinal shrub widely recognised for its diverse biological activities, including insecticidal, antimicrobial, and molluscicidal properties (Valdez-Ramirez et al., 2023). The plant contains several bioactive constituents, such as phorbol esters, diterpenoids, flavonoids, saponins, tannins, and alkaloids, which contribute to its toxicity against freshwater snails (Devappa et al., 2012). Experimental studies have demonstrated that seed and leaf extracts of *Jatropha curcas* exhibit molluscicidal activity against medically important freshwater snails, including *Biomphalaria glabrata*, *Bulinus globosus*, and *Biomphalaria pfeifferi* (Chimbari and Shiff, 2008; Angaye et al., 2014). The molluscicidal activity is primarily associated with disruption of cellular metabolism, membrane integrity, and enzymatic functions, leading to impaired movement, reduced feeding, and eventual death of the host. In addition, exposure to *J. curcas* extracts has been reported to suppress reproductive performance, thereby contributing to long-term snail population control. Despite its promising efficacy, the presence of highly toxic phorbol esters necessitates careful environmental risk assessment and further field-based validation before large-scale application. Although most available evidence concerns snail hosts of schistosomiasis, these findings provide broader evidence for the molluscicidal potential of *J. curcas.*

**[5.4] *Euphorbia* Species: Latex-Derived Molluscicidal Agents**

Species of the genus *Euphorbia* (family Euphorbiaceae) have long been recognised for their potent molluscicidal properties, largely attributed to the toxic latex produced by various species (Benjamaa et al., 2022). This latex contains a diverse array of bioactive compounds, including diterpenoids, triterpenoids, flavonoids, tannins, saponins, and phenolic compounds, which collectively contribute to its biological activity against freshwater snails. Several *Euphorbia* species have demonstrated significant molluscicidal activity against medically important freshwater snails. *Euphorbia royleana* is effective against *Lymnaea acuminata*, (Singh et al., 2005), whereas *Euphorbia splendens* has shown potent activity against *Biomphalaria glabrata*, (Schall et al., 2001) highlighting the potential of the genus for the control of snail vectors of parasitic diseases. These phytochemicals disrupt cellular membranes, inhibit essential metabolic enzymes, induce oxidative stress, and damage digestive and reproductive tissues, ultimately resulting in reduced feeding, impaired reproduction, and snail mortality. In some studies, latex extracts have shown high efficacy even at relatively low concentrations. Regardless of their strong molluscicidal potential, the irritant nature of *Euphorbia* latex and possible toxicity to non-target organisms necessitate careful

formulation, dose optimisation, and ecological risk assessment before field application. Nevertheless, *Euphorbia* species remain promising candidates for environmentally sustainable snail control.

**[5.5] *Phytolacca dodecandra*: A Potent Natural Molluscicide**

*Phytolacca dodecandra* (family Phytolaccaceae), commonly known as endod, has been extensively investigated as a botanical molluscicide, particularly against snail hosts of schistosomiasis, with potential relevance to broader snail control programmes. (Lemma, 1970a; Beressa et al., 2020). The molluscicidal activity of the plant is primarily attributed to triterpenoid saponins, particularly those concentrated in its berries, which exhibit strong toxicity toward snail species at relatively low concentrations (Teressa, 2023). An experimental studies have demonstrated that berry extracts of *P. dodecandra* are highly effective against several medically important snail species, including *Biomphalaria* and *Bulinus,* highlighting their potential for schistosomiasis vector control (Lemma, 1970b). The active saponins disrupt cell membranes, impair physiological functions, and cause rapid snail mortality. Owing to its high efficacy and biodegradability, *P. dodecandra* has been extensively explored as an affordable alternative to synthetic molluscicides, particularly in endemic regions of Africa (WHO, 1983; Augusto and de Mello-silva, 2018). However, variations in saponin content among plant varieties, together with concerns regarding formulation stability, large-scale cultivation, and potential effects on aquatic non-target organisms, remain important challenges for its widespread application. Continued field validation and standardised product development are therefore essential to facilitate its incorporation into integrated snail control programmes.

**[5.6] Other Promising Botanical Molluscicides**

In addition to the extensively studied botanical molluscicides discussed above, several other medicinal plants have been investigated for their potential to control freshwater snails. Among these, *Sapindus mukorossi* has demonstrated significant molluscicidal activity against *Lymnaea acuminata* under laboratory conditions. (Upadhyay and Singh, 2011) Beyond individual plant species, a wide range of medicinal plants has been reported to contain bioactive phytochemicals with potential molluscicidal properties, including saponins, alkaloids, flavonoids, terpenoids, phenolics, and essential oils. These compounds are known to disrupt vital physiological processes in snails by affecting membrane integrity, energy metabolism, antioxidant defence systems, enzyme activity, and reproductive functions. Despite encouraging laboratory findings, the practical application of many botanical molluscicides remains limited by variability in phytochemical composition, lack of standardised extraction protocols and formulations, insufficient field validation, and inadequate assessment of long-term environmental safety and effects on non-target organisms. Future research should therefore focus on the isolation of active compounds, formulation development, field evaluation, and ecological risk assessment to facilitate the integration of botanical molluscicides into sustainable and One Health-based fasciolosis control programmes.

**[6] BIOACTIVE PHYTOCHEMICALS AND MECHANISMS**

Botanical molluscicides derive their efficacy from a diverse array of secondary metabolites that target multiple physiological processes in freshwater snails (Chaturvedi et al., 2021). Unlike many synthetic molluscicides, plant-derived phytochemicals often act through multiple complementary molecular targets, thereby enhancing molluscicidal efficacy while potentially reducing the risk of resistance development. Among the major bioactive constituents, terpenoids, flavonoids, alkaloids, saponins, tannins, and essential oils have been extensively investigated because of their potent molluscicidal properties (Singh et al., 1996; Kashyap et al., 2019).

**[6.1] Terpenoids:** Terpenoids represent one of the largest classes of plant secondary metabolites with proven molluscicidal activity. They disrupt cellular membranes, impair energy metabolism and neuromuscular coordination, and induce oxidative stress, ultimately leading to reduced feeding, impaired reproduction, and snail mortality (Srivastava and Singh, 2019). Bioactive terpenoids such as artemisinin, azadirachtin, and phorbol esters exemplify their diverse mechanisms of action (Câmara et al., 2024).

**Table 3.** Major phytochemical classes involved in botanical molluscicidal activity and their proposed mechanisms of action

| Phytochemical class | Representative compounds | Principal mechanism(s) | Biological effects on snails |
|---|---|---|---|
| **Terpenoids** | Artemisinin, azadirachtin | Membrane disruption, oxidative stress, and neuromuscular impairment | Mortality, reduced reproduction |
| **Flavonoids** | Quercetin, luteolin | Antioxidant imbalance, enzyme inhibition | Reduced feeding and fecundity |
| **Alkaloids** | Berberine, solanine | Neurotoxicity, metabolic disruption | Reduced locomotion and mortality |
| **Saponins** | Triterpenoid saponins | Membrane permeabilization | Cell lysis, egg inhibition |
| **Tannins** | Hydrolysable and condensed tannins | Protein precipitation, digestive enzyme inhibition | Growth retardation, reduced feeding |
| **Essential oils** | Thymol, eugenol, cineole | Membrane damage, oxidative stress | Rapid snail mortality |

**[6.2] Flavonoids:** Flavonoids contribute to molluscicidal activity by disrupting antioxidant defence systems and inhibiting key metabolic enzymes in freshwater snails. These compounds induce oxidative stress, impair feeding and reproductive performance, and may inhibit embryonic development, thereby limiting snail population growth. Their biodegradability and relatively low environmental persistence make them attractive candidates for eco-friendly botanical molluscicides (Ullah et al., 2020; Singab et al., 2006).

**[6.3] Alkaloids:** Alkaloids exert molluscicidal effects primarily through interference with neurotransmission, enzymatic activity, and cellular metabolism (Ke et al., 2017). These actions impair locomotion, reduce feeding efficiency, and ultimately cause snail mortality. Some alkaloids also suppress reproductive functions and larval development, supporting their potential as multitarget botanical molluscicides (Delbrouck et al., 2023).

**[6.4] Saponins:** Saponins are among the most potent natural molluscicides owing to their ability to interact with membrane sterols, increasing membrane permeability and causing cell lysis (Oakenfull and Sidhu, 1989). In addition to inducing rapid mortality, they reduce fecundity and inhibit egg development, making saponin-rich plants valuable candidates for long-term snail population management (Yang et al., 2017).

**[6.5] Tannins:** Tannins exhibit molluscicidal activity by binding to proteins and inhibiting digestive enzymes, thereby disrupting nutrient utilisation and cellular metabolism. Although generally less acutely toxic than other phytochemicals, they reduce feeding, growth, and reproductive performance and may enhance the efficacy of botanical extracts through synergistic interactions with other bioactive constituents (Ballada and Baoanan, 2025; Schaufelberger and Hostettmann, 1983).

**[6.6] Essential oils:** Essential oils are complex mixtures of volatile compounds, predominantly monoterpenes and sesquiterpenes, that readily penetrate biological membranes and disrupt nervous system function, membrane integrity, and oxidative homeostasis (Ramsey et al., 2020). Their composition and efficacy vary according to plant species, geographical origin, and environmental conditions. Nevertheless, their rapid action, biodegradability, and multitarget mode of toxicity make them promising candidates for environmentally sustainable molluscicide development (Radwan and Gad, 2021).

Collectively, these phytochemicals act through complementary mechanisms that disrupt membrane integrity, oxidative homeostasis, neuromuscular function, digestion, and reproduction in freshwater snails. Their multi-target mode of action enhances molluscicidal efficacy while supporting the development of environmentally sustainable plant-based strategies for integrated fasciolosis control.

## [7] INTEGRATING BOTANICAL MOLLUSCICIDES INTO ONE HEALTH STRATEGIES

The effective control of fasciolosis requires a holistic approach that simultaneously addresses human health, animal health, and environmental sustainability. As freshwater snails are indispensable intermediate hosts in the parasite life cycle, their effective management can substantially reduce disease transmission across multiple sectors (Djirmay et al., 2024). Botanical molluscicides offer a valuable opportunity to integrate snail control within the One Health framework owing to their biodegradability, lower environmental persistence, and diverse mechanisms of action (Pathak et al., 2024). However, the greatest potential lies in their integration with broader disease management strategies rather than their use as standalone interventions.

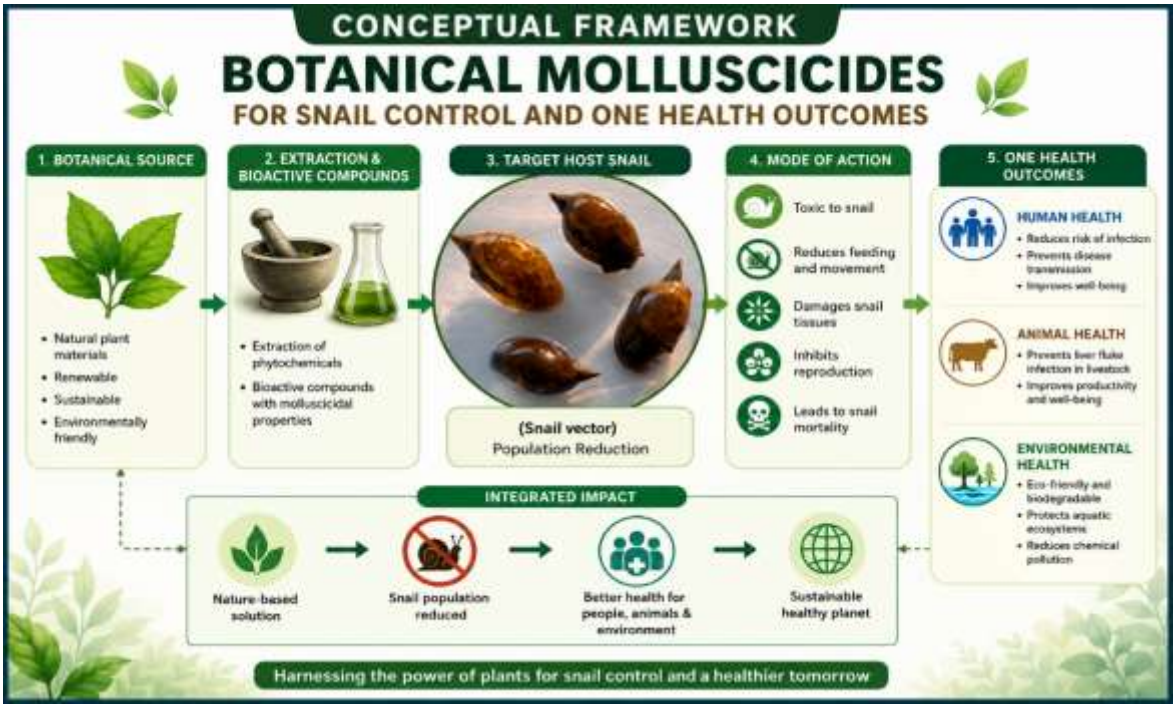


Figure 2. Conceptual framework illustrating the integration of botanical molluscicides into a One Healthstrategy for sustainable fasciolosis control**.**

**[7.1] Environmental Sustainability**

Botanical molluscicides offer important environmental advantages over many conventional chemical molluscicides (Richter et al., 2023; Olivier et al., 2016). Their biodegradable nature and relatively rapid degradation reduce the risk of long-term contamination of aquatic ecosystems and minimise exposure of non-target organisms to persistent chemical residues. Consequently, they have the potential to support sustainable freshwater ecosystem management (Kloos and McCullough, 1982; Singh et al., 2005). Nevertheless, comprehensive field-based ecological risk assessments remain essential to ensure their environmental safety and appropriate application.

**[7.2] Livestock Health**

Livestock serve as the principal reservoir hosts of fasciolosis, making snail control an important component of disease prevention (Regasa and Seboka, 2021; Hassan et al., 2025). By reducing populations of intermediate host snails, botanical molluscicides can interrupt the parasite life cycle and lower infection pressure in grazing animals. (Postevoy and Andreyanov, 2020). This may improve animal productivity through enhanced milk yield, weight gain, reproductive performance, and overall herd health while reducing reliance on repeated anthelmintic treatments.

**[7.3] Human Health**

Fasciolosis is an important food-borne zoonosis that continues to pose a public health challenge in many endemic regions (Mohammed, 2026). Botanical molluscicides can contribute to disease prevention by limiting environmental transmission through effective control of intermediate host snails. When integrated with health education, improved sanitation, safe food practices, and appropriate chemotherapy, plant-based snail control can strengthen community-based strategies for reducing human fasciolosis (Giji et al., 2026).

**[7.4] Biodiversity Conservation**

Compared with many synthetic molluscicides, botanical products have the potential to exert lower ecological impacts because of their biodegradable nature and reduced environmental persistence (Olivier et al., 2016; Chaturvedi et al., 2021; Richter et al., 2023). However, they should not be regarded as inherently risk-free, and their effects on non-target organisms require careful evaluation before large-scale application. The development of species-specific formulations and optimised application strategies will be essential to maximise efficacy while safeguarding aquatic biodiversity.

**[7.5] Integrated Snail Management**

Botanical molluscicides should be regarded as one component of integrated snail management rather than a standalone solution. Their effectiveness can be enhanced when combined with habitat modification, environmental sanitation, biological control, targeted application of synthetic molluscicides where appropriate, routine surveillance of snail populations, and active community participation. Such integrated approaches improve long-term disease control while minimising environmental impacts and reducing selection pressure for resistance (Mas-Coma et al., 2009; WHO, 2017b).

**[7.6] Policy Implications**

The successful implementation of botanical molluscicides depends on supportive policies that encourage research, product standardisation, quality assurance, and large-scale field validation. Close collaboration among researchers, public health authorities, veterinary services, environmental agencies, and local communities will be essential for translating laboratory findings into practical control programmes. Integrating botanical molluscicides into national fasciolosis control strategies within a One Health framework could strengthen disease prevention while promoting environmental sustainability, livestock productivity, and public health (WHO, 2021).

**[8] CURRENT CHALLENGES**

**[8.1] Standardisation**

Variations in plant species, geographical origin, harvesting season, cultivation conditions, and extraction methods often result in inconsistent phytochemical composition and molluscicidal efficacy. The development of standardised protocols for plant selection, extraction, and quality control is therefore essential to ensure reproducibility and product consistency (WHO, 2011; Heinrich et al., 2012).

**[8.2] Field Validation**

Although numerous botanical molluscicides have demonstrated promising laboratory efficacy, relatively few have been evaluated under field conditions. Large-scale field trials are required to validate their effectiveness, environmental safety, and operational feasibility under diverse ecological settings (Agarwal and Singh, 1988; WHO, 2017a).

**[8.3] Formulation and Stability**

Many plant extracts are susceptible to degradation during storage and environmental exposure, limiting their shelf life and practical application. The development of stable, cost-effective, and user-friendly formulations remains a major challenge for large-scale implementation (Isman, 2020).

**[8.4] Commercialisation**

Despite encouraging experimental findings, only a limited number of botanical molluscicides have progressed towards commercial development. High production costs, scalability constraints, limited industrial investment, and inadequate technology transfer continue to hinder their market adoption (Isman, 2006).

**[8.5] Regulatory Challenges**

The lack of harmonised regulatory frameworks, quality standards, and clear approval pathways delays the registration and implementation of plant-based molluscicides in national disease control programmes. Strengthening regulatory support will be essential for their wider acceptance and utilisation (WHO, 2019).

## [9] FUTURE DIRECTIONS

### [9.1] Nano-formulations

Nanotechnology-based delivery systems offer promising opportunities to improve the stability, controlled release, target specificity, and bioavailability of botanical molluscicides while reducing application rates and minimising environmental impacts (Kah et al, 2013).

### [9.2] Green Extraction Technologies

Sustainable extraction techniques, including supercritical fluid extraction and ultrasound-assisted extraction, can improve the recovery of bioactive phytochemicals while reducing solvent consumption and environmental pollution, thereby supporting greener production processes (Chemat et al, 2012).

### [9.3] AI-Assisted Screening

Vamathevan et al., (2019) noted artificial intelligence, machine learning, and computational modelling can accelerate the identification of novel molluscicidal phytochemicals, predict their biological activity, and facilitate the rational design of efficient plant-based formulations.

### [9.4] Integrated Disease Management

Future control programmes should integrate botanical molluscicides with chemotherapy, biological control, habitat management, environmental sanitation, routine surveillance, and community participation to achieve sustainable fasciolosis control within the One Health framework (Mas-Coma et al, 2009).

### [9.5] Climate Change Considerations

Climate change is expected to influence the distribution of freshwater snails and alter fasciolosis transmission dynamics. Continuous surveillance and climate-resilient snail control strategies will therefore be critical for future disease prevention and management (Mas-Coma et al, 2008; Fox et al., 2011).

## [10] CONCLUSION

Fasciolosis remains a major One Health challenge with significant consequences for human health, livestock production, and environmental sustainability. Although conventional chemical molluscicides have contributed substantially to snail control, concerns regarding environmental persistence, non-target toxicity, and long-term sustainability have intensified the search for safer alternatives. Botanical molluscicides derived from medicinal plants, including *Artemisia* spp., *Azadirachta indica*, *Jatropha curcas*, *Euphorbia* spp., and *Phytolacca dodecandra*, have demonstrated considerable potential as environmentally compatible agents for controlling freshwater snails. Their diverse bioactive phytochemicals act through multiple complementary mechanisms, offering promising molluscicidal activity while supporting environmentally sustainable disease management.

In the face of these promising advances, challenges related to standardisation, formulation development, large-scale field validation, commercialisation, and regulatory approval must be addressed before widespread implementation. Continued interdisciplinary research, technological innovation, and supportive policy frameworks will be essential to translate laboratory findings into practical applications. Integrating botanical molluscicides with chemotherapy, environmental management, surveillance, and community-based interventions within a comprehensive One Health framework offers a promising strategy for sustainable control of fasciolosis. Such an integrated approach has the potential to reduce disease transmission, protect ecosystem health, and improve both animal and human well-being.

**CRediT authorship contribution statement**

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