International Journal of Biology Education Towards Sustainable Development
Vol.5, No.1, 2025 pp. 34-53
e-ISSN 2809-5073. DOI. 10.52889/ijbetsd.v5i1.636

Exploring the Educational Potential of Mutualistic Interaction between *Cynometra cauliflora* and Arbuscular Mycorrhiza in PT Chandra Asri's Biodiversity Park: A Content Analysis for High School Biology Learning

Submitted 21 April 2025, Revised 26 April 2025, Accepted 26 April 2025

Najmi Firdaus[1], Dian Rachmawati[2], Rida Oktorida Khastini[3*], Siti Gia Syauqiyah Fitri[4], Evi Amelia[5], Desi Eka Nur Fitriana[6], Rifki Survani[7], Indria Wahyuni[8]

[1,2,3,4,5,6,7,8]Department of Biology Education, Faculty of Teacher Training and Education, Universitas Sultan Ageng Tirtayasa, Serang, Indonesia
Corresponding Email: *rida.khastini@untirta.ac.id

Abstract

Arbuscular mycorrhizal fungi (AMF) form mutualistic interactions with plants, including *Cynometra cauliflora* (Namnam), a tropical indigenous species from the Fabaceae family. This study explores the educational potential of this biological relationship to enrich high school biology education under the Kurikulum Merdeka framework. Field research was conducted at PT Chandra Asri's Biodiversity Park in Cilegon, Banten Province, Indonesia, an area with rich local biodiversity and a tropical rainforest climate. The study used a qualitative content analysis approach following an exploratory-descriptive model. Nine naturally growing *C. cauliflora* individuals were selected for morphological observations and root sampling. Morphological characteristics were documented following standard botanical protocols, while AMF colonization was assessed through root clearing, Phillips and Hayman staining method, and microscopic observation. The percentage of AMF colonization was calculated using the gridline intersect method. Habitat characterization to understand the ecological context. Curriculum analysis reviewed Indonesian biology standards, textbooks, and scientific literature to map potential integrations. Key concepts such as mutualism, nutrient cycling, biodiversity conservation, and plant physiology were identified for curriculum enrichment. The findings suggest that studying *C. cauliflora* and its AMF association can effectively support learning outcomes (Capaian Pembelajaran), fostering student skills in scientific methods, environmental awareness, and critical thinking. Incorporating local examples promotes contextual and inquiry-based learning, aligning with the spirit of the Kurikulum Merdeka and strengthening students' ecological literacy. In conclusion, the mutualistic relationship between *C. cauliflora* and AMF offers a valuable, locally relevant scientific model for enhancing biology education. It bridges scientific knowledge, cultural understanding, and sustainability, preparing students for real-world ecological challenges.

Keywords: Arbuscular Mycorrhiza, Biology Subject, Namnam, Taman Kehati

INTRODUCTION

There has been a growing emphasis on environmental education in recent years in the schooling system, especially in the case of biology subjects. This transition responds to the pressing requirement for students to grasp ecological arrangements and the importance of biodiversity in maintaining life on planet Earth (Hong *et al.,* 2022). However, while the feature is prominently coupled with the concepts in most textbooks, there is still a disconnect between what is available in theory and practice and investment and conservation decision-makers facing local biodiversity issues. In Indonesia, the variety of native flora and fauna provides a gateway for bridging that gap. However, it is often under-explored in the classroom. With its abundant biodiversity, Indonesia offers a beautiful yet tangible context for engaging with important conservation issues. Unfortunately, this potential is often underutilized in many classrooms, where examples of local ecology have been largely replaced by generalized or foreign material that inhibits students' ability to connect environmental issues to their surroundings and foster deeper stewardship of their natural heritage (Darling-Hammond *et al.*, 2019).

As an example, the Namnam plant (*Cynometra cauliflora*) is a native Southeast Asian tree species that thrives in Indonesia and illustrates just how ecologically intricate and educational local biodiversity can be. The plant goes by many different names in various regions of the country, a testament to its rich cultural diversity. In Manado it is known as namu-namu; in Ternate, namo-namo; in Halmahera, it is called namet; and in Central Maluku, it is known by several names, including namute, lamute, lamu-da and klamute. In Java (known as pukih or kopi anjing), in Bima as puci anggi, in Makassar as puti anjeng (Heyne, 1987; Verheij & Coronel, 1997). Designated as a crucial component of biodiversity as it is likely to support local wildlife or of value in maintaining soil integrity, the Namnam plant has the potential to be a bulwark for local ecosystems.

Arbuscular mycorrhiza is a ubiquitous and abundant group of fungi, well known to support soil health and improve plant nutrient uptake. Mutualistic interactions represent a fundamental concept for ecology that depicts the reciprocal benefits as exchanged between any two different organisms. *C. cauliflora*, in addition to arbuscular mycorrhizal fungi (AMF), has such a prominent symbiotic relationship for the key reason that the fungi uptake even more mineral nutrients directly from the soil, whilst the plant receives carbohydrates that it produces via photosynthesis. Ecosystem balance maintenance and biodiversity preservation each depend greatly on this interaction. Furthermore, it provides for a concrete framework for examining interspecific dynamics within natural settings (Khaliq *et al.,* 2022). Though they play critical ecological roles, mycorrhizal fungi rarely make it into standard high school biology syllabi, which favor general ideas of energy flow, biodiversity, and ecosystem dynamics. Biologically, mycorrhizae constitute a significant part of ecosystem function. *C. cauliflora* is a mycorrhizal plant, and up to 80% of all plant species globally have been shown to form mycorrhizal fungal symbioses (Khastini *et al.,* 2025). The fungi infiltrate the plant root systems and form specialized structures e.g. arbuscules and vesicles or develop extensive hyphal networks. They serve as essential structures for promoting the health of plants and boosting the fertility of soils. In particular, mycorrhizal associations increase plant access to essential elements, such as phosphorus, and thus play an important role in the cycling of nutrients (Chiu & Paszkowski, 2019; Han *et al.,* 2023). The dense hyphal networks also improve water uptake (Hewedy *et al.,* 2023) and increase plant drought resistance. Mycorrhizal fungi improve soil structure by merge soil particles, leading to better aeration and water-holding capacity and blocking soil-borne pathogens. These benefits enhance plant vigor and improve holistic ecosystem stability (Rillig & Mummey, 2006). Conservation and sustainable development are not single solutions, and adapting *C. cauliflora* in its natural association with mycorrhizal fungi is a great anticipation solution for the conservation and sustainable use of *C. cauliflora*. Also, the decline in cultivation and rarely reported habits of *C. cauliflora* need to be explained.

Integrating local plant species such as Namnam and ecological concepts like mycorrhizal relationships in biological education would provide an innovative contextual learning experience. However, initiatives that promote native biodiversity curricular integration are still far from achieving broader reach. Looking at current teaching materials, however, we can see that quite the opposite makes the standard because examples used are often too general ideas and do not necessarily align with the student's regional context, making it harder for students to relate to counterpart simulation to their environmental context (Buerkle *et al.,* 2023). Active-learning strategies, widely promoted as means for inquiry-based learning and real-world application by recent science education reforms (NRC, 1997, 2003; NSF, 1996), effectively engage students in contrast to traditional methodologies, though their implementation, particularly at high-enrollment institutions is hindered at times by student resistance as well as resource and institutional constraints (Smith *et al.,* 2005; Felder & Brent, 1996; Boyer Commission, 1998). However, in the face of these challenges, there is increasing evidence that implementing low-cost, scalable, active-learning strategies can promote critical thinking and long-term retention of content (Handelsman *et al.,* 2004; Allen & Tanner, 2005). Integrating local examples such as namnam and its symbiotic interactions with mycorrhizal fungi into active learning further mitigates educational reform by helping students connect biodiversity and scientific inquiry to their everyday lives.

Translational background is a primary challenge to educationalizing biological curricula because of the lack of connection between theory and its virtual context. The challenge is further compounded by the fact that ecological concepts, frequently introduced abstractly, make it difficult for many students to see their relevance to the environments that are part of their daily lives. The study is dedicated to filling this gap by exploring the potential of bringing the local biodiversity to the classroom, using the Namnam plant and arbuscular mycorrhiza as case studies. The results of this study are expected to be educational content that connects lessons in the classroom with real-world ecological practices to educate people about environmental sustainability, which is adapted from the resources in the Biodiversity Park of PT Chandra Asri Pacific Tbk. (hereinafter referred to as PT Chandra Asri).

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The study is novel in its relevance to integrating local and ecologically important species in biology education, which is still lacking in schools. This study aims to contribute an innovative tool for enhancing ecological literacy by focusing on indigenous species, situating itself among the less common species in academic literature, such as the namnam plant. At the same time, it seeks to add to the knowledge base on integrating local biodiversity conservation into high school curricula to raise a generation that is environmentally literate and committed to sustainability. The study also resolves an important research gap regarding the application of biodiversity in education. It tackles the challenge of using real-world biodiversity to ground more abstract ecological concepts for students and explores how anchoring some local, sustainable practices might be incorporated into the high school science curriculum. This focus on the correct parameters for an effective model for inserting environmental sustainability into education could function everywhere in Indonesia and many biodiverse regions elsewhere. Therefore the study aims to explore the educational potential of the mutualistic interaction between Namnam and arbuscular mycorrhiza, focusing on how these biological elements can be integrated into high school biology education.

METHOD

Data Collection Site and Technique

This study employed a qualitative content analysis approach. The research followed an exploratory-descriptive model to identify key concepts, themes, and opportunities for contextual learning within existing educational frameworks. Data collection was conducted at PT Chandra Asri's Biodiversity Park, Taman Kehati Asri in Gunung Sugih Village, Ciwandan District, Cilegon City, Banten Province, Indonesia, Cilegon, Banten, Indonesia (6°2′45″S, 106°2′30″ E). Taman Kehati Asri, an area known for its rich local biodiversity and conservation initiatives established by PT Chandra Asri on September 23, 2021 (Figure 1). Geographically, the area lies in the western part of Java Island, characterized by a tropical rainforest climate (Af in the Köppen-Geiger classification). The region experiences an average annual temperature of approximately 26°C, with the warmest month being August (around 28°C) and the coolest in April (around 24°C). The average annual rainfall is about 3,674 mm, with December being the wettest month (average 456 mm) and September the driest (average 87 mm). Topographically, Taman Kehati Asri is situated in a lowland area with gentle slopes, making it suitable for various conservation activities. The park serves as a biodiversity conservation area, housing diverse flora and fauna.

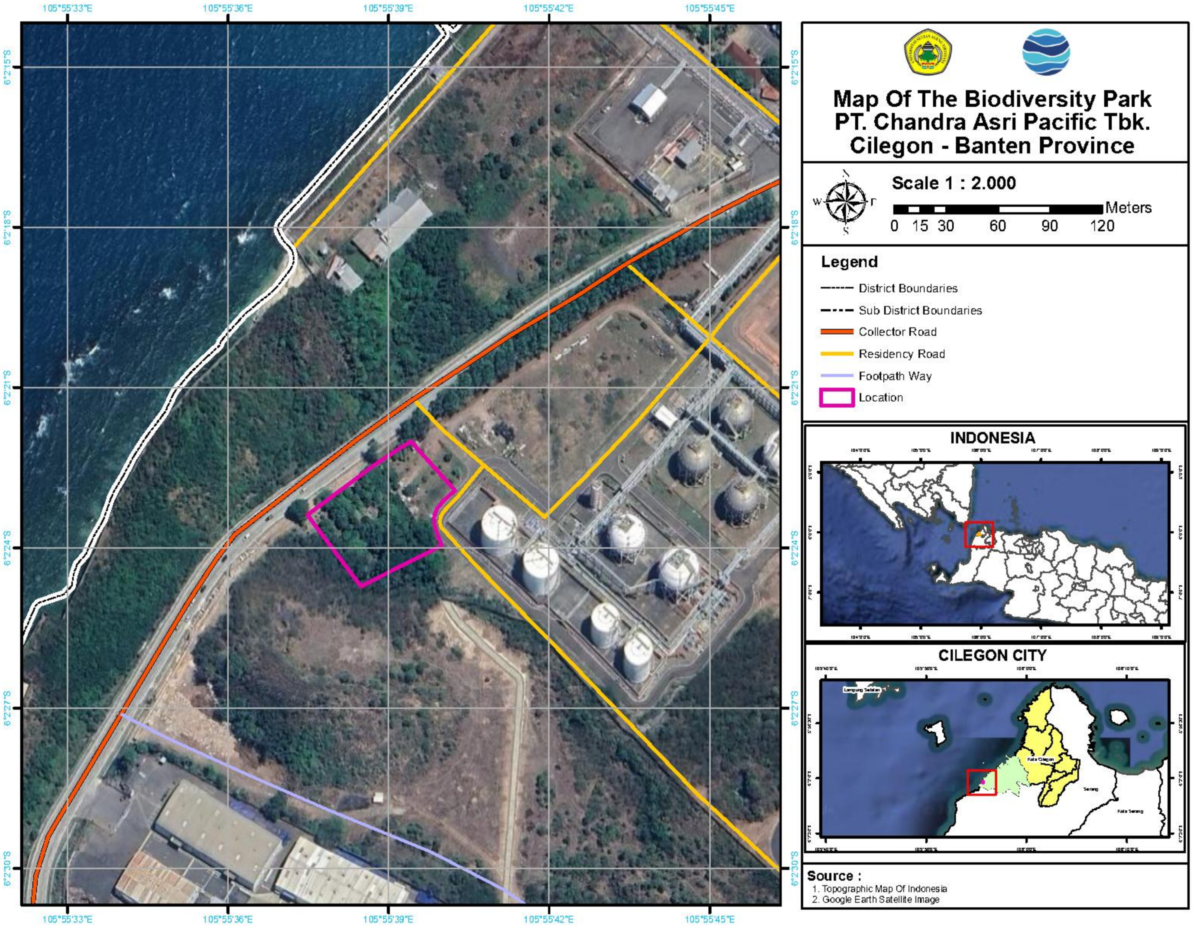


Figure 1. Data Collection Site in Taman Kehati Asri

The study focused on namnam individuals and naturally occurring arbuscular mycorrhiza associated with the park's soil ecosystem. Nine naturally growing individuals of *C. cauliflora* were identified as sampling points across the site. Each individual represented one independent sampling unit for morphological observation and root sampling. The geographic coordinates of each plant were recorded using a handheld GPS device to map their spatial distribution within the conservation area.

Field Observation and Plant Morphology Documentation

Morphological observations were made in detail for each sampling point. Standard botanical descriptive protocols according Na-Ah *et al.* (2024) were followed for recording the vegetative (leaf morphology, stem characteristics) and reproductive structures (flower and fruit morphology, seed characteristics) of *C. cauliflora*. Morphological measures, including leaf length and width, petiole length, flower diameter, and fruit size, were measured using a digital caliper (±0.01 mm precision). High-resolution images were taken using a DSLR camera (Canon EOS D3000) with a macro lens to document diagnostic characteristics under natural light. Voucher specimens containing representative parts (leaves, flowers, fruits) were gathered from each plant, pressed, and preserved according to herbarium protocols for taxonomic verifications. Environmental data were recorded at each sampling point to characterize the microhabitat of *C. cauliflora.*

Root Sampling and Assessment of Arbuscular Mycorrhizal Association

Fine lateral root samples (diameter <2 mm) were collected from the rhizosphere of each *C. cauliflora* individual. Roots were carefully excavated at approximately 0–20 cm soil depth, gently washed with distilled water to remove soil debris, and preserved in 50% (v/v) ethanol for laboratory analysis. Assessment of AM fungal colonization followed the modified method of Phillips and Hayman (1970). Root samples were processed. First roots were cleared with 10% (w/v) KOH at 90°C for 30 minutes. Then, rinse thoroughly with distilled water. Acidified with 1% (v/v) HCl for 15 minutes. Stained with 0.05% (w/v) trypan blue in lactoglycerol (lactic acid:glycerol:water = 1:1:1) at 90°C for 20 minutes.. Stained roots were mounted on glass slides in lactoglycerol and observed under a compound microscope (Olympus CX43) at magnifications of 100× to 400×. The presence and types of AM fungal structures (hyphae, arbuscules, vesicles) were recorded. Root colonization rates were quantified using the gridline intersect method described by Giovannetti & Mosse (1980), counting a minimum of 100 intersections per sample. The percentage of colonized root length was calculated using the formula:

$$\text{Colonization (\%)} = \frac{\textit{Number of intersections with AM structures}}{\textit{Total Number Intersection}} \times 100$$

Curriculum Content Analysis

National and regionally developed high school biology curriculum documents were reviewed for biodiversity, ecological interactions, and sustainability education topics to conduct content analysis of the Merdeka Curriculum. In addition, Indonesian biology textbooks taught in the classroom and scientific literature on *C. cauliflora*, arbuscular mycorrhiza, and ecological significance were analyzed. A learning outcome (capaian pembelajaran) and learning objectives (tujuan pembelajaran) relevant to the research topic are determined based on an analysis of the learning components. Following this, we conducted a thorough investigation into integrating the mutualistic relationship between *C. cauliflora* and arbuscular mycorrhiza in the current taught curriculum. The study identified these current representations and gaps in having local examples based on a content analysis of these current mutualisms, soil ecology, and local biodiversity course content; the study showed how including local examples would enhance students' ecological understanding. The analysis also examined the extent to which educational material supports environmental sustainability and ecological understanding, thus indicating opportunities for deepening biology education with genuine, place-relevant scientific applications generated by PT Chandra Asri's Biodiversity Park, Taman Kehati Asri.

A focused literature review was performed to synthesize scientific knowledge on the ecological roles and benefits of *C. cauliflora* and arbuscular mycorrhiza, aiming to map key learning points that can be adapted for high school students. Themes related to ecological interactions (e.g., mutualism, nutrient cycling, biodiversity conservation) were identified from field observations and literature.These themes were then mapped onto relevant high school biology curriculum sections to identify alignment opportunities. Gaps between existing curriculum content and potential local contextual content were systematically documented.

Validation

Triangulation was used to enhance the credibility of the analysis by Cross-referencing field data with scientific literature (Carter *et al.,* 2014). The analysis reduced potential biases and increased confidence in inter- and extrapolations of field observations by systematically comparing these field observations to peer-reviewed studies and current ecological knowledge. The results of all three methods confirmed the correctness of the mutualistic documented relationships. Also, they reinforced both the interpretation of what could be learned during these interactions and how we could successfully put these interactions into high school biology learning. This approach allowed the authors to obtain a broader picture of biological content and applicability related to education, thereby fostering the production of authentic, evidence-based learning material.

RESULTS AND DISCUSSION

Identifying Morphological Characteristics of *C. cauliflora* in PT Chandra Asri's Biodiversity Park, Taman Kehati Asri.

This species is known for its cauliflorous growth habit, where its fruits and flowers grow directly from the trunk (Setiani *et al.*, 2022). This plant has already spread into several countries, including the Philippines, Sri Lanka, Thailand, and even India, even though its native distribution covers five of the major Indonesian islands (Kalimantan, Java, Sulawesi, and Sumatra) [data Plants of The World Online, 2021]. *C. cauliflora* is commonly grown as an ornamental plant because its young leaves are pink and beautiful. Its fruit is used as a traditional food in the form of rujak, pickles, and sambal, and it has a delicious sweet and sour taste. However, the plant is increasingly rare in communities because it does not consistently bear fruit yearly, resulting in less interest in its cultivation (Setiani *et al.,* 2022). Moreover, according to the IUCN (2022) database, *C. cauliflora* has yet to be registered in any conservation status, indicating a large gap in public knowledge and research efforts regarding this species.

The *C. cauliflora*, locally known as nam nam, is a member of the Fabaceae family, and its distinctive and unique morphology can be seen in Figure 2. The roots of this plant include strong taproots and branches, functioning to support the tree. The stem is round with monopodial branching and upright growth direction. The bark is grayish brown, rough surface, and has lenticels. The roots of this plant are strong tap roots and branches, functioning to support the tree that can grow up to 6-15 meters (Datumaya & Angio 2023). Namnam leaves are compound with a pair of almost sitting leaflets, oval to obliquely oval and asymmetrical. The size of the leaflets ranges from 5.5-16.5 cm long and 1.5-5.5 cm wide, with a shiny surface and smooth texture. Young leaves are pale pink, while old leaves are shiny dark green. Morphologically, the main characteristic of *C. cauliflora* lies in its flowers that appear directly from the main stem or branches (cauliflory phenomenon). The flowers are small with pale pink or white petals and a white lanceolate crown. The stamens number 8-10 strands are free (Setiani *et al.,* 2022). The fruit is a thick, fleshy, and grooved pod, green when young and turning brownish yellow when ripe, and has a distinctive odor and a sour-sweet taste. The fruit is a thick, fleshy pod, wrinkled kidney-shaped with a pointed tip, measuring 3-9 cm long, 2-6 cm wide, and 1-4 cm thick. The fruit hangs on the stem, is scaly brown when young and greenish or yellowish when ripe. Single seed, flat kidney-shaped, measuring 3-6 cm long and 2-4 cm wide, brown in color.

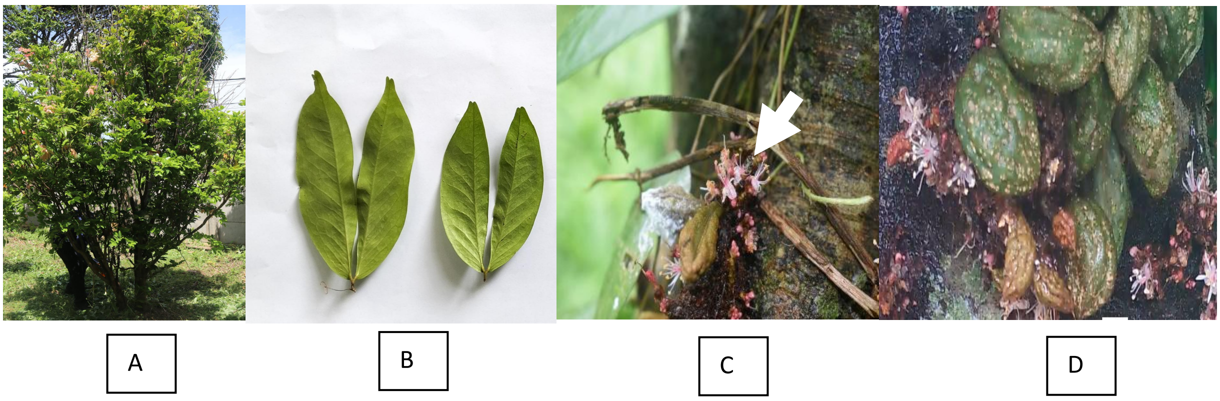


Figure 2. Morphological Characteristics of *C. cauliflora* (Namnam): (A) Habit of the whole tree; (B) Compound leaves with asymmetrical leaflets; (C) Cauliflorous flowers emerging directly from the trunk (indicated by arrow); (D) Thick, fleshy, wrinkled fruits attached to the stem.

Arbuscular Mycorrhizal (AM) Association with *C. cauliflora* Roots

Microscopic analysis revealed a high frequency of AM fungal colonization in the fine roots of *C. cauliflora.* Table 1 shows the colonization of AMF in namnam trees.

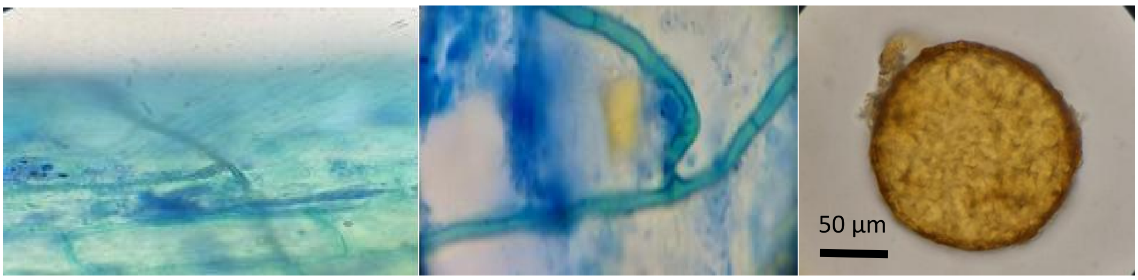
Table 1. AMF Colonization Infection Rates at Different Namnam Tree Sites

Tree Number	GPS Coordinates (Latitude, Longitude)	AMF Colonization Infection Rate (%)
Namnam 1	S 06°02.390' E 105°55.638'	68
Namnam 2	S 06°02.388' E 105°55.636'	72
Namnam 3	S 06°02.387' E 105°55.635'	75
Namnam 4	S 06°02.388' E 105°55.631'	78
Namnam 5	S 06°02.390' E 105°55.629'	63
Namnam 6	S 06°02.392' E 105°55.626'	72
Namnam 7	S 06°02.393' E 05°55.624'	63
Namnam 8	S 06°02.395' E 105°55.623'	75
Namnam 9	S 06°02.395' E 105°55.625'	61

The results show that *C. cauliflora* roots exhibit consistently high arbuscular mycorrhizal fungi (AMF) colonization, ranging from 61% to 78%. Despite minor variations, the colonization rates were relatively similar, with an average of approximately 69.6%. The GPS coordinates of all sampled trees are clustered closely within the same area of PT Chandra Asri's Biodiversity Park, indicating that the trees share similar environmental conditions such as soil type, microclimate, and canopy cover.

The relatively uniform colonization rates across trees nearby suggest that the habitat provides favorable conditions for AMF development. This is supported by previous research showing that AMF colonization tends to be high in stable, nutrient-poor tropical soils where symbiosis greatly benefits plant nutrient uptake (Birhane *et al.,* 2020; Ilyas *et al.,* 2024). Even trees with slightly lower colonization rates (such as Namnam 9 at 61%) are still within the expected range for healthy symbiotic relationships, possibly influenced by subtle local differences like soil compaction, moisture levels, or minor variations in root health.

The presence of AMF structures (hyphae, arbuscules, and spores) in all root samples further confirms the strong and active symbiosis throughout the study area, as seen in Figure 3.



A B C

Figure 3. Arbuscular Mycorrhiza Colonization Structure in *C. cauliflora* root. A. Arbuscule B. Internal hyphae B. Arbuscule. C Spore.

Arbuscular mycorrhizal fungi (AMF) are beneficial microorganisms that play a significant role in plant growth, including legumes such as the namnam tree. AMF colonization rates for leguminous trees such as *Cassia siamea* in tropical regions can reach up to 60% (Setyaningsih, 2023). However, different colonization rates depend on soil depth, nutrient availability, and environmental conditions. AMF colonization, for instance, is generally higher in upper soil layers (0–10 cm) than in deeper layers, and soil phosphorus availability is an important factor determining the colonization degree (Birhane *et al.,* 2020). In addition, nutrient-poor soils and AMF lead to more dependency on these symbionts. In contrast, richer soils reduce dependency on AMF (Ilyas *et al.,* 2024).

The information could provide insights into agroforestry and conservation of Namnam and related leguminous species within diverse ecosystem processes (AMF colonization). In low-nutrient availability areas, AMF applied to soils may considerably promote the growth and resilience of trees. Moreover, preserving appropriate environmental factors like good soil depth and moisture can facilitate AMF-leguminous tree symbiosis. In addition, naturally planting species with a higher affinity for AMF can enhance the connection with AMF and benefit the trees and the ecosystem (Wahab *et al.,* 2023).

Analysis of Potential Research Results For Biology Learning Content

The mutualistic interaction between *C. cauliflora* and arbuscular mycorrhizal fungi (AMF) offers rich potential for developing high school biology learning content aligned with the Kurikulum Merdeka, which can be seen in Table 2. The curriculum emphasizes student-centered, inquiry-based learning and the integration of local contexts. By investigating the symbiotic relationship between *C. cauliflora* and AMF, students can deepen their conceptual understanding of ecosystem interactions, plant physiology, and soil fertility, directly addressing several learning outcomes (Capaian Pembelajaran-CP) that emphasize mastery of biological processes and ecological principles.

The practical exploration of arbuscular mycorrhizal fungi (AMF) and their role in enhancing nutrient absorption offers students a valuable opportunity to apply core scientific methods such as observation, experimentation, data analysis, and conclusion drawing. Those skills are essential within the Contextualized Pedagogy framework (Jeffs *et al.,* 2016). In this process, students actively engage in hands-on activities that reflect real-world scientific inquiry. For example, students learn to carefully handle biological samples to observe fungal colonization under the microscope during root preparation for staining. Additionally, filtering soil to isolate AMF spores introduces students to microbial ecology techniques and enriches their laboratory skills, precision, and critical thinking. These steps, integrated into the learning

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e-ISSN 2809-5073. DOI. 10.52889/ijbetsd.v5i1.636

process, deepen conceptual understanding of symbiotic relationships in ecosystems and cultivate a strong foundation in scientific literacy and technical competence.

Research by Hester *et al.* (2018) emphasizes that inquiry-based learning involving authentic scientific practices significantly enhances students' understanding of complex biological systems and promotes higher-order thinking. Moreover, a study by Kong (2021). supports the integration of experiential learning in science classrooms, noting that engaging students in meaningful scientific tasks, such as those involving soil microorganisms and plant-microbe interactions, helps develop problem-solving skills and fosters a deeper appreciation for the relevance of science in addressing global challenges like food security and sustainability. Thus, embedding AMF-related investigations in the curriculum aligns with international educational best practices and empowers students to think and act like scientists.

Table 2. Educational Potential of the Mutualistic Interaction Between *Cynometra cauliflora* and Arbuscular Mycorrhiza in High School Biology Learning

Educational Focus Area	**Description of Research Result and Literature Review**	**Connection to Biology Concepts**	**Relevance to Kurikulum Merdeka**	**Biology Learning Topics**
Symbiosis	Investigating the mutualistic relationship between *Cynometra cauliflora* and AMF.	Understanding mutualistic relationships in ecosystems.	Encourages the development of critical thinking and scientific inquiry through local context.	Ekosistem dan Interaksi Organisme (Ecosystems and Organism Interactions)
Soil Fertility and Plant Growth	Exploring how AMF enhances nutrient absorption for *Cynometra cauliflora*: Phosphorus (Qi *et al.,* 2022), Nitrogen (Wu *et al*., 2024).	Plant physiology, nutrient uptake, and the role of fungi in ecosystems.	Promotes inquiry-based learning and experiential activities in local environments.	Pertumbuhan dan Perkembangan Tumbuhan (Plant Growth and Development)
Ecological Interactions	Analyzing how AMF supports plant resilience and ecosystem stability (Hovland *et al*., 2019).	Ecosystem dynamics, interdependent relationships, and energy flow.	Integrates real-world ecosystems into biology content, fostering environmental stewardship.	Interaksi dalam Ekosistem (Interactions in Ecosystems)

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Educational Focus Area	**Description of Research Result and Literature Review**	**Connection to Biology Concepts**	**Relevance to Kurikulum Merdeka**	**Biology Learning Topics**
Biodiversity and Conservation	Role of namnam (*C. cauliflora*) as a native Indonesian species in ecosystem function and biodiversity conservation (Samling *et al.*, 2021; Datumaya & Angio, 2023; Renjana *et al.*, 2024)	Biodiversity surveys in local areas; creating conservation proposals for underutilized native species	Profil Pelajar Pancasila: Environmental responsibility and sustainable thinking; Capaian Pembelajaran: Analyzing biodiversity in ecosystem levels	Keanekaragaman Hayati (Biodiversity)
Ethnobotany Study	Studying *C. cauliflora* as a local flora and how people use it in everyday life: food, medicine, and cosmetics (Ado *et al.*, 2015; Samling *et al.*, 2021).	Local Biodiversity plant, plant classification, and benefit of biodiversity (plant)	Promotes active learning with Project Based Learning (PjBL) or Inquiry, where students conduct mini research on local plants and their use in society. It can also be used as content in strengthening the profile of Pancasila students in Kurikulum Merdeka	Biodiversity/ Ecosystems and Interactions
Field-based Learning	Conducting research at PT Chandra Asri's Biodiversity Park (Oliveira *et al.*, 2025).	Hands-on scientific research, data collection, and analysis.	Promotes active learning, scientific observation, and application of theoretical knowledge.	Metode Ilmiah (Scientific Methods)

Educational Focus Area	Description of Research Result and Literature Review	Connection to Biology Concepts	Relevance to Kurikulum Merdeka	Biology Learning Topics
Biotechnology	Exploring the role of arbuscular mycorrhizal fungi (AMF) in enhancing plant health and their potential application in biotechnology, particularly through the production of secondary metabolites with mechanisms involving cytotoxicity, antiproliferative effects, and the induction of apoptosis (Tajudin *et al*., (2012).	Biotechnology applications in agriculture, genetic and microbial engineering.	Integrates modern biotechnology with ecological studies, enhancing students' understanding of its applications in sustainable agriculture.	Bioteknologi (Biotechnology)

The study of *C. cauliflora* fosters students' awareness of local biodiversity. It promotes environmental stewardship, in line with CP outcomes that focus on the appreciation and sustainable use of biological diversity. Integrating ethnobotanical aspects such as the traditional use of namnam fruit for food and medicine, further strengthens the connection between scientific concepts and societal applications, supporting holistic, contextual learning approaches.

The morphology and anatomy of tissue material in namnam can also be used as content for plant cell and tissue material to improve students' visual literacy in understanding plant anatomy. A study conducted by Susiyawati & Treagust (2021) revealed that the low visual literacy of students in understanding plant anatomy photographs is due to a lack of conceptual understanding. Therefore, it is recommended that plant anatomy learning be integrated with morphological content, supported by visual interpretation training, and connected to real-life contexts. One potential solution is using clear and distinct colors to differentiate plant tissues, making them easier for students to recognize. This is in line with the findings of Vydra &

Kováčik (2024), who stated that teaching the anatomy of roots, stems, and leaves, combined with the preparation of fresh microscopic slides and histochemical staining (using phloroglucinol tests and Duha green textile dye), can enhance students' ability to recognize and understand plant tissues, especially xylem and phloem. Hands-on experience in preparing and staining slides also helps students better comprehend the functions of tissues. This study emphasizes the significant role of color in distinguishing different types of plant tissues. One of the advantages of the Nam nam plant is its naturally distinctive tissue colors, making it highly suitable for plant anatomy practicums, particularly in schools with limited access to tissue stains.

Suprapto *et al*. (2024) also stated that visual transformation from 2D images into 3D models can convert abstract concepts of plant anatomy into more concrete and easily understandable ones. This approach helps students identify cell shapes in detail and classify plant organs based on their cellular and tissue structures. However, before students can effectively perform a 2D to 3D transformation, they must first recognize each type of tissue, which becomes easier when each tissue is differentiated by color. Furthermore, a study by Yang *et al.* (2024) showed that the appropriate selection and combination of colors can reduce students' cognitive load in processing visual information. In the context of plant anatomy learning, using the right colors can help improve focus, facilitate tissue identification, and support a more comprehensive understanding of anatomical concepts.

Activities such as field research at PT Chandra Asri's Biodiversity Park and microscopic observation of *C. cauliflora*'s root tissues help enhance students' critical thinking, creative inquiry, and problem-solving skills. In particular, the anatomical clarity of *C. cauliflora* roots—where tissues like the epidermis, cortex, endodermis, vascular bundles, and pith are distinctly visible (Sujarwo *et al.,* 2017), provides an excellent model for plant anatomy studies, facilitating more effective visual learning and memory retention. This directly supports the Scientific Methods competencies within the CP.

The concept of biotechnology, in terms of the role of AMF in enhancing plant health and their potential application in biotechnology, is closely related to science literacy. By studying this complex topic, students are trained to develop their science literacy, involving knowledge of scientific concepts, understanding the nature of science, and applying scientific reasoning. Furthermore, through science literacy-based learning, students are expected to have an understanding of scientific processes and practices, be familiar with how science and scientists work, be able to weigh and evaluate science products, and be able to engage in civic decisions about the value of science (Dibner *et al.*, 2016).

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Vol.5, No.1, 2025 pp. 34-53
e-ISSN 2809-5073. DOI. 10.52889/ijbetsd.v5i1.636

In the broader ecological context, research on how AMF contributes to plant resilience and ecosystem stability (Das & Sarkar 2024) introduces students to concepts of energy flow, interdependence, and dynamic relationships within ecosystems, reinforcing topics under Ecosystem Interactions. Furthermore, discussions on AMF's role in improving plant health and its applications in sustainable agriculture help connect the topic to modern biotechnology and real-world innovations, preparing students for future scientific challenges.

Through Project-Based Learning (PjBL) and inquiry-based approaches, students are encouraged to actively explore their environment (Lattimer & Riordan 2011), conduct mini-research projects, and develop the Pancasila Student Profile traits such as collaboration, independence, ecological awareness, and global citizenship. Thus, incorporating the study of *C. cauliflora* and AMF into biology learning aligns with the content and pedagogical approaches of the Kurikulum Merdeka and nurtures critical scientific skills, ecological literacy, and environmental responsibility among high school students.

CONCLUSION

The study of *Cynometra cauliflora* (Namnam) and its mutualistic relationship with arbuscular mycorrhizal fungi (AMF) provides valuable insights for enriching high school biology education under the Kurikulum Merdeka. The distinct morphology of *C. cauliflora*, especially its cauliflorous flowering habit, combined with its cultural and ecological importance, highlights its potential as a local biodiversity resource. Field research confirmed a high rate of AMF colonization in its roots, emphasizing the role of mycorrhizae in enhancing plant nutrient uptake, soil fertility, and ecosystem resilience. Incorporating this study into the curriculum supports Capaian Pembelajaran (CP) targets, particularly in understanding ecosystem interactions, plant growth, biodiversity conservation, and scientific methods. Practical fieldwork, morphological observations, and AMF microscopic analysis promote inquiry-based learning, critical thinking, and environmental awareness. Moreover, linking AMF's benefits to sustainable agriculture introduces real-world biotechnology applications, preparing students for future scientific and ecological challenges. The ethnobotanical relevance of *C. cauliflora*, traditionally used in food and medicine, also fosters interdisciplinary learning, connecting biology to cultural studies and sustainability. Using local species in education strengthens students' ecological literacy and deepens their connection to their environment. Integrating *C. cauliflora* and AMF studies into biology education offers a rich, place-based learning model that aligns with Kurikulum Merdeka's emphasis on student-centered, contextual, and experiential education. It nurtures scientific competence, ecological responsibility, and the development of future citizens who are environmentally aware and culturally grounded.

ACKNOWLEDGEMENT

This research is part of a collaborative project between PT Chandra Asri Pacific Tbk and the Biology Education Program at Universitas Sultan Ageng Tirtayasa under project No. SHE/22-0054 and 210/UN43/HK.06.00/2022. The authors thank biology education students for assisting with field data collection throughout the research period. We would also like to thank the anonymous reviewers for their insightful comments on the manuscript.

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