Integrating India's plant biodiversity conservation with global frameworks

[1]Shakti Nath Tripathi, [2]Arpita Tripathi, [3,4,5]I. Valentin Petrescu-Mag, [6]Praveen Pandey

[1] Department of Botany, Nehru Gram Bharati Deemed to Be University, Prayagraj 221505, India; [2] Faculty of Education, Teerthanker Mahaveer University, Moradabad, India; [3] Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, Cluj-Napoca, Romania; [4] Bioflux SRL, Cluj-Napoca, Romania; [5] Doctoral School of Engineering Science, University of Oradea, Oradea, Romania; [6] Division of Plant Breeding and Genetic Resource Conservation, CSIR-Central Institute of Medicinal and Aromatic Plants, Lucknow 226015, India. Corresponding author: S. N. Tripathi, tripathishaktinath@gmail.com

Abstract. In order to preserve ecological balance, human health, and sustainable development, plant biodiversity must be conserved using both in-situ and ex-situ methods. Through protected places like national parks, wildlife sanctuaries, biosphere reserves, and community-driven projects like sacred groves, in-situ strategies maintain species in their natural habitats. Ex-situ methods, such as tissue culture, botanical gardens, and seed banks, offer backup assistance by protecting species away from their natural habitats, facilitating subsequent reintroduction initiatives. India and other countries integrate traditional knowledge with legal frameworks, including the Biological Diversity Act, 2002, to meet local conservation needs. The importance of international collaborations is demonstrated by the way organizations work together globally through initiatives like the Millennium Seed Bank and conventions like the Convention on Biological Diversity (CBD). However, issues like habitat loss, climate change, resource scarcity, and illicit trafficking still exist, necessitating a concerted effort that incorporates community involvement, scientific breakthroughs, and flexible conservation strategies.
Keywords: plant biodiversity conservation, in-situ conservation, ex-situ conservation, threatened plant species, plant genetic resources, biodiversity hotspots, traditional ecological knowledge (tek), protected areas, seed banks and cryopreservation, conservation policy and sustainable development.

Introduction. The term "conservation approaches" describes methods and techniques used to preserve, maintain, and restore plant habitats and biodiversity. These strategies fall into two general categories: Ex-situ and In-situ techniques. Ex-situ conservation refers to methods that preserve plant species outside of their natural environments, such as tissue culture, seed banking, and keeping plants in botanical gardens (Raven, 2011). By creating protected areas, national parks, biosphere reserves, and animal sanctuaries, on the other hand, In-situ conservation aims to preserve species in their native environments (Myers et al., 2000). While combined, these strategies seek to preserve genetic variety, protect against habitat loss, and sustain ecosystems against threats like urbanization, overexploitation, and climate change (Mace et al., 2007; Oldfield, 2009).

Despite of their ecological, therapeutic, and economic importance, threatened plants must be conserved. As primary producers, plants promote biodiversity through intricate food webs and serve as the building blocks of the majority of terrestrial ecosystems (Singh & Upadhyay, 2020). Furthermore, many plants have therapeutic qualities and provide resources for raw materials, food, and shelter, making their conservation essential to human wellness and sustainable development. Based on studies, habitat loss, climate change, and unsustainable resource use are the main causes of the almost one-fifth of plant species facing extinction worldwide (Maunder et al., 2001; Oldfield, 2009, Bachman et al., 2019). As a result, protecting these species safeguards not only biodiversity but also the ecological equilibrium and resources that are vital to human existence.

Numerous plant species, many of which are endemic to particular places like the Himalayan region and the Western Ghats, can be found in India, one of the world's hotspots of biodiversity (Myers et al., 2000). The Botanical Survey of India (BSI) and the National Bureau of Plant Genetic Resources (NBPGR) are two of the institutions that carry out conservation activities in India, which are governed by national policies such as the Biological Diversity Act (2002). According to Khumbongmayum et al., (2005), these organizations engage local populations in customary conservation practices such as holy groves and carry out both ex-situ and in-situ conservation initiatives. A significant ex-situ initiative to preserve seeds of threatened plants from all over the world is the Millennium Seed Bank Project in the United Kingdom (Smith et al., 2014).

Comparing conservation initiatives in India and abroad, this review highlights ex-situ and in-situ techniques, the incorporation of traditional and community knowledge, scientific developments, policy frameworks, and climate adaption strategies. Recognizing the various methods and difficulties in different geographical areas emphasizes the necessity of cooperative conservation initiatives that adjust to particular ecological, social, and economic circumstances in order to preserve and strengthen the resilience of threatened species of plants.

Conservation Approaches with Special Reference to India

In-situ Conservation Methods. The safeguarding of species in their native environments while preserving evolutionary processes and ecosystem dynamics is known as "in-situ conservation" of plant genetic resources. It provides a dynamic way for maintaining biodiversity, especially in regions vulnerable to environmental changes, by permitting ongoing adaptation and evolution (Hoban et al., 2013, Brussaard et al., 2022). The maintenance of genetic diversity within natural populations and agro ecosystems is the focus of in-situ conservation, which includes conservation within ecosystems, agricultural landscapes, and managed protected areas (Van Zonneveld et al., 2021).

The ultimate objective of In-situ conservation is to preserve plant species in their native environments. Protecting endangered plant species and the habitats they live in is largely the domain of national parks, wildlife sanctuaries, and biosphere reserves. With more than 500 wildlife sanctuaries and more than 100 national parks, India has biodiversity hotspots such as the Andaman Islands, the Eastern Himalayas, and the Western Ghats (Myers et al., 2000). The goal of biosphere reserves, like the Sunderbans and the Nilgiri Biosphere Reserve, is to preserve unique ecosystems while permitting sustainable human activity in specified buffer zones. The preservation of sacred groves forest areas saved because of cultural and religious customs is another important component of in-situ conservation in India. These sacred woodlands, which are especially common in southern and northeastern India, serve as unofficial conservation areas that preserve indigenous plants and promote biodiversity (Khumbongmayum et al., 2005). India's distinctive and varied flora is guaranteed to be preserved in their native habitats because to the combination of official protected areas and community-led conservation areas.

Approaches to in-situ conservation. The creation of protected areas, such as national parks, wildlife reserves, and natural sanctuaries, is one main strategy (Wyse Jackson & Sutherland, 2000). These protected areas play a crucial role in preserving natural ecosystems and safeguarding endangered plant species. Plant species are supported in their natural habitats in more than 15% of the world's terrestrial regions that are protected (UNEP-WCMC, 2022). Major protected areas in India, such the Eastern Himalayas and Western Ghats are hotspots for biodiversity, and the nation's national parks and biosphere reserves provide ecological and legal frameworks for the preservation of endemic and endangered plant species (Chitale et al., 2020).

Another crucial strategy is on-farm conservation, which emphasizes the preservation of landraces and traditional crops on farms, which is essential for preserving agro-biodiversity. Species that have adapted to regional climates, agricultural methods, and cultural customs can be preserved using this technique. Through the cultivation of diverse landraces that demonstrate exceptional resilience to environmental conditions and economic demands, farmers actively contribute to genetic diversity (Díaz et al., 2021).

Another essential component is community-based conservation, which highlights the part local communities' play in protecting plant resources in or near their native habitats (Shackleton et al., 2019). These programs, which support local biodiversity, frequently incorporate seed networks and community seed banks and are supported by local expertise, resource management techniques, and participatory frameworks (Jarvis et al., 2021). For instance, the Navdanya movement in India encourages the preservation of biodiversity and traditional seed storage, giving people the ability to protect and spread local crop types and wild relatives of domesticated species (Shiva & Crompton, 2021).

In addition, sacred groves and cultural landscapes, conserved for religious or cultural reasons, act as biodiversity reservoirs. These groves, found in India and across Asia, play a critical role in preserving plant genetic resources, especially endemic and medicinal species, within culturally significant landscapes. They reflect traditional ecological knowledge and provide a unique means of species protection (Ray et al., 2022).

Ultimately, conservation in agroforestry systems improves biodiversity and agricultural output. Agroforestry promotes in-situ conservation of genetic resources, reduces habitat fragmentation, and increases ecosystem resilience by integrating native trees and crops, all of which contribute to a sustainable agricultural landscape (Lasco et al., 2021).

Progress in in-situ conservation. Through a network of national parks, wildlife sanctuaries, and biosphere reserves that conserve a wide variety of indigenous species, India has also made impressive strides in in-situ conservation (Brancalion et al., 2019). The Western Ghats, Eastern Himalayas, and Andaman and Nicobar Islands are among the environmentally rich areas that make up this Protected Area Network, which spans more than 5% of India's geographical area (Chitale et al., 2020). The National Biodiversity Act of 2002 places a strong emphasis on community involvement in biodiversity protection and promotes the conservation of genetic resources. In order to promote ecological and social advantages, the National Mission on Biodiversity and Human Well-Being also combines ecosystem services with biodiversity protection. By protecting traditional rice, millets, and pulse types within existing farming systems, a number of regional programs concentrate on maintaining crop diversity through on-farm conservation (Shiva & Crompton, 2021). India's dedication to preserving agro-biodiversity is further strengthened by community-based conservation initiatives and traditional agroforestry techniques, which demonstrate a comprehensive approach to conservation that strikes a balance between ecological preservation and local livelihoods.

With over 200,000 protected areas already occupying 15% of the Earth's geographical area, in-situ conservation initiatives have significantly advanced worldwide. The Global Strategy for plant conservation places a high priority on protecting endangered species in their native habitats, while the Convention on Biological Diversity (CBD) emphasizes the urgent need to protect biodiversity hotspots (CBD, 2020). There is an increasing commitment to developing in-situ conservation areas, as seen by recent initiatives like as the 30x30 Initiative, which intends to safeguard 30% of the earth by 2030 (UNEP-WCMC, 2022).

In addition, it is becoming more widely acknowledged that on-farm conservation is essential for maintaining local landraces and traditional crops that promote genetic diversity and climate change resilience. For example, by conserving cultivars that are particularly suited to regional environmental conditions, participatory plant breeding initiatives enable farmers all across the world to add to crop improvement (Díaz et al., 2021).

Limitations of in-situ conservation. While in-situ conservation is quite successful in keeping species in their native environments, it has a number of serious drawbacks. The survival of species within protected areas may be threatened by environmental changes such as pollution, natural catastrophes, and climate change, which can modify ecosystems. Ecosystems are particularly disrupted by climate change, which modifies temperature and precipitation patterns and shifts species distributions. To maintain genetic variety, these effects might call for aided migration or translocations (CBD, 2020).

Urbanization, deforestation, and agricultural growth have resulted in habitat degradation and fragmentation, which can isolate populations, decrease gene flow, and lower genetic diversity necessary for long-term adaptation (Hoban et al., 2013, Van Zonneveld et al., 2021). This is a significant restriction. Due to inbreeding, competition, and a lack of habitat connectedness, species with small populations or those in fragmented habitats are more susceptible and struggle to thrive. Through actions like development, poaching, and deforestation, human intervention and encroachment further jeopardize protected areas and undermine conservation efforts.

Resource limitations also present a problem. Large protected areas require a lot of money, infrastructure, and staff to manage, and a lack of resources can make it difficult to carry out crucial enforcement and monitoring tasks, which lowers conservation effectiveness. Because local communities may be pushed to prioritize development or agriculture above conservation due to economic pressures and land-use conflicts, socioeconomic considerations also have an impact on in-situ conservation. Long-term success requires policies that strike a balance between socioeconomic well-being and conservation (Díaz et al., 2021).

Because high-diversity areas require intensive monitoring, maintaining biodiversity hotspots becomes even more challenging, making it challenging to conserve all species equitably. Effective management is hampered by inadequate monitoring and data gaps because many protected areas lack thorough ecological data, genetic studies, and species inventories. These difficulties are frequently made worse by a lack of financial and technical resources (Jarvis et al., 2021).

Another constraint, especially for community-based and on-farm conservation initiatives, is the loss of traditional knowledge and cultural traditions. For agro-biodiversity to be preserved and community engagement in conservation to be successful, traditional knowledge must be preserved (Ray et al., 2022). Furthermore, several protected areas may limit local communities' access to resources, resulting in conflicts that call for a delicate balancing act between conservation objectives and the rights and requirements of local populations.

Furthermore, when environmental changes occur more quickly than a species can adapt, in-situ conservation which mainly aims to preserve ecosystems as they are may not be sufficient. For species with limited ranges or specific habitat requirements, this is particularly troublesome. Since active genetic management is required to maintain variety, in-situ conservation may not be enough for species with small gene pools or under extreme stress.

Notwithstanding these difficulties, in-situ conservation is still essential for maintaining biodiversity, particularly when combined with ex-situ tactics to provide a more thorough approach to species protection (Mace et al., 2007).

For the continued survival of plant genetic diversity, ecological adaptation, and ecosystem services, in-situ conservation is still crucial. Integrating conservation tactics with climate adaption initiatives, boosting community involvement, and filling data gaps through better monitoring and research are all essential to improving in-situ conservation efficacy. Partnerships with local communities, policy integration, and a stronger focus on landscape-level planning can all support the growth and sustainability of in-situ conservation efforts. To ensure biodiversity for future generations, we can better assist the conservation of plant genetic resources in their natural environments by fusing traditional knowledge with contemporary conservation science.

Ex-situ conservation methods. The sustainability of agricultural operations and the stability of ecosystems depend on the preservation of plant genetic resources. Ex-situ conservation, or the preservation of species outside of their normal environments, provides a buffer for endangered genetic material as natural habitats are increasingly threatened. Ex-situ conservation techniques enhance climate change adaptation and biodiversity preservation by offering vital resources for breeding, research, and reintroduction programs (Pence, 2011; Engelmann, 2011, Khoury et al., 2022; Van Zonneveld et al., 2020).

Ex-situ conservation techniques are being used with the goal of protecting plant species away from their native environments. Through seed banks, field gene banks, and cryopreservation facilities, the National Bureau of Plant Genetic Resources (NBPGR) spearheads efforts to protect genetic material (Arora & Nayar, 2010). The conservation of threatened plants and crop wild relatives is the focus of botanical gardens and research facilities maintained by institutions like as the Indian Council of Agricultural Research (ICAR) and the Botanical Survey of India (BSI). Rare plant species, including medicinal plants, are frequently multiplied in controlled conditions using tissue culture and micropropagation techniques (Sharma & Kumar, 2013). Across the nation, botanical gardens such as the Lalbagh Botanical Garden in Bengaluru and the Acharya Jagadish Chandra Bose Indian Botanic Garden in Kolkata are vital to promoting plant conservation research and increasing public awareness. By maintaining genetic diversity, carrying out restoration operations, and acting as study locations for additional conservation advancements, these ex-situ techniques offer an imperative backup to in-situ activities.

Approaches to ex-situ conservation. Different kinds of techniques are used in ex-situ conservation of plant genetic resources to maintain biodiversity away from natural ecosystems. The foundation of this strategy is seed banks, where seeds are kept in regulated environments to preserve their viability and genetic integrity over an extended length of time. Numerous plant species, especially those essential to agriculture and food security, are protected by renowned institutions like the Svalbard Global Seed Vault in Norway and India's National Gene Bank, which is run by the National Bureau of Plant Genetic Resources (NBPGR). These seed banks save resources for upcoming restoration needs by acting as crucial contingency plans in the case of genetic erosion or natural disasters (Li & Pritchard, 2009, Pandey et al., 2023; Volis, 2020).

By preserving living plants, field gene banks provide a workable substitute for species whose seeds are resistant to drying or cold storage. This technique is especially helpful for vegetative propagated perennial species, such coconut (*Cocos nucifera*), banana (*Musa spp*.), and mango (*Mangifera indica*), as it ensures that their genetic characteristics are maintained through active cultivation (Maxted & Kell, 2021). Another option is in vitro conservation, which involves storing plant tissues or organs in sterile conditions using tissue culture methods. The conservation of species that might otherwise be difficult to keep as seeds is made possible by this technique, which is particularly useful for plants with complicated genetic systems or short-lived seeds (Harding et al., 2020).

For species with seeds that are sensitive to desiccation, cryopreservation allows for the long-term preservation of genetic material by storing plant tissues at extremely low temperatures, usually in liquid nitrogen at -196°C. Meristems, embryos, and pollen are among the plant tissues that have successfully undergone cryopreservation, offering a vital long-term conservation alternative (Engelmann, 2011, Reed, 2021). The Indian Botanical Garden in Kolkata and the Royal Botanic Gardens in Kew are examples of botanical gardens and arboreta that act as living archives of genetic variation. According to Sharrock et al. (2022), these establishments support research, teaching, and the possible restoration of species into their native habitats in addition to conservation efforts (Wyse Jackson & Sutherland, 2000; Oldfield, 2009).

Subsequently, pure DNA samples are kept in DNA banks; protecting vital genetic information that is beneficial to molecular breeding and genetic studies but is not directly related to plant regeneration. To improve agricultural resilience, this strategy encourages further study and the development of breeding methods (Khoury et al., 2022). When combined, these ex-situ conservation techniques offer strong choices for protecting plant genetic resources, each of which is customized to fit the unique requirements and traits of various species.

Progress in ex-situ conservation. Institutions like the Consultative Group on International Agricultural Research (CGIAR), which has built significant ex-situ collections to preserve the diversity of staple crops, assist global efforts in ex-situ conservation (Thormann et al., 2020). With seeds from more than 1,700 genebanks worldwide, the Svalbard Global Seed Vault is a prime example of global collaboration (Westengen et al., 2023). Technological developments in molecular methods, tissue culture, and cryopreservation have increased the ability to store and manage genetic variation (Engelmann, 2011; Pence, 2011; Harding et al., 2020).

The National Gene Bank of India, which is governed by the NBPGR, preserves more than 450,000 accessions, including horticulture and agricultural crops. In regional areas like Shillong and Ladakh, specialized gene banks serve the conservation needs of local biodiversity by maintaining distinct ecotypes and species that are suited to particular climates (Pandey et al., 2023). To preserve resistant species, institutions such as the Indian Council of Agricultural Research (ICAR) use cutting-edge cryopreservation and tissue culture methods (Ramawat & Goyal, 2020). By preserving and sharing traditional seed varieties, community seed banks, like those supported by the Navdanya network, assist in grassroots conservation (Shiva & Crompton, 2021).

Limitations of ex-situ conservation. Although it has significant drawbacks, ex-situ conservation is essential for protecting plant genetic resources. Since ex-situ samples might not fully represent the genetic variety of natural populations, genetic degradation is a major problem. Periodically regenerating stored seeds can result in genetic drift and the loss of alleles necessary for adaptation in agricultural or natural environments (Li & Pritchard, 2009; Volis, 2020).

In vitro storage techniques, seed banks, and cryopreservation facilities require a significant amount of infrastructure, funding, and qualified staff to establish and operate. In these places, developing nations frequently face constraints that hinder their ability to carry out successful ex-situ conservation initiatives (Thormann et al., 2020). Furthermore, organisms that are removed from their natural habitats under ex-situ conditions may lose adaptations unique to their new habitat. Reintroduction of ex-situ conserved plants into the wild can be challenging because they might not have the characteristics needed to survive in their native environments (Maxted & Kell, 2021).

In order to maintain the health of the collection, seed viability also decreases with time in storage, requiring periodic regeneration. Unintentional selection and genetic drift could change the genetic composition of conserved populations, and this process can be expensive and time-consuming (Reed, 2021). Furthermore, the availability of sophisticated methods like cryopreservation and DNA banking is restricted due to their need for certain equipment and knowledge. Disaster-resilient infrastructure is crucial because ex-situ facilities are also susceptible to environmental hazards such natural catastrophes and climate-related events (Westengen et al., 2023).

Notwithstanding these difficulties, ex-situ conservation is still an essential part of the global effort to protect plant genetic resources in the face of swift environmental change. Ex-situ conservation efforts can be improved by bolstering global cooperation, making investments in cutting-edge cryopreservation and molecular procedures, and growing community seed banks. A strong basis for future food security and biodiversity conservation will be provided by enhanced digital databases, sophisticated molecular tools, and more integration with in-situ activities, all of which will promote the sustainable preservation of plant genetic resources.

Legal Framework for Conservation. A strong legal framework aimed at managing and preserving biodiversity serves as the foundation for India's conservation initiatives. One of the first and most important measures of legislation was the Wildlife Protection Act of 1972, which limited the trade in endangered animals and gave legal support for the establishment of protected areas. The Biological Diversity Act of 2002 is a further significant law which provides a framework for biodiversity conservation, sustainable use, and the fair distribution of genetic resource advantages (Singh, 2017). Under this Act, the State Biodiversity Boards (SBBs) and the National Biodiversity Authority (NBA) were established to supervise biological resource access, conservation initiatives, and compliance. The 1972 Wildlife (Protection) Act had been amended in 2022 in order to address new conservation issues and global biodiversity objectives. These changes, which strengthened India's legal framework for biodiversity conservation, improved the management of protected areas and imposed harsher punishments for wildlife offenses. These changes, which strengthened India's legal framework for biodiversity conservation, improved the management of protected areas and imposed harsher punishments for wildlife offenses. The Biological Diversity (Amendment) Bill, 2023, however, makes substantial modifications to the Biological Diversity Act of 2002 with the goals of simplifying regulations, facilitating business transactions, and resolving issues brought up by a range of stakeholders, including members of the industry sector and practitioners of Indian medical systems. The amendments aim to strike a balance between supporting biodiversity-related economic activity and conservation efforts.

Additionally, local and indigenous people can manage and safeguard forests and their biodiversity due to the Forest Rights Act of 2006, which encourages community participation in conservation (Ghate & Nagendra, 2005). In 2024, India started creating a National Wildlife Health Policy to combat the risk of zoonotic diseases and bolster biodiversity conservation initiatives. By addressing wildlife health issues, this strategy seeks to create a thorough framework for protecting wildlife populations and public health. When taken as entirety, these acts give conservation efforts in India a strong legal foundation and aim to combine traditional wisdom with sustainable methods.

Plant Biodiversity Conservation Approaches in the Rest of the World

International agreements and conventions. A number of important conventions and accords serve as the foundation for international plant conservation initiatives, offering frameworks for nations to adopt uniform conservation measures. One of the most extensive agreements, the Convention on Biological Diversity (CBD) was created in 1992 and advocates the conservation, sustainable use, and equal benefit-sharing of genetic resources. Countries have established National Biodiversity Strategies and Action Plans (NBSAPs) under the CBD, which coordinate regional initiatives with international biodiversity objectives (CBD Secretariat, 2010). Another important role is played by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), which aims to avoid overexploitation and regulate and monitor the trade of threatened species (Reeve, 2002). In order to conserve plant diversity, the CBD launched the Global Strategy for Plant Conservation (GSPC), which has set aggressive goals such as conserving at least 75% of threatened species both in situ and ex situ by 2020 (Sharrock et al., 2014). By encouraging cooperation, data exchange, and financing for conservation projects, these agreements form the cornerstone of conservation policies around the globe (Wyse Jackson & Sutherland, 2000).

Conservation strategies in different regions. Different conservation techniques that are appropriate for their ecosystems and biodiversity concerns are used in different parts of the world. One of the major coordinated protected area networks in Europe is Natura 2000, which focuses on habitat and species conservation in all EU member states (European Commission, 2016). In North America, the Endangered Species Act offers endangered species legal protection, and public lands overseen by organizations such as the U.S. Fish and Wildlife Service and national parks help preserve uncommon flora and unique ecosystems (USFWS, 2018). Due to habitat loss and economic pressures, Africa, which is home to distinctive ecosystems including savannas and rainforests, suffers a variety of hurdles. Through programs like the International Union for Conservation of Nature's (IUCN) African Plant Specialist Group, which emphasizes both plant conservation and environmentally friendly living for local communities, African nations collaborate on cross-border conservation (Smith et al., 2018). Using traditional knowledge to safeguard forests and native plant species, indigenous groups in South America collaborate with environmental organizations to save threatened plants in the Amazon Basin (Holt, 2005).

The various environmental, socioeconomic, and cultural factors that are reflected in each region's policies underscore the necessity of conservation measures that are tailored to the particular setting.

Similarities and Differences between India and Global Approaches. In-situ and ex-situ conservation strategies, community engagement, and a reliance on legislative frameworks are just a few of the numerous objectives and approach that India's and the world's conservation initiatives have in common. In order to maintain biodiversity in natural environments, India and other nations use in-situ techniques by creating protected areas like national parks, wildlife sanctuaries, and biosphere reserves (Myers et al., 2000). On a national and worldwide scale, ex-situ conservation is also greatly aided by seed banks, botanical gardens, and research institutes; for example, the UK's Millennium Seed Bank and India's National Bureau of Plant Genetic Resources (NBPGR) are comparable (Smith et al., 2014). The socioeconomic and geographic conditions that affect conservation measures, however, give rise to significant variations. As seen by the safeguarding of sacred groves, which are maintained by local communities out of cultural or religious convictions, India, for example, places a higher value on traditional knowledge and community-led conservation (Khumbongmayum et al., 2005). On the other hand, in order to address ecological issues, Western conservation strategies might rely increasingly on cutting-edge technology like genetic engineering, GIS mapping, and predictive modeling. The scope and scalability of conservation programs may also be constrained by India's resource constraints, as the country has less infrastructure and finance than wealthy countries (Sharma & Kumar, 2013). While international strategies frequently place an emphasis on standardized methods and cutting-edge scientific methodologies, India's combination of traditional and modern practices reveals a culturally adapted approach (Brancalion et al., 2019; Shackleton et al., 2019; Figure 1).

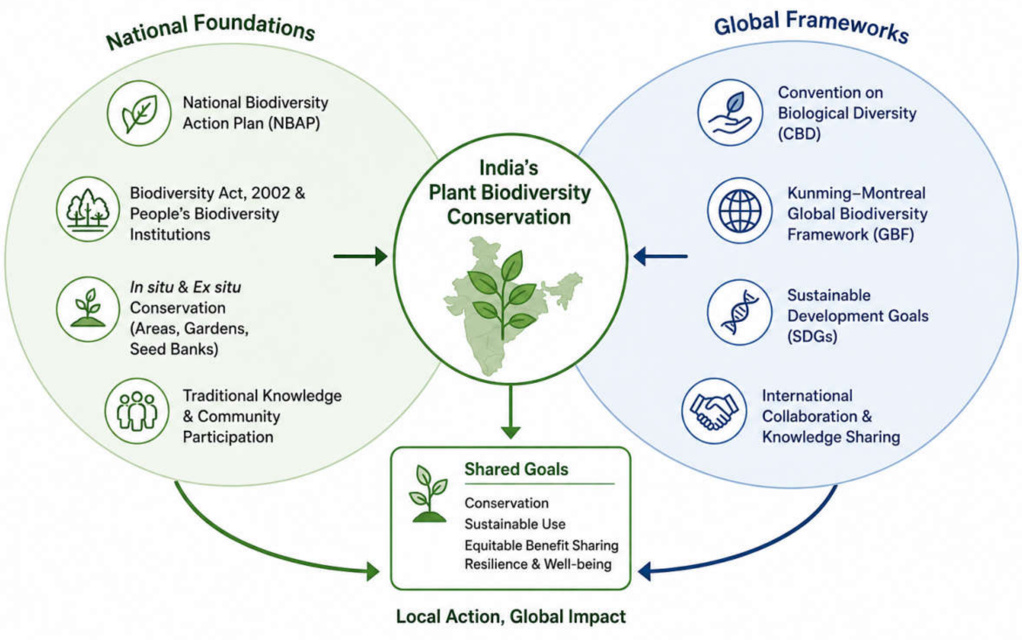

Figure 1. India's approaches to plant biodiversity conservation, bridging nations actions with global goals.

Challenges Faced in Conservation Efforts. There are a number of obstacles that prevent conservation initiatives in India and around the world from effectively protecting threatened species of plants. Urbanization, agriculture, and infrastructure development are the primary causes of habitat loss, which splits ecosystems and decreases the amount of suitable habitat for plant species (Myers et al., 2000). Another layer of complexity is brought on by climate change, which disturbs ecosystems and complicates conservation planning due to shifting patterns of precipitation and temperature (Singh &

Upadhyay, 2020). Conservation endeavors in India are severely hampered by a lack of funding and access to high-tech equipment, which forces the use of community-based conservation and more straightforward, affordable alternatives (Ghate & Nagendra, 2005). Conservation efforts around the world are complicated by problems with international coordination and regulatory compliance, especially when species cross national borders, as is the case in Africa's trans-border ecosystems where unified protection is challenging to accomplish. Furthermore, despite legal frameworks like CITES, the illicit trade and exploitation of rare species still pose a threat to conservation efforts (Mace et al., 2007; Maunder et al., 2001).

Effectiveness of Different Conservation Methods. The variety of plant, the environment, and the situation all affect how effective measures for conservation are. Because in-situ conservation is so successful at maintaining intricate ecosystems and encouraging organic interactions between species, it is especially advantageous for safeguarding biodiversity hotspots in India and around the world. Large protected areas with little human intervention, including national parks and biosphere reserves, have been shown to be effective in halting habitat degradation and preserving species variety over time (Holl & Aide, 2011; Brancalion et al., 2019; European Commission, 2016). Ex-situ techniques, however, provide a crucial fallback for species whose habitats are under imminent danger or that are extremely threatened. Another method used to preserve genetic material is through seed banks, botanical gardens, and tissue culture techniques, which may eventually enable the return of species into their native environments (Smith et al., 2014). This strategy is demonstrated by initiatives such as the Millennium Seed Bank, which has been successful in conserving thousands of species globally (Bunn et al., 2007; Li & Pritchard, 2009).

As shown with sacred groves and community-managed forests in India, community-led conservation techniques have demonstrated efficacy in combining sustainable practices with biodiversity preservation (Khumbongmayum et al., 2005). Technology-driven methods, including using genetic tools to examine plant populations or GIS mapping to monitor ecosystems, help improve planning and increase the precision of species recovery efforts worldwide (Sharma & Kumar, 2013). In conclusion, a complete and flexible strategy to plant conservation that addresses both short-term and long-term demands for biodiversity protection is provided by a combination of in-situ and ex-situ methods, community engagement, and technological improvements.

Policy Recommendations for Improved Conservation Strategies. For in-situ and ex-situ conservation techniques to be effective, biodiversity conservation policies must be strengthened. To promote ecosystem health and connectivity, future strategies should prioritize habitat restoration, climate resilience, and biodiversity corridor conservation (Brancalion et al., 2019; Shackleton et al., 2019; Giam & Scholes, 2020). The success of conservation initiatives can be increased and local stewardship can be encouraged by regulatory frameworks that support community involvement in conservation, such as implementing biodiversity-friendly land-use planning and increasing local communities' access to conservation financing (CBD, 2022). Furthermore, measures aimed at lowering pollution, invasive species, and habitat fragmentation might lessen the risks to plant biodiversity and aid in the preservation of important habitats.

Integration of Traditional Knowledge with Modern Conservation Practices. Enhancing biodiversity results and advancing culturally sensitive conservation techniques are two benefits of integrating scientific conservation strategies with traditional ecological knowledge (TEK). In order to identify resilient plant species and maintain local ecosystems, indigenous and local groups frequently hold extensive ecological knowledge that has been gathered over many generations (Berkes, 2018). Because TEK frequently promotes natural resilience, combining it with contemporary methods can be very beneficial for climate change adaptation. Agroforestry and native water management practices, for instance, have been demonstrated to provide substantial contributions to soil and water conservation, boosting ecosystem services and biodiversity

(Raygorodetsky, 2018). Thus, inclusive conservation policies that honor and take into account TEK can result in robust, long-lasting conservation plans (Shackleton et al., 2019).

Importance of Public Awareness and Education Initiatives. Education and public awareness initiatives are essential for building sustained support for biodiversity conservation. Raising public awareness of the significance of plant biodiversity and the risks it confronts can be accomplished through media outreach, educational initiatives, and community-based conservation efforts (Krasny et al., 2020). People can support conservation policies and embrace sustainable practices by developing a greater understanding of ecological interconnections through conservation education at all levels. For example, programs aimed at young pupils can raise awareness early on; while citizen science projects let the general public directly participates in data collecting and conservation monitoring (McKinley et al., 2017). Considering how human activity contributes to biodiversity loss, public involvement is essential to building a conservation-minded society (Oldfield, 2009) (Figure 2).

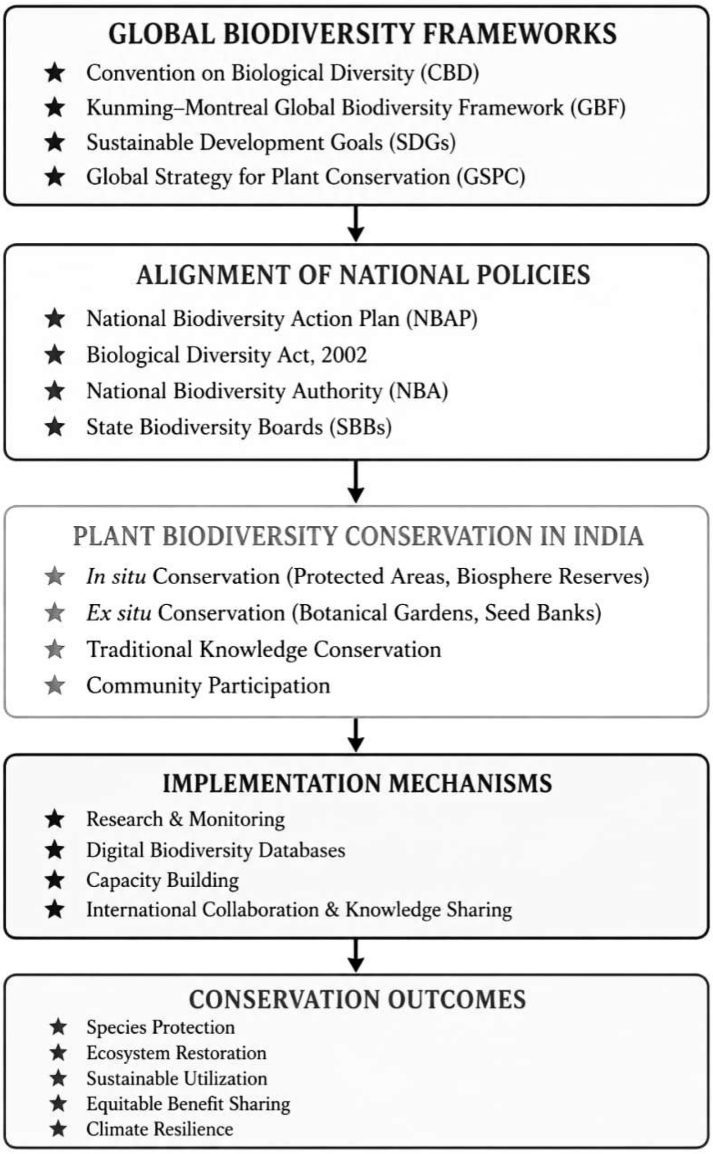

Figure 2. India’s hierarchical approach to biodiversity conservation, moving from international framework down to local outcomes.

Conclusions. In order maintain biodiversity, ecological stability, and resources crucial to human health and well-being, it is imperative that threatened plants be conserved. Protected areas, botanical gardens, seed banks, and tissue culture facilities collaborate to conserve endangered plant species in India and around the world. Conservation efforts use both in-situ and ex-situ methods. While worldwide approaches frequently use cutting-edge technologies and international frameworks like the Convention on Biological Diversity (CBD) and CITES to protect plant diversity, India's conservation framework places more emphasis on community-led initiatives and traditional knowledge. Significant obstacles still exist in spite of these initiatives, including as habitat loss, climate change, resource scarcity, and complicated cross-border regulations.

It will take more financing, cutting-edge research, and the implementation of technology-driven solutions to improve conservation results. Expanding protected areas and implementing stricter habitat protection laws can help in-situ conservation, especially in places with high biodiversity. To improve the long-term survivability of plant species kept outside of their natural environments, ex-situ efforts should invest in genetic research, cryopreservation, and cutting-edge seed storage technology. In India, encouraging collaborations between conservation groups and local people can support the integration of indigenous knowledge into conservation strategies, encouraging community involvement and sustainable resource use. Globally, producing more climate-resilient plant varieties and strengthening enforcement of laws governing the trade of endangered species could help combat the growing challenges posed by illicit exploitation and climate change.

For plant conservation to be successful and long-lasting, collaboration is required. Aligning conservation priorities and strategies across areas requires the use of international conventions, cross-border conservation efforts, and knowledge-sharing platforms. Countries can overcome financing and infrastructure gaps by pooling resources, technology, and skills, especially those with abundant biodiversity but low resources. A worldwide commitment to biodiversity goals is also fostered by collaborative efforts, which enable nations to work together to combat global concerns like invasive species and climate change. In the end, preserving the diversity of plants around the world will necessitate a cohesive, collaborative strategy that honors regional ecosystems, strengthens indigenous and local communities, and makes use of scientific discoveries to preserve biodiversity for coming generations.

Authors Contributions. SNT, AT wrote the manuscript; PP, IVPM read and revised the manuscript.

Conflicts of Interest. The authors declare that there is no conflict of interest.

Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Funding. This research received no external funding.

References

Arora, R. K., & Nayar, E. R. (2010). Ex-situ conservation of plant genetic resources: Approaches, progress, and limitations in India. *Plant Genetic Resources, 8*(3), 234-245.

Bachman, S., et al. (2019). Extinction risk assessment and threats to the world's plant species: A global overview. *Nature Plants, 5*(7), 742-750.

Berkes, F. (2018). Sacred Ecology. Routledge.

Brancalion, P. H. S., Garcia, L. C., Loyola, R., Rodrigues, R. R., Pillar, V. D., & Lewinsohn, T. M. (2019). A critical analysis of the Native Vegetation Protection Law of Brazil (2012): updates and current trends. *Natureza & Conservação, 17*(1), 1-16.

Brussaard, L., Caron, P., Campbell, B., Lipper, L., Mainka, S., Rabbinge, R., Babin, D., & Pulleman, M. (2022). Reconciling biodiversity conservation and food security:

Scientific challenges for a new agriculture. *Current Opinion in Environmental Sustainability, 4*(1), 34–42.
Bunn, E., Turner, S. R., & Panaia, M. (2007). The contribution of ex situ conservation and cryogenic storage to the preservation of biodiversity. *Australian Journal of Botany, 55*(3), 345-355.
CBD Secretariat. (2010). *Global biodiversity outlook 3*. Secretariat of the Convention on Biological Diversity.
CBD. (2020). *Global biodiversity outlook 5*. Secretariat of the Convention on Biological Diversity.
Chitale, V. S., Behera, M. D., Roy, P. S., & Joshi, P. K. (2020). Conservation planning in biodiversity-rich regions of India. *Environmental Monitoring and Assessment, 192*, 1–15.
Convention on Biological Diversity (CBD). (2016). Global Biodiversity Outlook 4: A mid-term assessment of progress towards the implementation of the Strategic Plan for Biodiversity 2011-2020. Montreal: CBD Secretariat.
Convention on Biological Diversity (CBD). (2016). Guidelines on Biodiversity and Tourism Development. Montreal: CBD Secretariat.
Convention on Biological Diversity (CBD). (2022). Global Biodiversity Outlook 5.
Díaz, S., Zafra-Calvo, N., Purvis, A., Verburg, P. H., Obura, D., Leadley, P., Chaplin-Kramer, R., De Meester, L., Dulloo, E., Martín-López, B., Shaw, M. R., Visseren-Hamakers, I., Broadgate, W., Bruford, M. W., Burgess, N. D., Molnár, Z., Hill, R., Jackson, P. W., Jonas, H. D., et al. (2021). Biodiversity and ecosystem resilience in agricultural landscapes. *Nature Ecology & Evolution, 5*(4), 447–457.
Engelmann, F. (2011). Use of biotechnologies for the conservation of plant biodiversity. *In Vitro Cellular & Developmental Biology-Plant, 47*(1), 5-16.
European Commission. (2016). Natura 2000 network. European Union.
Ghate, R., & Nagendra, H. (2005). Role of indigenous institutions in sustainable use of forest resources in the Western Himalayas. *Forest Policy and Economics, 7*(1), 113-129.
Giam, X., & Scholes, R. J. (2020). Policy options for biodiversity conservation in the face of climate change. *Conservation Letters, 13*(5), e12795.
Harding, K., Benson, E., & Reed, B. M. (2020). Ex situ conservation of plant genetic resources: From freezing seeds to freezing cells. *Plant Biotechnology Journal, 18*(1), 11–25.
Hoban, S., Schlarbaum, S. E., & Goldstein, D. B. (2013). Applications of genetic data to improve management and restoration of a threatened tree species: an example using Castanea dentata. *Forest Ecology and Management, 291*, 268-275.
Holl, K. D., & Aide, T. M. (2011). When and where to actively restore ecosystems? *Forest Ecology and Management, 261*(10), 1558-1563.
Holt, F. L. (2005). Indigenous knowledge and conservation in the Amazon Basin. *Conservation and Society, 3*(2), 342–360.
Jarvis, D. I., Brown, A. H. D., Cuong, P. H., Collado-Panduro, L., Latournerie-Moreno, L., Gyawali, S., Tanto, T., Sawadogo, M., Mar, I., Sadiki, M., Hue, N. T. N., Arias-Reyes, L., Balma, D., Bajracharya, J., Castillo, F., Rijal, D., Belqadi, L., Ranamukhaarachchi, S. L., Subedi, A., & Sthapit, B. (2021). Community-based conservation and management of plant genetic resources. *Biodiversity and Conservation, 30*(2), 421–440.
Khoury, C. K., Carver, D., & Jarvis, A. (2022). Priorities and challenges in conserving crop biodiversity for food security. *Nature Food, 3*(9), 715–722.
Khumbongmayum, A. D., et al. (2005). Sacred groves: Biodiversity conservation values and strategies in the northeastern Himalayas. *Biodiversity and Conservation, 14*(8), 1541-1561.
Krasny, M. E., et al. (2020). Environmental education research: Current status and future directions. *Environmental Education Research, 26*(8), 1193-1206.
Lasco, R. D., Delfino, R. J. P., & Catacutan, D. C. (2021). Agroforestry systems and biodiversity conservation. *Agroforestry Systems, 95*(4), 567–579.

Li, D. Z., & Pritchard, H. W. (2009). The science and economics of ex situ plant conservation. *Trends in Plant Science, 14*(11), 614-621.
Mace, G. M., Norris, K., & Fitter, A. H. (2007). Biodiversity and ecosystem services: A multilayered relationship. *Trends in Ecology & Evolution, 22*(10), 543-551.
Maunder, M., Higgens, S., & Culham, A. (2001). The effectiveness of botanic garden collections in supporting plant conservation: a European case study. *Biodiversity & Conservation, 10*(3), 383-401.
Maxted, N., & Kell, S. P. (2021). Ex situ conservation of plant genetic resources in genebanks: A global perspective. *Genetic Resources and Crop Evolution, 68*(5), 1235–1250.
McKinley, D. C., Miller-Rushing, A. J., Ballard, H. L., Bonney, R., Brown, H., Cook-Patton, S. C., et al. (2017). Citizen science can improve conservation efforts and the study of plant biodiversity. *Frontiers in Ecology and the Environment, 15*(5), 283-291.
Myers, N., Mittermeier, R. A., Mittermeier, C. G., Da Fonseca, G. A., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature, 403*(6772), 853-858.
Oldfield, S. (2009). Botanic gardens and the conservation of tree species. *Trends in Plant Science, 14*(11), 573-574.
Pandey, V., Kumar, S., & Singh, N. P. (2023). Conserving crop diversity: Advances and challenges in the Indian National Gene Bank. *Indian Journal of Genetics and Plant Breeding, 83*(1), 45–60.
Pence, V. C. (2011). Evaluating costs for the in vitro propagation and preservation of endangered plants. *In Vitro Cellular & Developmental Biology-Plant, 47*(1), 176-187.
Ramawat, K. G., & Goyal, S. (2020). Cryopreservation and conservation of endangered plant species. In Cryopreservation and Biodiversity (pp. 75–95). Springer.
Raven, P. H. (2011). Ex situ plant conservation and the role of botanic gardens. *Trends in Plant Science, 16*(1), 30-35.
Ray, R., Ray, S., & Roy, S. (2022). Sacred groves as reservoirs of biodiversity and traditional ecological knowledge. *Environmental Conservation, 49*(1), 12–21.
Raygorodetsky, G. (2018). The Archipelago of Hope: Wisdom and Resilience from the Edge of Climate Change.
Reed, B. M. (2008). Plant cryopreservation: a practical guide. Springer Science & Business Media.
Reed, B. M. (2021). Cryopreservation for conservation of plant genetic resources. Critical *Reviews in Plant Sciences, 40*(1), 1–22.
Reeve, R. (2002). *Policing international trade in endangered species: The CITES treaty and compliance*. Earthscan Publications.
Shackleton, S., Paumgarten, F., Kassa, H., Husselman, M., & Zida, M. (2019). Opportunities for enhancing poor women's socioeconomic empowerment in the value chains of three African non-timber forest products (NTFPs). *International Forestry Review, 11*(2), 27-40.
Sharma, S., & Kumar, S. (2013). Plant tissue culture and biotechnology in conservation of endangered plants. *Plant Science Today, 8*(1), 43-47.
Sharrock, S., Jones, M., & Oldfield, S. (2022). The role of botanical gardens in plant conservation. *Journal of Botanic Gardens Conservation International, 20*(2), 74–88.
Sharrock, S., Oldfield, S., & Wilson, O. (2014). *Plant conservation report 2014: A review of progress in implementation of the Global Strategy for Plant Conservation*. Botanic Gardens Conservation International.
Shiva, V., & Crompton, T. (2021). Community seed banks as a solution to genetic erosion. *Agroecology and Sustainable Food Systems, 45*(4), 445–459.
Singh, B. (2017). Legal framework for biodiversity conservation in India. *Environmental Law Review, 19*(2), 151-170.
Singh, B., & Upadhyay, S. (2020). Climate change and plant conservation in India. *Climate Adaptation Journal, 15*(2), 98-112.
Smith, P., Dickie, J., Linington, S., Pritchard, H. W., & Probert, R. (2014). The role of seed banks in the conservation of plant biodiversity: the case of the Millennium Seed Bank Project. *Seed Science Research, 24*(S1), S55-S60.

Smith, P., Mace, G. M., & Miller, R. M. (2018). Plant conservation initiatives in Africa: Challenges and opportunities. *Biodiversity and Conservation, 27*(9), 2217–2234.
Thormann, I., Engels, J. M. M., & Frison, E. A. (2020). Global strategies for the conservation and use of plant genetic resources for food and agriculture. *Plant Genetic Resources, 18*(1), 1–10.
UNEP-WCMC. (2022). *Protected planet report 2022*. United Nations Environment Programme World Conservation Monitoring Centre.
USFWS. (2018). *Endangered species conservation and recovery program*. U.S. Fish and Wildlife Service.
Van Slageren, M. W. (2003). The Millennium Seed Bank: Building partnerships in arid regions for the conservation of wild species. *Journal of Arid Environments, 54*(1), 195-201.
Van Zonneveld, M., Dawson, I. K., & Ramírez-Villegas, J. (2020). Climate change and the future of plant genetic resources for food and agriculture. *Plant Genetic Resources, 18*(2), 133–148.
Van Zonneveld, M., Larranaga, N., Blonder, B., Coradin, L., Hormaza, J. I., & Jarvis, A. (2021). Human diets drive range expansion of megadiverse fruit species. *Proceedings of the National Academy of Sciences, 118*(39), e2025645118.
Volis, S. (2020). Ex situ plant conservation: What can it do, what should it do? *Plant Diversity, 42*(3), 177–181.
Westengen, O. T., Dawson, I. K., & Dempewolf, H. (2023). Safeguarding the world's crop diversity in the Svalbard Global Seed Vault. *Nature Reviews Earth & Environment, 4*(3), 147–158.
Wyse Jackson, P. S., & Sutherland, L. A. (2000). *International agenda for botanic gardens in conservation*. Botanic Gardens Conservation International.

Received: 10 April 2026. Accepted: 01 June 26. Published online: 01 June 2026.
Authors:
Shakti Nath Tripathi (SNT), Department of Botany, Nehru Gram Bharati Deemed to Be University, 221505 Prayagraj, India, e-mail: tripathishaktinath@gmail.com
Arpita Tripathi (AT), Faculty of Education, Teerthanker Mahaveer University, Street no, Post code, Moradabad, 244001, Uttar Pradesh, India, e-mail: arpitatripathi0391@gmail.com
Ioan Valentin Petrescu-Mag (IVPM), Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, 3-5 Calea Mănăștur street, 400372 Cluj-Napoca, Romania, ioan.mag@usamvcluj.ro
Praveen Pandey (PP), Division of Plant Breeding and Genetic Resource Conservation, CSIR - Central Institute of Medicinal and Aromatic Plants, Lucknow-226015, India, e-mail: pandeypraveen1986@yahoo.com

How to cite this article:
Tripathi, S. N., Tripathi, A., Petrescu-Mag, I. V., Pandey, P. (2026). Integrating India's plant biodiversity conservation with global frameworks. *AAB Bioflux, 18*(1), 1-14.