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The Research on Green Control Strategies and Techniques for Major Pests and Diseases of *Sapindus mukorossi*

Jie Zhang, Jianhui Li
Institute of Life Sciences, Jiyang College of Zhejiang A&F University, Zhuji, 311800, Zhejiang, China
Corresponding author: jianhui.li@@hitar.org

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Abstract This study focuses on the green control strategies and techniques for the main diseases and pests of *Sapindus mukorossi*, with the aim of enhancing the ability to resist diseases and pests and supporting sustainable development. *Sapindus mukorossi* is not only an economic crop but also an ecological resource, often used in landscaping, traditional medicine and bioenergy production. The risks are equally obvious: it is highly vulnerable to pests and diseases, and the output and quality will decline accordingly. To this end, the research will evaluate the effects of biological control and natural pesticides, and explore feasible paths to enhance resistance by combining molecular markers, gene editing and other means. It is worth noting that saponin extracts have strong insecticidal and antibacterial activities, can effectively control pests such as melon fruit flies, and have a relatively small impact on beneficial organisms. The significance of green prevention and control goes beyond this: it not only helps maintain ecological balance but also enhances the commercial value of *Sapindus mukorossi* products. Certain progress has been made at present, but further verification and expansion are still needed, especially in evaluating the wide application and stability of natural products such as saponins under different environmental conditions.

Keywords *Sapindus mukorossi*; Green control; Biological control; Saponins; Gene editing

1 Introduction

Sapindus mukorossi, also called the Sapindus tree, is a species with both economic and ecological value. It is native to southern China and now grows across tropical and subtropical regions, especially in Asia (Zhao et al., 2019). The tree has many uses: landscaping, traditional medicine, and bioenergy. Its fruit matters most because saponins can be extracted from it-a natural surfactant used in soaps, shampoos, and cosmetics (Liu et al., 2021). The seed oil can also serve as a potential biodiesel feedstock, which makes the species a good target for forestry bioenergy (Sun et al., 2017). It is also highly adaptable to local conditions, a trait that favors large-scale planting and breeding improvement (Sun et al., 2017; Liu et al., 2021).

Despite these advantages, *Sapindus mukorossi* is vulnerable to many pests and diseases, which reduces yield and quality. The cucurbitae (*Bactrocera cucurbitae*) is a major pest; it attacks the fruit and causes notable damage. Such pressure cuts economic returns and challenges long-term cultivation. Effective control strategies are therefore needed to protect the species and keep its contributions to bioenergy and related industries (Samiksha et al., 2019).

This study focuses on green control and adopts sustainable and environmentally friendly methods for the main pests of *Sapindus mukorossi*. The objective is to enhance its resistance to biological stress without sacrificing economic or ecological value. The research work includes the identification of bioactive compounds in plants, such as trypsin inhibitors. These seeds show potential in combating melon flies. This study will also assess the relationship between environmental factors and phenotypic traits to determine conditions conducive to growth and pest resistance. These measures aim to support the sustainable management and cultivation of *Sapindus mukorossi* and maintain its feasibility as a long-term resource.

2 Major Pests and Diseases of *Sapindus mukorossi*

2.1 The main pests and fungal, bacterial diseases affecting *Sapindus mukorossi*

Sapindus mukorossi, often referred to as Sapindus, is susceptible to various fungal diseases, among which the genus Diaporthe is the most common. The confirmed major pathogens include *Diaporthe biconispora*, *Diaporthe sapindicola*, *Diaporthe eres* and *Diaporthe unshiuensis*. They were identified as important pathogenic factors of leaf spot disease in China (Si et al., 2020; Si et al., 2021; Si et al., 2022. These fungi can form conidia, which are often identified by morphology combined with phylogenetic analysis and confirmed by pathogenicity assay (Si et al., 2021; Si et al., 2022.

In addition to fungi, there are also insect hazards. The melon fly (*Bactrocera cucurbitae*) is one of the important pests and causes significant damage. *Sapindus mukorossi* seeds contain bioactive trypsin inhibitors, which can inhibit their growth and development and have potential control effects (Samiksha et al., 2019). Meanwhile, the extract of *Sapindus mukorossi* has molluscidal activity against *Pomacea canaliculata*, showing application prospects in pest management (Huang et al., 2003).

2.2 Symptoms and damage caused by pests and diseases in *Sapindus mukorossi*

Leaf spot disease often starts with the appearance of small yellow spots on the leaves. Subsequently, the spots gradually darken to a dark brown color, with clear or irregular edges. Such symptoms suggest that the plants have been infected by the Diaporthe pathogen, which not only affects the health of the plants but also damages their ornamental value (Figure 1) (Si et al., 2020; Si et al., 2021; Si et al., 2022. The related lesions not only have impaired appearance, but also have decreased medicinal value (Si et al., 2020).

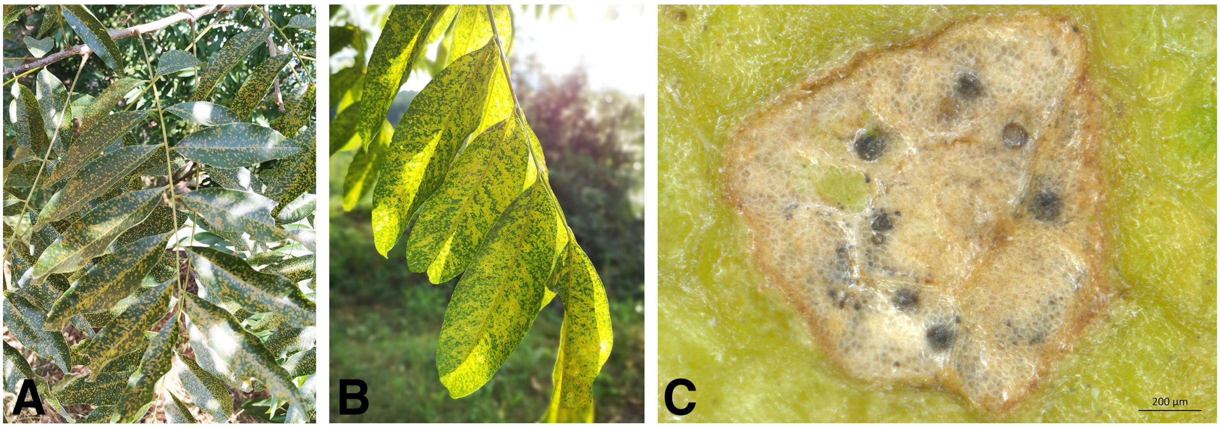

Figure 1 Symptoms on diseased leaves infected naturally (Adopted from Si et al., 2022)
Image caption: A and B, Diseased leaves of *Sapindus mukorossi* infected naturally; C, pycnidia on the leaf lesion (Adopted from Si et al., 2022)

In terms of pests, the larvae of the melon fly feed, causing tissue damage, making the fruit or tender parts vulnerable to damage. Studies have shown that trypsin inhibitors in *Sapindus mukorossi* seeds can down-regulate key digestive enzymes in pests, thereby reducing damage. In addition, saponins contained in plants can effectively control mollusks such as golden-threaded snails; otherwise, they may cause serious damage to crops (Huang et al., 2003; Samiksha et al., 2019.

2.3 The impact on yield and quality of *Sapindus mukorossi*

Leaf spot disease caused by the genus Diaporthe significantly weakens photosynthetic efficiency, resulting in growth restriction, reduced yield, and thereby affecting commercial quality (Si et al., 2020; Si et al., 2021; Si et al., 2022. The ornamental value and medicinal value decreased simultaneously, thus the commercial feasibility was frustrated (Si et al., 2020).

Pest infestation, especially the damage caused by fruit flies in pumpkins, will further amplify the yield reduction effect. The feeding of larvae reduces the vitality of the plant and damages the overall health of the plant. The utilization of bioactive components in Sapindus nutans, such as trypsin inhibitors and saponins, is expected to achieve effective control, thereby maintaining quality and alleviating yield loss (Huang et al., 2003; Samiksha et al., 2019.

3 Challenges in Pest and Disease Management of *Sapindus mukorossi*

3.1 The risks of over-reliance on chemical pesticides in *Sapindus mukorossi*

For a long time, chemical pesticides have been a commonly used method in the production of *Sapindus mukorossi*. Excessive reliance brings multiple risks: environmental degradation, damage to non-target organisms, and even poisoning in humans and animals (Eddaya et al., 2013). Once the use of pesticides is too high, the biodiversity of the surrounding ecosystem will also decline. Relevant studies have pointed out that similar hidden dangers are widespread in agricultural pest and disease management (Saha et al., 2010; Li et al., 2024). Another issue is bioaccumulation. Chemical components can be amplified step by step along the food chain, resulting in long-term toxic effects. Excessive pesticide application on other crops has shown this phenomenon, so its wide application in the Sapindus nutans ecosystem is also worthy of vigilance (Badoni et al., 2019).

3.2 Pest resistance issues in *Sapindus mukorossi*

Resistance is the main problem in control work today. When pesticides are used often—especially the same active ingredient again and again-pests adapt faster. Their genes change, and the products work less and less. Studies also show that “natural” options are not exempt. Even plant-based agents, like *Sapindus mukorossi* extracts, can face resistance in melon flies (Samiksha et al., 2019). In addition, chemical pesticides may lead to bioaccumulation, thereby causing long-term toxicity problems in the food chain. The excessive use of pesticides in other crops has shown this effect, which has also raised concerns about their wide application in the *Sapindus mukorossi* ecosystem (Badoni et al., 2019).

3.3 The difficulties in implementing green control strategies for *Sapindus mukorossi*

One of the main challenges in the pest and disease control of *Sapindus mukorossi* is the formation of pest resistance, which is usually caused by the frequent use of pesticides. The repeated use of pesticides with the same active ingredients will accelerate the genetic resistance of pests and reduce the control effect. Studies have shown that insect pests such as the *Bactrocera cucurbitae* can develop resistance even when using bioactive substances derived from natural sources (such as *Sapindus mukorossi*) (Samiksha et al., 2019). Environmental conditions can make this uncertainty bigger. Temperature and soil type both change how well a product works. Saponin solutions do inhibit pests like *Thysanoplusia orichalcea*, but stable results need careful mixing and strict application rules. That makes field work more complex (Saha et al., 2010).

4 Green Control Strategies for *Sapindus mukorossi*

4.1 The application of biological control and natural enemies in *Sapindus mukorossi*

Biological control uses natural enemies to keep pests and diseases down. It is a sustainable alternative to chemical pesticides. For *Sapindus mukorossi*, many studies point out that saponins can naturally repel insects. Peel extracts show insecticidal and antifungal activity and can lower numbers of pests such as *Bactrocera cucurbitae*, with relatively small effects on beneficial species (Samiksha et al., 2019). In controlled trials, saponin preparations also interfered with insect growth and reproduction. These findings support their use in Integrated Pest Management (IPM) systems (Saha et al., 2010). Enhanced biological control, such as the large-scale breeding and regular release of natural enemies, is also considered to have application potential. This method has achieved results in crops such as orchards and vineyards, but its promotion in *Sapindus mukorossi* is still limited by logistics and costs (Lenteren, 2012).

4.2 Agronomic practices such as crop rotation and resistant varieties in *Sapindus mukorossi*

Using crop rotation and choosing or breeding resistant varieties can greatly cut disease and pest pressure in plantations. Work on related crops shows that diverse rotations break pest life cycles and lower the need for chemicals. Direct data for *Sapindus mukorossi* are limited, but these steps have been shown to reduce soil-borne diseases and improve overall plant health (Eddaya et al., 2013). Breeding varieties that resist pests and diseases is just as important. The phenotypic differences in *Sapindus mukorossi* suggest clear room for breeding gains. Features such as a thicker fruit peel and higher saponin levels can raise natural resistance, so less external control is needed (Table 1) (Sun et al., 2017).

Table 1 CCA results for seed and fruit traits of *Sapindus mukorossi* with environmental factors

-	CCA1	CCA2
Statistics		
Pr(>F)	0.001***	0.001***
Eigenvalue	0.008 084	0.003 012
Proportion Explained	0.281 59	0.104 93
Cumulative Proportion	0.281 59	0.386 51
Total inertia (variance explained %)	0.028 57(47.22%)	
Intraset correlation coefficients between the CCA axes andthe environmental variables Terms		
Latitude	-0.569 85	0.166 12
Longitude	-0.545 17	0.375 94
Sunshineduration	0.095 48	0.077 66
Prec	0.444 16	0.283 78
Relativehumidity	-0.416 86	-0.104 82
Minimumrelativehumidity	0.487 33	0.122 37
Temp	0.855 13	0.191 68
maximumTemp	-0.163 58	0.540 29
lowestTemp	0.906 8	-0.100 21
Altitude	0.065 66	-0.755 4

Notes: *** extremely significant correlation at the $P<0.01$ level

4.3 The use of natural and plant-based pesticides in *Sapindus mukorossi*

Natural and plant-based pesticides - especially formulations derived from *Sapindus mukorossi* - have performed outstandingly in control. Saponin extracts have significant antibacterial and insecticidal effects. They can effectively control pests such as *Thysanoplusia orichalcea* and reduce fungal infections, such as apple black spot disease. Its main mechanism is to destroy the cell membranes of pests and pathogens, providing a degradable and environmentally friendly alternative for the synthesis of chemicals.

At the same time, the combination of saponin treatment with other plant-based pesticides (such as neem formulations or pyrethroids) can enhance the control effect and reduce the environmental burden. This approach conforms to the IPM principle, helps promote sustainable agriculture, and reduces chemical residues in the ecosystem (Yang et al., 2020).

5 Technological Innovations in Pest and Disease Control for *Sapindus mukorossi*

5.1 Molecular markers and gene editing technologies in *Sapindus mukorossi*

SSR, SNP, and similar markers offer a quick way to find resistant lines. They help screen genotypes and speed breeding. Molecular markers and gene editing are now key tools to raise disease and pest resistance in *Sapindus mukorossi*. Studies in related species have mapped variants tied to resistance, giving a clear path for use in this tree (Sun et al., 2017). When markers are built into the breeding pipeline, it becomes easier to pick plants with higher saponin levels and stronger natural repellent traits. This keeps selection simple and moves progress faster.

Technologies such as CRISPR-Cas9 offer higher accuracy. It can directly and precisely modify key resistance genes without introducing exogenous DNA, taking into account both effectiveness and social acceptance (Zhao et al., 2019). Although the direct application on *Sapindus mukorossi* is still limited, studies on materials of the same family have shown clear potential for enhancing disease and pest resistance.

5.2 Integrated pest management (IPM) practices in *Sapindus mukorossi*

IPM uses several tools together to keep pests down in a lasting way. It relies on biological control, farm practices, and only the chemicals that are needed. In *Sapindus mukorossi* fields, using natural enemies, planting resistant lines, and applying plant-based pesticides with saponins all show promise. Take saponin extract as an example: adding it to an IPM plan can control pests such as pumpkin fruit flies while keeping harm to non-target species low (Samiksha et al., 2019).

Farm practices matter just as much. Crop rotation, proper planting density, and careful canopy management can cut places where pests live and breed, and they can lift plant health. Studies on canopy light in *Sapindus mukorossi* show that tuning the scaffold and branch layout raises photosynthesis and lowers disease risk, which underlines the value of agronomic techniques inside the IPM framework (Yuan et al., 2018).

5.3 The application of monitoring and early warning systems in *Sapindus mukorossi*

Monitoring and early warning are the foundation for the proactive prevention and control of *Sapindus mukorossi*. Remote sensing and Internet of Things (IoT) devices can capture in real time the dynamic occurrence and symptom changes of pests and diseases, facilitating timely intervention. Such technologies have been successfully applied in the monitoring and early detection of tree canopy health in relevant agricultural systems, providing a reference for the research on the cultivation adaptability of Sapindus sapindus (Lenteren, 2012).

Prediction models that use environmental data-such as temperature and humidity-can flag outbreak risks early and guide management choices. When these tools are paired with routine field checks, accuracy and cost-effectiveness improve, reliance on chemicals drops, and long-term sustainability is strengthened (Zhao et al., 2019).

6 Environmental and Economic Impacts of Green Control for *Sapindus mukorossi*

6.1 Environmental benefits of green control methods for *Sapindus mukorossi*

Green control for *Sapindus mukorossi* aims to cut the use of chemical pesticides, which lowers the environmental load of pest and disease management. Using saponins extracted from *Sapindus mukorossi* as pesticides helps because they are biodegradable and reduce chemical residues in soil and water. At the same time, they are less toxic to non-target organisms, which supports biodiversity and keeps ecosystems in balance (Samiksha et al., 2019). Studies also show that the natural traits of saponins can suppress pests without harming beneficial species, which fits well with sustainable farming practices (Eddaya et al., 2013).

In addition, the combined application of biological control agents and natural enemies can help reduce greenhouse gas emissions related to the production and application of synthetic chemicals. In the cultivation system of *Sapindus mukorossi*, the adoption of enhanced biological control strategies can not only reduce the disturbance to the surrounding ecology, but also further amplify the above-mentioned environmental benefits (Lenteren, 2012).

6.2 Cost-effectiveness and market potential of green control in *Sapindus mukorossi*

The green control of *Sapindus mukorossi* is economically feasible because this plant has dual value of "medicine and application". Extracting saponins from fruit peels to replace some purchased pesticides can reduce chemical input and at the same time form value-added products. Studies have shown that saponins are effective against various types of pests and diseases, can reduce the need for additional intervention, and thereby compress the overall production cost.

With the rising demand for organic and eco-friendly agricultural products, the market prospects for *Sapindus mukorossi* are also expanding. Saponin biopesticides align with global sustainable and green label trends, creating opportunities to enter high-value markets. If the relevant practices are incorporated into the certification organic system, its economic attractiveness is expected to continue to increase (Yang et al., 2020).

6.3 Economic impacts of green control strategies for *Sapindus mukorossi*

Pushing green prevention and control in *Sapindus mukorossi* fields can raise farmers' income and lift the local economy. Cutting back on costly synthetic pesticides lowers inputs. Using the plant's own bioactive compounds helps too, so profit margins grow. Economic assessments of saponin extraction also point to value-chain uses, opening new income streams for producers (Sun et al., 2017).

At the same time, green control supports more sustainable production and adds diverse ways to earn. Making and selling saponin products, together with higher healthy yields, can strengthen the economic resilience of farming communities. These practices meet environmental goals and also deliver clear social and economic gains (Lenteren, 2012).

7 Future Developments and Research Needs for *Sapindus mukorossi*

7.1 Research gaps in green control methods for *Sapindus mukorossi*

Green control shows strong promise, but real-world use in *Sapindus mukorossi* still has clear gaps. Earlier studies show that saponins have insecticidal and antibacterial effects, yet full field trials are still limited, which holds back wider rollout. For example, saponin-based treatments work in labs and can suppress pumpkin fruit flies and some fungal pathogens (Samiksha et al., 2019). Even so, their long-term environmental impacts and overall economic fit are not well assessed.

There is also limited understanding of how the environment changes biopesticide performance. Climate shifts, soil conditions, and pest population cycles can all affect how natural products work. Studies in related plant systems show these factors can greatly change control outcomes (Eddaya et al., 2013). This highlights the need for local, flexible programs that adjust to site conditions.

7.2 The need for interdisciplinary research

To deal with the pests and diseases of *Sapindus mukorossi*, the collaborative efforts of agriculture, molecular biology, ecology and economics are needed. Molecular tools such as gene editing have great potential in enhancing resistance, but their combination with ecological assessment is indispensable to ensure the sustainability of technological pathways at the environmental level (Zhao et al., 2019).

Similarly, a timely economic review is needed to compare the costs and benefits of green control with those of traditional chemical methods. Evidence from other crops shows that higher upfront spending on sustainable practices can lead to gains over the long term. However, for Sapindus nutans pests and diseases, such quantitative analysis is still largely missing (Sun et al., 2017). Filling these gaps will require coordinated work from teams in different fields.

7.3 Future research directions and challenges

Subsequent research should focus on the development of highly efficient biopesticides derived from *Sapindus mukorossi*. The activity and cost can be enhanced and reduced by improving the extraction and formulation process of saponins (Sochacki and Vogt, 2022; Zhang, 2024). Meanwhile, exploring the synergistic effects of *Sapindus mukorossi* extract with other natural products may hold the hope of forming a broader combination for prevention and control.

Even so, getting these methods into use still runs into many hurdles. Approval rules are slow and complex. Public trust in bioengineering tools is mixed. Large-scale rollout also needs strong infrastructure, which is often not in place. To break these bottlenecks, policymakers, research teams, and industry should act together and coordinate their efforts (Lenteren, 2012).

8 Concluding Remarks

Green control strategies are central to the sustainable management of pests and diseases in *Sapindus mukorossi*. This tree supplies natural saponins, biodiesel, and other bioactive compounds, yet it is easily harmed by pests and pathogens, which lowers yield and affects cultivation. Using eco-friendly tools-such as biological control and plant-based pesticides-can cut environmental risk and bring down management costs. Studies also show that saponin extracts from *Sapindus mukorossi* have strong insecticidal and antibacterial effects, so they fit well as a core part of integrated pest management (IPM).

Putting green control into practice helps more than the field itself. It supports ecological balance and raises the market value of *Sapindus mukorossi* products. Demand for sustainably sourced inputs is growing in cosmetics, pharmaceuticals, and biodiesel, and this species plays a key role. To keep up, planting methods need to stay sustainable, and chemical pesticide residues should be kept as low as possible. There has been solid progress, but more work is needed to unlock the full potential of *Sapindus mukorossi* in sustainable agriculture. Molecular markers and gene editing can speed the study and use of resistance traits, which helps breed resistant lines faster.

Research on population genetic diversity already offers a base for targeted breeding, but it still needs deeper testing and wider application.

Better monitoring and early warning are also vital for proactive management. Pairing remote sensing with predictive models can change how plantations are watched, allow earlier action, and reduce reliance on chemicals. Future studies should also refine green formulations-such as saponin-based pesticides-so they work well across different farming climates and conditions.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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