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Conservation, Sustainable Utilization, and Emerging Prospects of *Zanthoxylum armatum* DC.: A Review

[1]Naresh Singh Chauhan, [2]Dr. Garima Bartariya
[1]Research Scholar, [2]Associate Professor
Department of Botany, School of Life Sciences and Technology
IIMT University, Meerut (U.P)

Abstract

Zanthoxylum armatum DC is an important medicinal and aromatic plant found in the Himalayan region. It holds great value in traditional medicine, cooking, and cosmetics. Because of its many uses, the demand for this plant has increased, leading to over-harvesting and damage to its natural habitat.

This review brings together all the latest information about the plant's current conservation status, how it can be used in a sustainable way, and its future potential. It discusses the plant's traditional uses, its active chemical compounds, and market demand. It also looks at the major threats it faces, such as overuse and climate change.

Different methods of conservation are examined, including protecting the plant in its natural environment (**in-situ**), outside of it (**ex-situ**), community-based efforts, and support from government policies. The review also explores recent developments like growing the plant on farms (domestication), using biotechnology, and improving its value in the market.

In conclusion, this review points out the areas where more research is needed and suggests future steps to protect the wild population of this plant while ensuring it is used in a fair and responsible way.

The main goal of this work is to help researchers, policy makers, and stakeholders who are working towards biodiversity conservation and the sustainable use of medicinal plants.

Keywords: *Zanthoxylum armatum, Conservation, Sustainable Utilisation, Himalayan Region.*

1. Introduction

Zanthoxylum armatum DC., commonly known as **toothache tree**, **timur**, or **tejphal**, is a small deciduous shrub or tree belonging to the family Rutaceae with over 200 species. It is native to the Himalayan region and adjacent areas as well as America, China, Japan and Africa where it has been an integral component of traditional medicine, culinary practices, and cultural heritage for centuries. The genus is indigenous to regions of India such as Meghalaya, Mizoramand Manipur (Gupta, et al.2011). The plant is widely valued for its diverse pharmacological properties, including anti-inflammatory, antimicrobial, antioxidant, and analgesic activities, largely attributed to its rich profile of bioactive compounds such as alkaloids, flavonoids, lignans, and essential oils (Dar et al., 2023). In addition to its medicinal applications, Z. armatum is commercially exploited for essential oils, spice products, and cosmetic formulations, contributing to rural livelihoods and regional economies (Gajurel et al., 2021).

However, increasing market demand, unsustainable harvesting from wild populations, habitat degradation, and limited cultivation efforts have placed growing pressure on natural stands of Z. armatum, raising significant conservation concerns (Gairola et al., 2021). The plant is listed as threatened or vulnerable in several local assessments, and sustainable management practices are urgently needed to balance utilization with biodiversity conservation (Khoury et.al, 2019). Recent research emphasizes the need to develop integrated conservation strategies, promote community-based management, and explore biotechnological interventions to secure the future of this valuable species (Berkeys F.,2007).

This review aims to synthesize current knowledge on the conservation status, sustainable utilization strategies, and emerging prospects of Zanthoxylum armatum. By bridging insights from ethnobotany, pharmacology, ecology, and policy, this paper seeks to inform researchers, practitioners, and policymakers working toward the sustainable management of Z. armatum and similar medicinal plant resources.

2. Botanical and Ecological Overview

2.1 Taxonomy and Nomenclature

Zanthoxylum armatum DC. belongs to the Rutaceae family, which includes many aromatic plants, especially citrus species. The Zanthoxylum genus has more than 250 species found mostly in tropical and subtropical regions around the world (Verma et al., 2021). This plant is known by several common names, such as toothache tree, tejphal, timur, or prickly ash, depending on the local language and region in the Himalayan belt."(Suman et.al, 2024).

The plant is scientifically known as Zanthoxylum armatum DC. But in older records or traditional studies, it is also sometimes referred to as Zanthoxylum alatum Roxb. (Barua et al., 2018).

2.2 Botanical Description

Zanthoxylum armatum is a small tree or thorny shrub that loses its leaves in certain seasons and usually grows about 3 to 6 meters tall. It can be easily identified by its features:

- The bark is grey or light brown with many small thorns on the stem and branches.
- Its leaves are made up of 5 to 11 small leaflets, and when crushed, they give off a lemon-like smell because of the natural oils inside.
- The flowers are small, greenish-yellow, and usually appear in bunches at the ends or sides of the branches.
- It produces bright red to brown fruits (capsules), each having a shiny black seed inside."

One special feature of the fruit is that it causes a tingling and numbing feeling on the tongue. This happens because of natural compounds called sanshools, which is why the plant is used in traditional medicine and cooking (Bisht et al., 2022; Chhetri et al., 2005). The plant has separate male and female plants, which means it needs both for reproduction. This can make it harder for the plant to reproduce in areas where the wild population is scattered (Badoni et al., 2017).

2.3 Geographical Distribution and Habitat Range

Zanthoxylum armatum naturally grows in the Himalayan region. It is found in:

- Northern Indian states like Uttarakhand, Himachal Pradesh, Jammu & Kashmir, Sikkim, and Arunachal Pradesh
- Nepal, Bhutan, parts of southern China, Myanmar, and Thailand

It usually grows at heights between 900 and 2,500 meters above sea level and prefers subtropical to cool (temperate) climates. You can often find it on well-drained slopes, forest edges, and worn-out hills.

It commonly grows in forests with trees like oak, pine, and rhododendron (Kala, 2006; Gairola et al., 2023). In some Himalayan villages, people grow it near farms or use it as a natural fence because of its thick and thorny branches."

2.4 Ecological Role in Native Ecosystems

Zanthoxylum armatum contributes significantly to ecosystem structure and services in its native habitat:

- Acts as a pioneer species in degraded forest areas, contributing to forest regeneration
- Its flowers attract pollinators, while the fruits are consumed by birds and mammals, supporting local trophic networks
- Serves a soil-binding function, stabilizing slopes and reducing erosion in hilly terrains
- Its prickly branches provide a natural defense mechanism in agroforestry systems, making it suitable for fencing around farms

However, the species is now under ecological stress due to overharvesting of fruits and bark for commercial purposes, leading to reduced regeneration in the wild (Bisht et al., 2022; NMPB, 2020). Fragmentation of habitats, selective harvesting of female plants, and poor seedling survival further threaten population viability (Badoni et al., 2017).

Table: 1. Geographical Distribution, Altitudinal Range, and Habitat Types of Zanthoxylum armatum DC.

Region/Country	State/Area	Altitude Range (m)	Habitat Type	Remarks
India	Uttarakhand, Himachal Pradesh, J&K	900–2,500	Temperate forests, scrub forests, moist deciduous slopes	Often semi-wild near village farms
	Sikkim, Arunachal Pradesh	1,200–2,800	Subtropical to temperate mixed forests	Found in forest edges and community lands
Nepal	Central and Eastern Nepal	1,000–2,600	Mid-hill forests, disturbed areas, forest margins	Widely used in traditional medicine
Bhutan	Western and Central Bhutan	1,000–2,400	Moist evergreen forests, river valleys	Wild and cultivated in some regions
China (SW)	Yunnan, Sichuan	1,500–2,700	Montane subtropical forests	Limited studies on wild populations
Myanmar	Northern highlands	1,000–2,000	Shady forest slopes, secondary growth	Often confused with closely related species

3. Ethnobotanical and Traditional Uses

3.1 Medicinal Uses Across Regions

Zanthoxylum armatum DC holds great significance in traditional medicine systems across the Himalayan region, including parts of India, Nepal, Bhutan, and China. Its fruits, seeds, bark, and roots are widely used in indigenous healthcare practices to treat various ailments such as toothaches, digestive issues, fever, colds, coughs, and parasitic infections. (Kala, 2006; Chhetri et al., 2005). In Ayurveda and traditional healing practices, the fruit of this plant is often chewed to relieve toothaches and mouth ulcers. A decoction made from its bark and seeds is commonly used to treat intestinal worms, diarrhea,

and bloating. (Samant et al., 1998; Badoni et al., 2017). The seeds are also used in Unani and Tibetan medicine systems for treating respiratory issues and skin diseases.

In Nepal, Z. armatum is included in the national pharmacopeia and is known locally as timur. It is traditionally used in postpartum care, oral hygiene, and rheumatism treatment (Sharma et al., 2004). Similarly, in Bhutan, it is utilized by traditional healers for its warming properties and is often included in herbal incense and spiritual rituals (UNESCO, 2009).

3.2 Culinary, Cosmetic, and Cultural Applications

Beyond medicinal use, Z. armatum is deeply embedded in the culinary and cultural practices of Himalayan communities. The pericarp is a widely used spice in chutneys, pickles, and traditional meat preparations—valued for its pungent flavor and tingling, mouth-numbing effect, similar to Sichuan pepper. In several Indian states, including Uttarakhand and Sikkim, the spice is sold in local markets and fetches high prices due to its aromatic and medicinal properties (NMPB, 2020).

In the cosmetic and personal care domain, essential oils from the fruits and seeds are used in herbal toothpastes, mouthwashes, and aromatic oils. Its antimicrobial properties lend it utility in natural skin care remedies for acne and inflammation.

Culturally, the plant holds significance as a sacred shrub, used in ritual purification, religious offerings, and local festivals. The thorny branches are also employed as natural fencing and protective hedges around homes and fields (Samant et al., 1998).

3.3 Value in Indigenous Healthcare Systems

Traditional knowledge surrounding Zanthoxylum armatum reflects the deep ecological and medicinal awareness of indigenous communities in the Himalayan region. Its uses are transmitted orally across generations and are often gender- and caste-specific, with women playing a key role in medicinal preparation and application (Chauhan, H., & Martoliya, J. (2025).

Table: 2. Traditional Uses of Zanthoxylum armatum DC. Across Different Regions

Region / Country	Local Name(s)	Traditional Uses	Plant Parts Used	Mode of Preparation / Administration
Uttarakhand (India)	Timur, Tejphal	Toothache remedy, digestive stimulant, cold and cough treatment	Fruits, bark, leaves	Chewed raw, decoction, powdered spice
Himachal Pradesh (India)	Dambara, Timbru	Antiseptic, relief for respiratory issues, oral infections	Fruits, bark	Decoction, paste, infused oil
Nepal	Timur, Timmur	Gastric troubles, toothache, throat infections, seasoning	Fruits, seeds, bark	Spice powder, decoction, chewing raw
Bhutan	Thingye	Traditional spice, digestive tonic, used in religious offerings	Fruits	Dried and powdered for food and medicine
Tibet / China (SW)	Hua Jiao	Toothache, sore throat, flavoring in traditional cuisine	Pericarp, oil	Oil extract, spice in soup
Myanmar (Northern Hills)	Not well documented	Believed to be used in folk medicine for digestive and dental conditions	Likely fruits and bark	Not clearly reported — more ethnobotanical research needed

The plant's inclusion in community-based healing systems supports primary health care in remote regions where access to modern medicine is limited. Importantly, this ethnomedicinal reliance contributes to cultural identity, biocultural heritage, and resilience against ecological change (UNESCO, 2009; Sharma, et.al, 2024).

4. Phytochemical Composition and Bioactive Compounds

Zanthoxylum armatum DC., belonging to the Rutaceae family, is well known for its richness in natural bioactive compounds. These chemical substances, known as secondary metabolites, are not only responsible for the plant's use in traditional healing systems but are also gaining attention in modern medicine, health supplements (nutraceuticals), and commercial industries (Okagu IU, et al., 2021).

Various research studies have confirmed the presence of important groups of phytochemicals in this plant, such as alkaloids, flavonoids, terpenoids, and aromatic essential oils (Boukhatem et al., 2020). These compounds are the reason behind its wide range of biological effects, including antimicrobial, antioxidant, anti-inflammatory, and insect-repellent properties.

4.1 Major Phytoconstituents

Phytochemical studies on Zanthoxylum armatum have shown that the plant contains a wide range of bioactive compounds (Barua et al., 2018):

1.Alkaloids

The bark and roots are rich in alkaloids like berberine, magnoflorine, and chelerythrine. These compounds are well-known for their antimicrobial, anti-inflammatory, and antidiabetic effects (Seal, et al., 2024).

2. Flavonoids and Polyphenols

Flavonoids such as rutin, quercetin, and kaempferol have been identified in the leaves and fruit pericarp. These compounds are powerful antioxidants and help protect body cells from oxidative stress (AI Hoque, et al., 2025).

3. Essential Oils and Volatile Compounds

The fruits and their outer covering are especially rich in aromatic oils, including limonene, linalool, geraniol, β-caryophyllene, and sanshools. Sanshools are the reason behind the tingling and numbing sensation felt on the tongue. These oils contribute to the plant's antibacterial, antifungal, and insect-repellent properties (Wijaya, et al., 2018).

4.Terpenoids and Steroids

Stem and seed parts contain compounds such as β-sitosterol, stigmasterol, and lupeol, which are linked with anti-inflammatory, antipyretic (fever-reducing), and pain-relieving properties (Moniruzzaman, M. 2015).

5. Tannins and Saponins

Tannins and saponins have been found in the bark and seeds. These compounds are known for their astringent nature and are used in treating diarrhea and intestinal worm infections (Fraga-Corral et al., 2021).

4.2 Known Pharmacological Activities

Numerous in vitro and in vivo studies have confirmed that Z. armatum exhibits a broad spectrum of biological activities:

Table.3.

Activity	Plant Part / Compound	Model / Target	Reference
Antioxidant	Flavonoids, polyphenols (leaves, fruits)	DPPH, ABTS assays	Bisht et al., 2022
Antimicrobial	Essential oil (fruit), alkaloids	Gram+/- bacteria, fungi (in vitro)	Badoni et al., 2017; Kala, 2006
Anti-inflammatory	β-sitosterol, lupeol	Carrageenan-induced rat paw edema	Gairola et al., 2023
Analgesic	Fruit extract, sanshools	Acetic acid writhing model (mice)	Verma et al., 2021
Insecticidal	Essential oil	Mosquito larvae and aphid repellence	Tiwari & Joshi, 2012
Antidiabetic (preliminary)	Berberine and related alkaloids	Streptozotocin-induced diabetic models	Negi et al., 2020

4.3 Relevance of Chemical Diversity for Commercial and Therapeutic Value

The wide variety of chemical compounds found in Zanthoxylum armatum forms the basis for its multiple uses in medicine and industry.

• **Medicinal and Pharmaceutical Use**:

Bioactive components of the plant have shown potential as anti-inflammatory, antioxidant, and neuroprotective agents, which can be explored for new drug development (Chhetri et al., 2005).

• **Aromatic and Cosmetic Industry**:

Essential oils obtained from the fruits and seeds are useful in oral care products, perfumes, and aromatherapy due to their pleasant aroma and therapeutic effects (Gairola et al., 2023).

• **Food and Flavouring**:

The pericarp of the fruit, rich in sanshools, provides a tingling taste similar to Sichuan pepper and is widely used as a natural spice and flavouring agent (Bisht et al., 2022).

• **Biopesticide Development**:

Due to its natural insect-repelling compounds, Z. armatum offers promise in making eco-friendly pest control products for agricultural and household use (Kala, 2006).

• **Rural Economy and Livelihood**:

The plant supports rural communities through the production of herbal teas, tooth powders, oils, and other value-added products, contributing to local income generation (Samant et al., 1998).

The variation in its chemical profile—due to differences in altitude, soil, and geographic location—also allows for selecting specific types (chemotypes) that can be cultivated for targeted industrial applications (Chhetri et al., 2005).

5. Threats and Conservation Challenges

Zanthoxylum armatum DC., though highly valued for its medicinal and aromatic benefits, is now facing serious threats from multiple directions—environmental, social, and policy-related issues (Bisht et al., 2022; Gairola et al., 2023). In its native Himalayan region, natural populations of this plant are gradually shrinking. The main challenges can be explained as follows:

5.1 Overharvesting and Unsustainable Collection

One of the biggest threats to Z. armatum is the unscientific and excessive harvesting of its fruits, bark, and roots from the wild. Due to rising demand—especially for its essential oils and spices—many collectors gather plant material without following sustainable practices. Often, unripe fruits are picked,

or the bark is stripped off entirely, which harms the plant and reduces its ability to regrow (Kala, 2006). Since most of the supply comes from the wild and not from cultivated sources, certain areas are now facing a decline in natural populations (Samant et al., 1998).

5.2 Habitat Loss and Land Use Change

Human activities like deforestation, farming expansion, road building, and urban development in the Himalayan zone have damaged the natural habitats of Z. armatum. The plant, which usually grows on hill slopes, forest edges, and scrublands, is losing space to agriculture and construction (Chhetri et al., 2005). Moreover, harmful practices such as forest fires and shifting cultivation—common in parts of northeast India and Nepal—are adding to habitat destruction (Gairola et al., 2023).

5.3 Poor Natural Regeneration and Cultivation Barriers

Although this species produces good seeds, natural regeneration in forests is very low. This happens due to seed-eating by birds and rodents, slow germination rates, and the poor quality of soil in degraded areas (Bisht et al., 2022). The plant's dioecious nature—meaning separate male and female plants—makes pollination harder in scattered populations. There is also very limited adoption of farming or nursery techniques, so the plant is not widely cultivated even today (Gairola et al., 2023).

5.4 Effects of Climate Change

Since Z. armatum grows mainly in mid-altitude zones (900–2,500 meters), it is highly sensitive to climate changes. Changes in temperature, rainfall patterns, and extreme weather events may shift the areas where the plant can survive. This can also disturb flowering and pollination timing and increase risks from pests and diseases (Chhetri et al., 2005). Climate models suggest that the natural habitat of many Himalayan medicinal plants, including Z. armatum, may shrink—especially in lower-altitude areas—in the near future (Kala, 2006).

5.5 Weak Policy Implementation and Lack of Awareness

Even though there are various conservation policies at both national and state levels—such as protection under state forest laws and inclusion in threatened species lists—the actual implementation on the ground remains very weak (Gairola et al., 2023; Samant et al., 1998).

Some of the major issues include:

- **No proper system to monitor** how much of the plant is being collected and traded
- **Lack of support** for conservation efforts that involve local communities
- **Little use of traditional knowledge** from indigenous people in official conservation plans

Moreover, many villagers and local harvesters are not even aware that Zanthoxylum armatum is under threat. Also, there are hardly any government schemes or benefits to encourage people to grow this plant on their farms or harvest it in a sustainable manner (Kala, 2006). Without community awareness and incentives, conservation efforts are unlikely to succeed in the long run.

Table 4. Summary of Major Threats (for potential table or visual):

Threat Type	Description	Impact
Overharvesting	Excessive collection of fruits/bark from the wild	Population decline, regeneration loss
Habitat degradation	Deforestation, agriculture, infrastructure development	Loss of habitat, species fragmentation
Low regeneration	Seedling mortality, dioecy, slow growth	Natural regeneration impaired
Climate change	Temperature and rainfall variability	Range shift, phenological disruption
Weak policy enforcement	Inadequate implementation of conservation laws and trade regulation	

6. Conservation Strategies

The conservation of Zanthoxylum armatum has become increasingly important due to the decline in its natural populations, rising market demand, and its ecological value in forest ecosystems (Bisht et al., 2022; Gairola et al., 2023). To protect this species effectively, a combined approach involving ecological protection, community involvement, and strong policy support is needed. Conservation strategies mainly include **in-situ**, **ex-situ**, **community-based**, and **policy-driven** efforts.

6.1 In-situ Conservation

In-situ conservation means protecting the species in its natural habitat. This can be done by:

- Creating **Medicinal Plant Conservation Areas (MPCAs)** in forests with rich biodiversity. Such efforts are ongoing in parts of India and Nepal through forest department initiatives (Kala, 2006).
- Safeguarding wild populations in **community-managed forests**, national parks, and sanctuaries.
- Encouraging natural growth by preventing forest fires, controlling grazing, and avoiding harmful collection practices—especially during flowering or when fruits are not fully matured.

In states like **Uttarakhand** and **Himachal Pradesh**, Van Panchayats and Eco-Development Committees play a major role in managing Zanthoxylum-rich areas (Samant et al., 1998).

6.2 Ex-situ Conservation

Ex-situ conservation involves protecting the plant outside its natural habitat to secure its long-term survival. This includes:

- Growing the plant in **botanical gardens and research farms**, supported by organisations like the **National Medicinal Plants Board (NMPB)** and **GB Pant National Institute of Himalayan Environment**.
- Using **seed banks, tissue culture, and germplasm conservation** to store genetic material and improve the chances of successful propagation (Chhetri et al., 2005).
- Applying **micropropagation techniques** to overcome difficulties like poor seed germination and the plant's dioecious nature.

Although tools like **DNA fingerprinting** and **somatic embryogenesis** are being explored, these are still at the early research stage for Z. armatum (Gairola et al., 2023).

6.3 Community-Based Conservation

Since Z. armatum often grows on community lands, involving local people is crucial. Community-focused strategies include:

- **Training local harvesters** to collect mature fruits without harming the plants.
- Promoting **cultivation in farmlands, backyard gardens, or as boundary hedges**, to reduce pressure on wild populations.
- Implementing **benefit-sharing schemes** so that locals get economic returns for their conservation efforts.

- Running **awareness drives** to spread knowledge about the plant's ecological importance and its potential income benefits (Kala, 2006).

6.4 Policy and Institutional Support

Many national and international programmes support the conservation of medicinal plants, but stronger implementation is still needed. For instance:

- The **NMPB and forest departments** encourage conservation through MPCAs, nursery programs, and subsidy-supported farming.
- **Global frameworks** like the **Convention on Biological Diversity (CBD)** and **Nagoya Protocol** support benefit sharing and funding for conservation.
- The **IUCN Red List** helps identify and prioritise threatened species—although Z. armatum is still only regionally assessed.
- At the state level, **forest working plans** and **biodiversity action plans** in Himalayan regions list Z. armatum as a key species for conservation (Samant et al., 1998).

Table5: Summary of Conservation Strategies:

Strategy Type	Methods	Key Institutions / Stakeholders
In-situ	MPCAs, forest protection, regeneration measures	Forest departments, local panchayats
Ex-situ	Seed banks, tissue culture, nursery propagation	NMPB, research institutes, botanical gardens
Community-based	Sustainable harvesting, local cultivation, awareness programs	NGOs, SHGs, village communities
Policy & Institutional	NMPB schemes, CBD/Nagoya Protocol, state policies	Government agencies, IUCN, biodiversity boards

7. Sustainable Utilisation of Zanthoxylum armatum: A Balanced Approach

Protecting Zanthoxylum armatum for the future is not just about conservation—it is equally important to use it responsibly. There needs to be a balance between meeting the livelihood needs of local communities and fulfilling commercial demand while ensuring that the plant remains in the wild for future generations (Bisht et al., 2022; Gairola et al., 2023). The following strategies can support sustainable use without harming natural populations.

7.1 Sustainable Harvesting Practices

A major concern is the overexploitation of wild plants due to harmful harvesting methods. To overcome this, the following sustainable techniques are recommended:

- **Right Time Collection**: Only harvest mature fruits at the correct season to allow proper seed development.
- **Selective Picking**: Do not remove all the fruits or bark from one plant; leave some for regeneration.
- **Avoid Bark Stripping**: Instead of removing bark (which may kill the plant), use fruits or seeds or harvest bark in small amounts.

- **Rotational Harvesting**: Leave some parts of the population untouched, so they can recover naturally for the next harvesting cycle.

Training locals under India's **Good Collection Practices (GCP)** and guidelines from the **National Medicinal Plants Board (NMPB)** has shown positive results in regions like Uttarakhand and Himachal Pradesh (Kala, 2006).

7.2 Cultivation and Agroforestry Approaches

To reduce dependence on forest harvesting, farmers are encouraged to grow Z. armatum in their own fields. Some successful models include:

- **Home gardens and boundary hedges** in Himalayan households.
- **Agroforestry systems**, where Z. armatum is grown with crops like turmeric, ginger, and pulses.
- **Silvi-medicinal plantations** on degraded forest areas or field edges.

Research in Sikkim and Uttarakhand shows that nursery raising and transplanting the plant is possible, especially with support from government schemes and cultivation subsidies (Gairola et al., 2023).

7.3 Strengthening the Value Chain

Encouraging sustainable use also requires building market connections and economic incentives for growers. This can be achieved by:

- Setting up **local processing units** for essential oil extraction and spice packaging, which adds value.
- Building **direct links between farmers and companies** in Ayurveda, spice, or herbal wellness sectors.
- Promoting **organic certification and fair trade practices**, which help farmers get better prices.
- Introducing **market information systems** to help villagers track prices and consumer demand.

Studies from Himachal Pradesh and parts of Nepal show that when farmers are given proper training and assured markets, they are more likely to grow the plant instead of collecting it from the wild (Samant et al., 1998).

7.4 Supporting Global and National Sustainability Goals

Using Z. armatum in a sustainable way supports several important development goals:

- **SDG 15 (Life on Land)**: Protecting ecosystems and promoting forest biodiversity.
- **SDG 12 (Responsible Consumption and Production)**: Encouraging eco-friendly harvest and use.
- **SDG 1 & 8 (No Poverty and Decent Work)**: Creating jobs and income through herbal enterprises.

Collaborations with institutions like the **National Biodiversity Authority**, **UNDP**, and various NGOs have shown that medicinal plants like Z. armatum can be part of nature-based solutions that support both conservation and rural livelihoods (Chhetri et al., 2005).

8. Emerging Prospects and Future Directions

With the rising demand for sustainable use of medicinal plants, Zanthoxylum armatum DC. offers great potential in biotechnology, commercial cultivation, herbal medicine development, and

policy inclusion. These growing opportunities not only help in the conservation of this valuable plant but also provide income for Himalayan communities and open new doors in natural product research (Bisht et al., 2022; Gairola et al., 2023).

8.1 Advances in Biotechnology and Plant Propagation

Traditional ways of growing Z. armatum through seeds face challenges like slow germination, poor seedling survival, and complications due to separate male and female plants. Therefore, scientists are now focusing on **tissue culture methods** such as:

- **Callus formation** from plant tissues
- **Somatic embryogenesis** for regenerating plants from cells
- **Shoot multiplication** from stem nodes

These in vitro techniques help produce large numbers of healthy plants in a short time, ensuring both **commercial cultivation** and **genetic conservation** of rare or high-value varieties (Badoni et al., 2017; Verma et al., 2021).

8.2 Potential in Herbal Drug and Phytochemical Research

Z. armatum is known for its rich blend of medicinal compounds like **sanshools**, **limonene**, **linalool**, **β-sitosterol**, **flavonoids**, and **alkaloids**. These substances have proven benefits such as:

- Reducing inflammation
- Fighting infections
- Acting as antioxidants
- Providing pain relief

Some recent studies are even exploring their effects on **nerve function**, **dental health**, and **pain relief** products. The numbing sensation caused by sanshools is gaining popularity in the flavour and sensory industries (Bisht et al., 2022). If scientific formulations from cultivated plants are standardised, Z. armatum could become a valuable source for herbal drug development.

8.3 Commercial Farming and Product Innovation

Due to increasing global interest in natural and organic products, there is strong potential to:

- Expand **organic farming** of Z. armatum in Himalayan states under government-supported schemes
- Create **value-added products** like:
    - Herbal toothpastes and mouthwashes
    - Pickles and aromatic oils
    - Essential oil-based perfumes and wellness supplements

Small businesses in India and Nepal have already started making products using timur (local name). Supporting local **entrepreneurs**, building **partnerships between farmers and industries**, and promoting **fair-trade markets** can boost the economic value of this plant (Gairola et al., 2023).

8.4 Research Needs and Scope for Collaboration

Even though interest in this plant is growing, several **gaps in research** still exist:

- No proper **clinical trials** to confirm medicinal benefits

- Limited **genetic diversity studies** to support conservation
- Lack of research on **post-harvest storage** to maintain oil quality
- Weak connection between **traditional knowledge** and modern science

To explore the full potential of Z. armatum, we need combined efforts from different fields like **ethnobotany**, **biochemistry**, **conservation**, and **rural development** (Chhetri et al., 2005).

8.5 Role in Policy and International Frameworks

Considering its ecological, economic, and medicinal value, Z. armatum must be included in:

- **Priority species lists** under India's biodiversity conservation programs
- **IUCN Red List monitoring**, at least at the regional level
- **Payment for Ecosystem Services (PES)** programs, to reward communities for conserving the plant
- **Nagoya Protocol** mechanisms, to ensure fair sharing of benefits from its commercial use (Samant et al., 1998)

This kind of policy support will help integrate the species into both national and global conservation agendas.

9. Conclusion

Conclusion: The Future of Zanthoxylum armatum – Balancing Conservation and Utilisation

Zanthoxylum armatum DC., a highly valued medicinal and aromatic plant of the Himalayan region, plays a major role in traditional healthcare, village economies, and biodiversity conservation. People across northern India, Nepal, and Bhutan have long used this plant for its healing properties, flavouring in cooking, and even in local religious practices—making it a true multipurpose species (Gairola et al., 2023; Bisht et al., 2022).

However, the increasing pressure from **unsustainable harvesting**, **forest degradation**, and **poor policy enforcement** has put the natural populations of this species at risk. If not addressed, these issues may lead to long-term ecological and economic losses (Kala, 2006).

To protect and promote this valuable plant, a **multi-layered approach** is needed. Conservation efforts must combine:

- **In-situ protection** of wild populations in natural habitats
- **Ex-situ strategies** like botanical gardens and tissue culture labs
- **Community-led resource management**
- **Agroforestry-based cultivation**
- **Training in sustainable harvesting**, and
- **Market linkages for value-added products**

Such integrated practices have already shown positive results in some Himalayan states under projects supported by the National Medicinal Plants Board (NMPB) and local NGOs (Samant et al., 1998).

Scientific advancements in areas like **phytochemistry**, **plant tissue culture**, and **ecological modelling** now offer new tools to boost both conservation and utilisation. For example, tissue culture techniques such as somatic embryogenesis have helped in mass propagation of elite genotypes (Badoni et al.,

2017). Phytochemical studies have highlighted the plant's potential in developing herbal medicines for pain relief, oral care, and inflammation (Bisht et al., 2022).

Yet, **many research gaps still remain**—such as the need for proper **clinical validation**, **genetic diversity studies**, and better **post-harvest processing methods** to maintain oil quality. Also, greater efforts are needed to include local communities in benefit-sharing and conservation policy-making through tools like the **Nagoya Protocol** (Gairola et al., 2023).

As the world shifts toward sustainable healthcare and nature-based solutions, Z. armatum has the potential to serve as a **model species** where traditional knowledge and modern science work hand in hand. It can help protect biodiversity, support mountain livelihoods, and contribute to sustainable development goals.

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