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Invisible Treasures: Assessing Indonesia's Unique Agrobiodiversity for Food and Nutrition Security

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Abstract: Indonesia is a biodiversity hotspot with high levels of endemism of globally important food crops and their crop wild relatives, as well as locally adapted cultivars. This rich diversity is essential to Indonesia's food and nutrition security, while underpinning the livelihood strategies of small-scale farmers (both men and women) and traditional communities, who act as guardians of this genetic heritage. However, many of Indonesia's plant genetic resources for food and agriculture are experiencing genetic erosion due to increased crop uniformity and the reduced use and demand for local varieties. Changes in food preferences and consumption patterns have driven the species into agricultural neglect with only some smallholder farmers cultivating the species for cultural reasons. These problems are exacerbated by land-use changes and climate variability. Recognizing the imperative to conserve agrobiodiversity in the region to ensure future food security and sustain livelihoods, the status of conservation and sustainable use of taro, yams, cloves and nutmeg in three target provinces in Indonesia was assessed. Mixed-method analyses were used to document existing conservation efforts and what is currently known of these target crops' conservation status, both in ex situ collections and in the field, to identify unique biodiversity, as well as the barriers and knowledge gaps on how to better conserve and use this unique genetic diversity for future generations.

Keywords: agrobiodiversity conservation and use; agrobiodiversity mainstreaming; food crops; food security; Indonesia; plant genetic resources for food and agriculture (PGRFAs); nutrition security; sustainable livelihoods

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1. Introduction

As the largest country in Southeast Asia, Indonesia boasts remarkable levels of biodiversity including a wealth of plant genetic resources for food and agriculture (PGRFAs) [1]. As the center of diversity of globally significant food crops and their crop wild relatives (CWRs) (including rice, taro and yam), Indonesia is also rich in locally adapted cultivars [2] and has the largest number of endemic tree species, including spice trees like nutmeg (*Myristica* spp.) and trees with medicinal properties, for example, cloves (*Syzygium* spp.) [3]. These distinctive PGRFAs—particularly the diversity that exists within species (intraspecific diversity)—are vital to Indonesia's present and future food and nutrition security. They are also crucial for the development of the country's rural economy, largely driven by men and women smallholder farmers and *Masyarakat Adat* (traditional communities) who are also important custodians of many local crops and varieties as well as of plant genetic resources that are only found in the wild [4,5]. Latest estimates indicate that 40 million rural Indonesians depend on the country's biodiversity for their livelihoods [5–7].

This rich diversity and the ecosystem services it provides are in jeopardy. In Southeast Asia, reports highlight ongoing losses of agrobiodiversity and genetic resources, mostly due to land being repurposed for aquaculture, agriculture and infrastructure development [8–11]. This is also the case in Indonesia, where the issue is further exacerbated by the lack of coordinated conservation strategies and centralized facilities for preserving vulnerable agrobiodiversity [12]. The same study [12] reports severe genetic erosion of traditional Indonesian PGRFAs, which aligns with a study by [6] conducted in 2019 estimating that approximately 75% of Indonesia's PGRFAs have been replaced by improved varieties because of the introduction and widespread cultivation of one or a few improved, non-autochthonous cultivars [13]. A key example of this is the severe genetic erosion of Indonesian rice, supplanted by one improved rice variety (IR64) for intensive farming, under the Green Revolution in the early 1970s. Within two decades, this intensive monocropping had dramatically reduced Indonesia's rice diversity and resulted in higher incidences of severe pest (brown planthopper, *Nilaparvata lugens*) and disease (leaf blight, tungro virus) outbreaks [14–16]. The use of improved, high-yielding varieties in monoculture systems such as this, replacing many traditional varieties on farms, coupled with the massive application of pesticides, has narrowed the genetic base of all agricultural crops, not only rice [17]. This has reduced on-farm crop diversity that allows the natural evolution of traditional crops' adaptive traits that are important to farmers and breeders alike.

In the case of CWRs, deforestation, forest degradation and conversion of other natural habitats are the major drivers of genetic erosion. Indonesia has one of the highest rates of deforestation in the world with forest fires and conversion of forest land to oil palm and pulpwood plantations mostly driving deforestation [18]. Between 1990 and 2021, Indonesia lost over 27 million hectares of forest (equivalent to 17% of its forest land area) [19] and only about 50% of Indonesia's remaining forest is old-growth forest [20,21]. Habitat destruction and significant declines in species' populations are also occurring due to local communities' overharvesting of natural resources. Further, habitat-specific rare and endemic species are strongly affected by climate change. Temperature rises and rainfall variability in particular are predicted to have profound effects on species' future occurrence across landscapes but also impact agricultural production [22]. Once these species are lost, so is the potential to identify and use valuable traits, such as disease resistance, drought tolerance and nutritional quality, in breeding programs aimed at developing improved and resilient varieties.

To date, the conservation status and the occurrence of local cultivars and CWRs of many of the crops for which Indonesia is the center of diversity remain undocumented—both within and beyond their conservation areas, as well as in farmers' fields. Indonesia's Ministry of Environment and Forestry has undertaken some work to prioritize Indonesia's CWR diversity to determine the distribution range of priority CWRs and ensure they are available to breeders to develop climate-smart varieties [2,23]; however, CWR checklists and databases are mostly developed within academic settings rather than being recognized or supported by the national authorities. Lack of baseline assessments and dependable tools for effectively monitoring PGRFA status are also constraints for in situ conservation and on-farm management. Consequently, in situ conservation has been limited to the setting aside and management of protected areas, such as nature reserves, wildlife sanctuaries, national parks, natural recreation parks, protected forests, river boundaries, germplasm areas and peat areas [12].

Recognizing the imperative to better document and conserve Indonesia's remaining agrobiodiversity, our study aimed to assess the diversity, conservation status and sustainable use of five globally important food crops with their center of diversity in Indonesia, namely cloves, nutmeg, rice, taro and yams. The five target crops continue to serve as vital food sources for a significant portion of the Indonesian population, ensuring food security and sustaining livelihoods. The assessment covered three provinces known for high diversity of the target crops, yet with different sociocultural and land-use contexts: Central Java, Central Kalimantan and the Maluku Islands. Mixed-method analyses were used to document what conservation efforts are in place in Indonesia and what is currently known of the conservation status of these target crops, both ex situ at facilities such as genebanks and in the field, as well as to identify knowledge gaps on how to better conserve the genetic diversity of these crops, including barriers to their greater promotion. Recommendations are provided to address identified barriers and further improvement for the conservation and use of Indonesia's unique agrobiodiversity, specifically for the five target crops in this study.

2. Materials and Methods

2.1. Target Crops: Rice, Taro, Yam, Clove and Nutmeg

Indonesia's most important cereal crop is rice, making up between 97 and 100% of urban and rural household consumption. Indonesia's history of rice production has been favored by its archipelago's rich ecosystem diversity, which, over time, has provided an enormous diversity of local rice varieties. Several wild rice species exist in Indonesia, namely *Oryza meyeriana* (Zoll. & Moritzi) Baill., *O. granulata* Nees ex G. Watt, *O. longiglumis* Jansen, *O. officinalis* Wall. ex Watt, *O. ridleyi* Hook.f., *O. rufipogon* Griff. and *O. schlechteri* Pilg. in West Java [2].

As in other regions, rice genetic diversity conservation is also ensured through small-scale farmers selecting, cultivating and nurturing their favorite cultivars [24]. For example, in Central Java, farmer groups including the Kelompok Tani Bina Sari Alam in Cipari, Cilacap, continue planting several local rice varieties (e.g., *mentik wangi*, *mentik susu*, *rojo lele*, *sintanur* and *lembayung* red rice).

Indonesia is one of taro's centers of origin, as well as the center of taro domestication, and once harbored a wide range of taro genetic diversity and morphological variation [25]. Natural populations of wild taro are still found growing on roadsides, field edges or abandoned cultivated areas and contribute to the calorie intake of populations and customary (traditional) communities living in remote areas.

Yam, like taro, was once used in Indonesia as a rice substitute, particularly in Maluku, Sulawesi, Lesser Sunda and Central Java [26,27]. Yam, *Dioscorea alata*, *D. esculenta*, *D. aculeata* Balb. ex Kunth, *D. hispida*, *D. bulbifera* L. and *D. pentaphylla* L. are all found in Indonesia, with 50 different cultivars identified in Central Java and 100 cultivars identified in the Maluku Islands [26,27]. *Dioscorea alata* and *D. esculenta* are by far the predominant species, presenting the highest degree of variation. As a perennial root crop that does not rot if left unharvested, yam represents an important food reserve and continues to be of primary importance in the diets of forest-dwelling and rural communities [28]. Customary communities such as the Kanum tribe living in Merauke, the Papua tribe and the Sentani tribe of Jayapura between them are known to maintain in excess of 30 local yam varieties [29].

Clove is a perennial spice crop native to the Maluku Islands in eastern Indonesia. It has been cultivated and harvested in these islands for generations for its unopened aromatic flower buds and holds high economic value. Clove farmers can earn around USD 5.6 per dried kilogram, although prices can fluctuate depending on production and supply (field observations). The islands are still important centers for clove production and harbor a high diversity of clove germplasm [30,31], including unconfirmed reports of cloves growing wild in the forests [32]. Local cloves, native to North Maluku, include the *Afo 1*, *Afo 2*, *Tibobo*, *Tauro*, *Dokiri* and *Leaf Buntal* [33,34]. The *Sibela* and *Indari*, also found on North Maluku, are considered wild forest types [31]. In addition, farmers have planted domesticated varieties including the *Zanzibar*, *Siputih*, *Sikotok* and *Ambon* [34].

Nutmeg is also native to Indonesia and specifically to the Maluku (Moluccas) archipelago [35,36]. This tropical evergreen tree, which can reach a height of 10 m, is better known for producing the two spices nutmeg and mace. The aril, from which mace is derived, is an edible, fleshy appendage that partly or entirely covers the seed, which is ground to produce nutmeg powder [37]. With a volume of 22.821 tonnes produced in 2020 for the export market, Indonesia's nutmeg industry was valued at around USD 158 million in 2020 [38]. In Central Maluku, other parts of the fruit are central to cottage industry and are processed into candy, pickles, nutmeg wine and jam. Nutmeg seeds are also sometimes distilled to make nutmeg oil, which contains the component myristicin, a natural compound that has been traditionally used in medicine for its psychoactive properties and in plant protection due to its insecticidal and antifungal effects [37,39].

2.2. Target Provinces

Three project sites were selected in distinct geographical locations representing the main ecoregions of Indonesia and containing the greatest landscape, economic and cultural diversity, as well as diversity of land-use trends and potential drivers of PGRFA conservation or loss (Figure 1). Their location, at the intersection of four tectonic plates and two continental blocks, makes the Maluku Islands (or Moluccas) geologically unique. This archipelago, comprising 805 islands, is predominantly mountainous, featuring only a few coastal plains. This geographic diversity has given rise to an exceptionally high diversity of plant species and genetic resources. In contrast, lowland and inland montane rainforests characterize the island of Kalimantan (the Indonesian portion of Borneo), which is home to many different ethnic communities. Much of the original forest cover has been replaced with oil palm plantations, with only 54% of natural forests remaining [40]. The last island, Java, retains areas of montane rainforests along with drier, semi-evergreen rainforests. The high human population density that characterizes the island provides market, job and income opportunities from PGRFA conservation and sustainable use. Within these locations, North Maluku, Central Kalimantan and Central Java were chosen as target provinces due to the reported presence of the five priority species and to capture the greatest possible diversity of the five target crops (Figure 1).

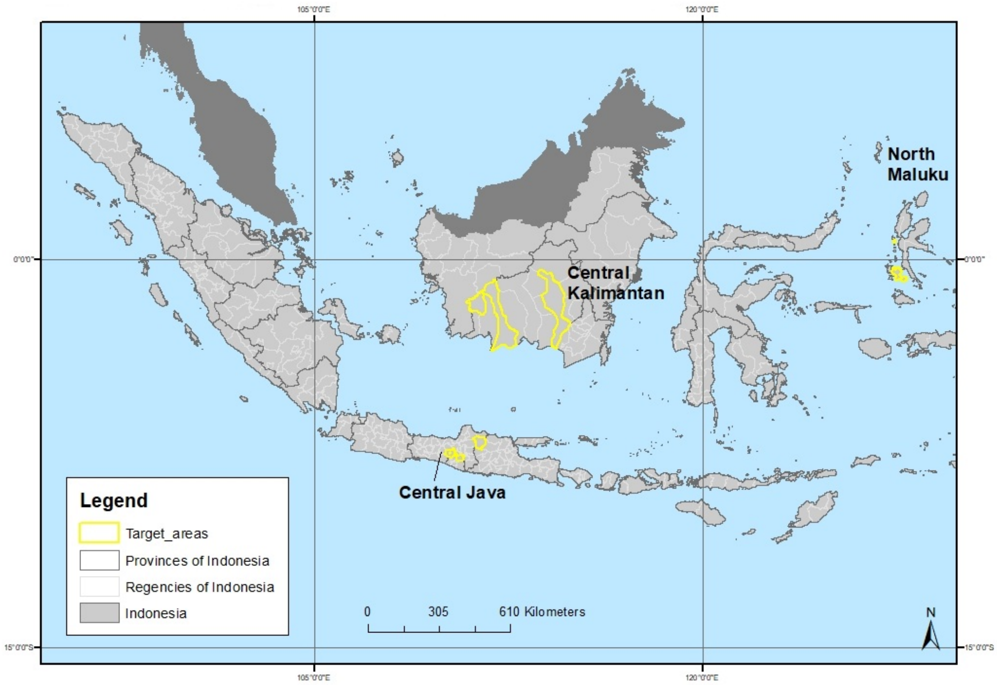

Figure 1. The three target provinces selected for the study and the target sites and locations within those provinces. Source: Bioversity International, 2021.

2.3. Methods

The assessment combined multiple methods and information sources, recognizing that information could be scattered and/or resting with a broad range of stakeholders. Three distinct activity types were applied to collect data at the national level and within the three target provinces between February and May 2021 (Table 1): (i) desk reviews on target species and the study sites were conducted through inclusive national and subnational multi-stakeholder consultations; (ii) national and international expert consultations to identify knowledge gaps and validate the literature review findings and gain insights into other information to be collected in the field; and (iii) baseline field assessments in

17 villages across the target provinces, using focus group discussions (FGDs) and rapid field observations.

Table 1. Activities used for information gathering at international, national and subnational level.

Activities	Level	Objectives	Informants
1. Literature review on target species and study sites (desk review)	National, provincial	Gather information on the following: • Policies, programs and awareness • Target species conservation status and use • Characteristics of the project sites and agroecosystems • Key knowledge gaps to be addressed via expert consultations and field assessments • Key experts to consult	N/A
2. Stakeholder and expert consultations	National, provincial	• Validation of literature findings • Address and refine knowledge gaps from literature review • Insights on other key information to be collected in the field	One national online workshop with 76 participants from government agencies, research institutions, academia and civil society. Three provincial online workshops including 96 participants from government agencies, research institutions, academia and civil society.
3. Baseline field assessments	Provincial, district (regency)	• Mapping of key stakeholders and their capacity, including socioeconomic and gender characteristics and roles • Plant diversity and use assessment • Reasons for cultivation and use or abandonment • Value chain assessment • Assessment of threats, barriers to adoption and opportunities for the target crops' conservation	Central Java: Five public and three civil society organizations, five private sectors actors; FGDs, interviews and site visits in 12 communities involving village and cultural leaders, farmers and extension officers. Central Kalimantan: Four public and one civil society organizations; FGDs. North Maluku: Seven public and four civil society organizations; two private sector actors; FGDs, interviews and site visits in five communities involving village leaders, farmers and extension officers.
4. Validation workshop	National	• Validate findings of provincial workshops and field assessments • Refine recommendations with stakeholders	One online workshop with 33 participants from government agencies, research institutions, academia and civil society.

2.3.1. Literature Review

A literature review was undertaken to understand the broader policy context that underpins the conservation of PGRFAs in Indonesia and to gain information on the target species' conservation status.

2.3.2. Expert Consultations

A total of 117 stakeholders, including those at the national level and from the three target districts, were consulted either virtually or through field assessments, with a nearly equal gender distribution of 51% women and 49% men. Most key informants were local government experts (64), highlighting the potential to more effectively involve data holders such as local communities, research centers, universities, NGOs and private sector companies. Most information gathered was shared during subnational online workshops (74 participants) and through virtual and face-to-face FGDs (25 participants). The key topics discussed varied depending on the themes and locations, ranging from Indonesia's agroecosystems and details about the traditional knowledge, processing, marketing and consumption of the target crops and their wild relatives to bioprospecting. Additionally, the discussions helped to map the relevant policies and institutions within the study sub-districts and identify programs, threats to and opportunities for the conservation of the target crops in each location.

2.3.3. Field Assessments

Between 19 April and 21 May 2021, 11 field assessments of approximately 4 days each were undertaken in select districts within two to three regencies in each of the three target provinces (Figure 2): Blora, Klaten and Magelang in Central Java; Kapuas, Lamandau and Seruyan in Central Kalimantan; and South Halmahera and Tidore in North Maluku. The field assessments consisted of FGDs, interviews and observations through visits to farms and small agrifood businesses, all of which yielded information on local varieties of the target crops. Key informants included farmers and custodian farmers, community and cultural leaders, food retailers and agricultural extension officers as well as representatives from the districts' agricultural and food security agencies, universities and local NGOs.

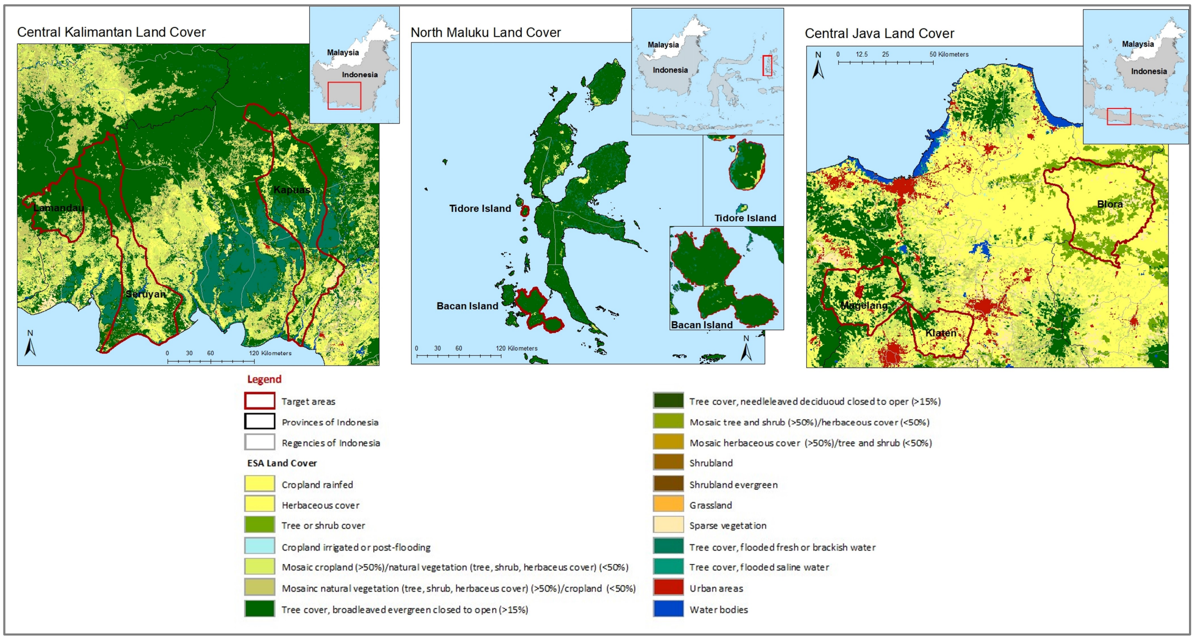

Figure 2. Land cover maps identifying the districts (outlined in red) where the field assessments were conducted within the three target provinces of Central Kalimantan, North Maluku and Central Java. Source: Bioversity International, 2021.

Most of the findings presented in this article for North Maluku and Central Java were collected during field assessments. Due to COVID-19 travel restrictions in Central Kalimantan, most of the findings included in the study were collected using online FGDs held in May 2021.

2.3.4. Validation Workshop

A national validation workshop to review findings from the field assessments was held virtually on 7 February 2022, bringing together key national and international stakeholders. Hosted by the Indonesian Center for Research and Development of Agricultural Biotechnology and Genetic Resources (ICABIOGRAD), the workshop was attended by 33 participants, including from the Indonesia office of the Food and Agriculture Organization of the United Nations (FAO ID), 12 agencies under the Ministry of Agriculture/Indonesian Agency for Agricultural Research and Development, the Provincial Commission on Biogenetic Resources (KOMNAS SDG), reserve stations and Bioversity International. Results of the field assessments were considered to provide a solid basis for developing a strategy to tackle the challenges hindering the effective conservation and sustainable use of PGRFAs in Indonesia, namely (1) the lack of coordinated policy support for PGRFAs; (2) limited institutional and community capacity for the sustainable use of PGRFAs; (3) restricted access to plant genetic material and associated information; and (4) agreement on the use and sharing of benefits deriving from PGRFAs (access and benefit sharing).

3. Results

The extent of the target species' collections—as reported in the literature and expert consultations—is presented in Table 2, highlighting ongoing efforts, especially for rice and taro. We found no evidence of clove or nutmeg field collections.

Table 2. Known collections of some of the target crops conserved in Indonesia.

Crop	No. of Accessions in Field Collections	Type
Rice (*Oryza* spp.)	10,092	Seed collection
Taro (*Colocasia esculenta* L. Schott)	245	Field collection
Taro (*Xanthosoma* sp.)	126	Field collection
Bitter yam (*Dioscorea hispida* Dennst.)	14	Field collection
Lesser yam (*Dioscorea esculenta* (Lour.) Burkill)	17	Field collection
Water yam (*Dioscorea alata* L.)	20	Field collection

Source: [41,42].

The results of the field assessments and key informant interviews revealed a high diversity of ethnovarieties by target crop. Provinces with the highest diversity were Central Kalimantan for rice (seventy-two varieties), Central Kalimantan for taro (nine), Central Java for yam (nine) and North Maluku for clove (two) and nutmeg (eleven) (Table 3).

Table 3. Ethnovarieties of the target crops identified through field assessments and interviews by geographical location. An ethnovariety associated with two or more sites within the target provinces was counted only once.

	Rice	Taro	Yam	Clove	Nutmeg
Central Java	**15**	**8**	**9**	**1**	**1**
Blora	6	2	3	-	-
Klaten	6	-	2	-	-
Magelang	3	6	4	1	1
Central Kalimantan	**72**	**9**	**2**	**-**	**-**
Kapuas	13	3	-	-	-
Lamandau	49	5	1	-	-
Seruyan	10	1	1	-	-
North Maluku	**4**	**2**	**4**	**2**	**11**
S. Halmahera	1	-	2	1	5
Tidore	3	2	2	1	6
Total	**91**	**19**	**15**	**3**	**12**

3.1. Rice (Oryza spp.)

3.1.1. Gaps in Active Collections

Exploration and collection of rice germplasm started in 1972 with increased efforts undertaken in the mid to late 1980s and 1990s in collaboration with the International Rice Research Institute (IRRI), the Department of Food Crops and Agriculture, non-governmental organizations (NGOs) and farmers across most of Indonesia. Today, there are a total of 10,092 rice accessions (Table 2), some 6092 held by the Indonesian Centre for Rice Research [42] and a further 4166 held by the Research Center for Food Agriculture, National Bureau of Research and Innovation (Badan Riset dan Inovasi Nasional, BRIN), including 54 red rice varieties collected from across Indonesia (former ICABIOGRAD collection) [43].

While substantial, the red rice collection at BRIN is only a small fraction of the red rice that continues to be grown by local communities. It has become clear that formal and informal collections of PGRFAs need to be recognized and instituted [44], shifting from a centralized approach—that requires considerable funding—to a decentralized collection program involving multiple stakeholders, including farmers [45]. Although some local landraces were used in the 2004 post tsunami aftermath to breed high-yielding varieties adapted to biotic and abiotic stresses [46,47], the potential of many of these landraces remains unexplored, particularly in isolated areas of Kalimantan, Sulawesi and Irian Jaya as well as some of the very small islands [48]. There have been recent efforts to establish a foundation for ex situ conservation of swamp rice (107 swamp rice accessions, 7 of which are from Central Kalimantan) [49]. While studies to date have made no mention of wild relatives of rice in Central Kalimantan, the study revealed the presence of *umbang* rice wild relatives in several Lamandau Regency (Central Kalimantan) villages, warranting verification.

3.1.2. Diversity Observed in Field Assessments

The online consultations and field assessments concluded that significant rice diversity is still preserved in the target provinces, with local rice varieties mostly conserved on-farm. In total, 91 rice ethnovarieties were observed during the field assessments, mostly in Central Kalimantan (72) and Central Java (15) (Table 3).

In Central Kalimantan, the indigenous rice cultivars observed were generally tall and husked, characterized by small grains, planted in dry areas (or *padi huma*, which can be translated to 'dry field rice' or 'uphill rice') and normally harvested once a year (Figure 3). Local farmers were also observed planting a single rice variety per plot (*petak sawah*). A total of 72 rice varieties were identified across the three regencies (S1), with many maintained by the customary communities (or *Masyarakat Adat*) of the Dayaks and Malays. Traditionally, each variety serves a specific purpose, whether for rituals, therapeutic use or protection against the evil eye. In the highlands of Lamandau, the renowned *dara ma'anya* cultivar endures (lit. 'Maiden of Ma'anya' from the legend of Mother Rice of the Manyaan Dayak tribe living in Central Kalimantan). Although the grains of *dara ma'anya* are small and hard, the rice's distinct flavor makes it a favorite among the inhabitants of Lamandau. Despite this, its limited market appeal [prices reported during field assessments ranged between IDR 25,000 and 30,000 (USD 1.8–2.1) per kilogram] has allegedly led many farmers in Central Kalimantan to replace this variety with introduced cultivars, particularly those with a higher market value.

Figure 3. Rice varietal diversity observed during field assessments in Batu Ampar sub-district, Seruyan Regency, Central Kalimantan. From left to right: (**a**) padi ungu; (**b**) padi garu; (**c**) padi sambung; (**d**) padi udang; (**e**) padi garagai; and (**f**) padi gagak. Source: Hajianur, S.P., BPP, Batu Ampar, Seruyan.

In Central Java, 15 traditional varieties and landraces were documented as surviving across the target regencies (S1), including the ancient *mentik* red rice cultivars in Magelang, the non-glutinous red rice *padi merah* in Blora and the *rojo lele* rice in Klaten (Figure 4). These varieties are mostly maintained by the Samin tribe and are conserved for their perceived medicinal properties. Research has demonstrated that *padi merah* and *padi hitam* (non-glutinous black rice) have a lower glycemic index and are rich in antioxidants [50]. Black rice contains many phytochemical compounds that could contribute to its use as a functional food with the potential for lowering the risk of hyperlipidemia and hyperglycemia and for cancer prevention [51].

Figure 4. The red rice cultivar *padi merah* grown by the Samin community in Blora, Central Java Source: NGO Duta Blora Indonesia.

In North Maluku, traditional cultivars (*Oryza sativa* var. *javanica* Körn.) such as *padi pulo* (glutinous rice), *padi hitam* (black rice) and *padi merah* (red rice), cultivated up until the 1980s, have almost completely disappeared from the Tidore and Bacan Islands of South Halmahera [52,53]. When needed, North Maluku imports improved and local rice varieties primarily from East Halmahera, where most of the region's rice production occurs.

Expert consultations showed that, in total, 28 local registered varieties exist on the other North Maluku regencies of East, North and West Halmahera, including *padi menyan* (No. PV: 487/PVL/2017), *padi taraudu* (No. PV: 689/PVL/2018), *padi herana* (No. PV: 690/PVL/2018), *padi misiri* (No. PV: 691/PVL/2018), *padi melewa* (No. PV: 754/PVL/2018) and *tamo siang* (No. PV: 755/PVL/2018). Key informants reported the cultivation of the local cultivar *beras asli* (real rice) by the Togutil and Tobelo people in North Halmahera Regency. Research carried out in 2014 to explore, make an inventory of and evaluate the performance of local rice varieties in 17 districts in North Maluku identified four local rice varieties, namely *merah*, *molulu*, *taraudu* and *manyanyi*, in need of protection for rice improvement [54]. *Kayeli* rice, a rare local variety originating from West Halmahera Regency, has high production potential [55,56]. It has a fluffier texture and a distinctive fragrant aroma; however, its morphological and agronomic characteristics and production potential are not fully explored.

At the time of this study's field assessments in 2021, key informants did not provide any information regarding the conservation status of local rice cultivars growing in the study sites. As a result, most local rice cultivars are thought to be inadequately conserved or maintained outside of their native habitats.

*3.2. Taro (Colocasia esculenta (*L.*) Schott)*

3.2.1. Gaps in Active Collections

In 2010, the collection in Cibinong, Bogor, contained 200 distinct taro morphotypes [57] and Indonesia was the largest contributor of taro accessions to the Centre for Pacific Crops and Trees (CePACT) [58]. A collecting mission conducted in 2014 across nine regencies in Central Java to assess taro diversity discovered 28 different types but estimated this diversity as constituting only 60% of the total taro diversity in the region [59].

No comprehensive geographical surveys have been undertaken on wild taro diversity, except for limited studies carried out in Maluku, and there have been none specifically on taro [60]. Because they contain more allelic diversity, wild taros are genetically more interesting than the cultivated forms, which, on the other hand, contain larger agromorphological variability [61,62]. Thus, distinct, locally adapted populations of *Colocasia* (local ecotypes) might become extinct before they are found or described. Rahman et al. (2019) [2] identified two CWRs of taro (*Colocasia esculenta* and *C. gigantea* (Blume) Hook. f.) as being priority species for in situ conservation in Indonesia.

3.2.2. Diversity Observed in Field Assessments

Similarly to rice, the consultations and field assessments in this study highlighted that significant amounts of taro diversity continue to be maintained in the target areas explored (Tables 3 and S2). In Central Java, the greatest diversity was observed in Magelang Regency, particularly in the foothills of the active stratovolcano Mount Merapi, where ashy deposits have provided long-term benefits to soil fertility and created a conducive environment for taro cultivation [63]. Popular, local taro cultivars in Magelang and Blora at the time of the assessment were *talas beneng*—characterized by reddish-brown leaf sheaths and petioles—and *talas benek,* which are grown along rice paddy dikes (Figure 5). Due to its pleasant taste and texture, *talas benek* is reportedly eaten regularly by local communities and is found on sale throughout Magelang. Another local favorite was *talas kasduto* (which means "preferred taro" in Javanese). Also planted along paddy field dikes, the plant resembles *talas beneng,* except for its bright, greenish-white leaf sheaths and petioles and smaller tubers. Also present in the foothills of Mount Merapi were the extremely rare *talas wungu* or purple taro, characterized by white tubers with noticeable purple tinges, and *talas banyu*, or "water taro", usually found growing in wild or semi-wild populations on the banks of small creeks or rice-field dikes. The plant produces a single, small tuber and leaves that cause extreme itching when touched. It is normally harvested from the wild and sold on roadsides at IDR 30,000 (USD 2.00) per sack.

Figure 5. From left to right, local taro cultivars observed in Central Java: *talas beneng* (black form); *talas benek*; and the unidentified taro *talas* "Borobudur" of the Salaman sub-district in Magelang. Source: Bioversity International, 2021.

Two unidentified local taro cultivars were found in Central Java during the field assessment. In Magelang, in Banyudono village, a local farmer continues to grow a local high-yielding taro cultivar that reportedly matures in 7–8 months, with the corms attaining 1–2 kg in weight. The second unknown cultivar was found in the Salaman sub-district and had bright, whitish-green leaf sheaths and petioles with pinkish-white tints (Figure 5—right image). The corm was globose (rounded) to depressed, with white to pinkish-white flesh. This local cultivar was temporarily named "Borobudur", due to its resemblance to a relief depicting taro carved in the nearby Borobudur temple. Farmers and local communities in Central Java were unaware of any wild relatives of taro in or around their villages, or any specific conservation measures or practices for these.

In Central Kalimantan, Lamandau Regency was found to house the richest taro diversity (Table 3). At least five indigenous taro cultivars known locally as 'keladi' belonging to *Colocasia esculenta* were identified (Figure 6) (S2). Commonly planted in shallow peat land or slopy mineral soils, *keladi korup matah merah* and *keladi korup matah kuning* are two local favorites. Used in home industries for preparing different snacks, the tubers of these cultivars can also be eaten fresh due to their low oxalate content. They were found on sale in traditional markets, with prices per tuber varying between IDR 4000 to 5000 (USD 0.3−0.35) for *keladi korup matah merah* and IDR 10,000 (USD 0.6) per kg for *keladi korup matah kuning*. However, the tubers are mostly grown for domestic consumption.

Figure 6. Taro cultivars: (**a**) *keladi korup matah merah*; (**b**) *keladi korup matah kuning*; (**c**,**d**) *keladi Delang* characterized by a small, light corm with yellow flesh. Source: Susilawati, S.P., NRIA/BRIN, and Yusi Subadri, S.P., Agriculture Office, Lamandau Regency, Central Kalimantan, 2021.

Similar in appearance to the more common *keladi korup matah merah*, the smaller *keladi korup matah Batang Kawa* is characterized by dark, reddish-brown petioles and leaf sheaths and is still grown in the sub-district of Batangkawa. *Keladi Delang* is still cultivated in the sub-district of Delang and can be recognized by its small, light, yellow-fleshed corms, which are bite-sized and practical to eat, and are the smallest corms in the genus (Figure 6—bottom). *Keladi Lopus* (Figure 7), named after Lopus village, has conspicuous black petioles and leaf sheaths, while the corm is white to yellowish-white.

On the islands of Tidore and South Halmahera, in North Maluku, taro was rarely found cultivated and was mostly harvested from the wild, particularly in forest areas where it continues to grow in semi-wild populations. When grown in home-gardens, taro is reportedly used for home consumption and seldom used to create value-added food products. In Jaya village, residents referred to a taro cultivar known locally as *komo*, characterized by a single straight corm and identified as *Colocasia esculenta*. Although found on sale in markets in Tidore, taro is mostly imported from the neighboring island of Halmahera. On both islands, local cultivars in the market were found supplanted by American taro (*Xanthosoma sagittifolium* (L.) Schott) varieties known locally as *bete,* which are either white or purple-fleshed.

Figure 7. The taro cultivar *keladi Lopus,* exhibiting conspicuous black petioles and leaf sheaths. Source: Susilawati, S.P., NRIA/BRIN, and Yusi Subadri, S.P., Agriculture Office, Lamandau Regency, Central Kalimantan, 2021.

Our assessment suggests that today, traditional taro varieties are seldom cultivated due to local varieties having been replaced with higher-yielding, improved cultivars, lack of planting material, their toxicity (e.g., high levels of calcium oxalate) and possibly lost traditional knowledge about their cultivation and preparation. The species continue to grow in wild environments and forest areas but are threatened by habitat destruction and fragmentation.

3.3. Yam (Dioscorea spp.*)*

3.3.1. Gaps in Active Collections

Wild yams are naturally tolerant to drier climates and are therefore a potential source for breeding new drought-tolerant varieties, further emphasizing the need to document and characterize them. In a study inventorying CWRs in Indonesia, Rahman et al. (2019) [2] identified 23 species of priority yam CWRs that could be used for breeding purposes. Yet, rapid genetic erosion of yam germplasm is observed among and within species [27]. Earlier studies that characterized 63 yam accessions noted a 75% genetic similarity between yams collected from different Indonesian provinces [64]. In Papua province, eight local yam accessions are conserved in the field genebank of the Papua Agricultural Technology Research Center (BPTP) [65].

3.3.2. Diversity Observed in Field Assessments

Expert consultations and field assessments revealed that many local cultivars exist within the project sites, but they are not adequately conserved and maintained (S3). The lesser yam (*Dioscorea esculenta*) was reported to be widespread in Central Kalimantan, particularly in Lamandau Regency, where it is occasionally intercropped with plantation trees and planted in shallow peatlands, slopy mineral soils and rice-field embankments. According to our informants, it is mostly grown for domestic consumption and rarely sold. In Seruyan, at least two yam species were reported by local farmers: *uwi putih* (white yam) and *uwi ungu* (purple yam). *Uwi ungu* is most probably *Dioscorea alata*, while for *uwi putih,* no specimens were available for identification.

In Central Java, yam cultivation and use vary greatly across the regencies. Aside from the widespread Asian bitter yam (*Dioscorea hispida*), known locally as *uwi gadung* and used for making 'gadung' chips, each study area revealed its own distinctive yams. Magelang, in the Salaman sub-district, exhibited the highest varietal diversity. Here, important local yam cultivars included a white-fleshed cultivar of lesser yam (*Dioscorea esculenta*), known locally as *gembili*, and two cultivars of greater yam (*D. alata*): *uwi ulo* (snake yam) and *uwi wungu* (purple yam) (S3). Magelang was also found to be home to several interesting local cultivars of lesser yam (*D. esculenta*) such as *tapak celenk*, which literally means "boar's hoofprint", referring to the tuber's unique shape (Figure 8). Both *tapak celeng* and *uwi wungu* are reportedly planted and sometimes sold in local markets but are more commonly grown for domestic consumption. Farmers in Kalirejo village also reported the existence of another local purple yam cultivar characterized by conspicuous purple flesh—the true *uwi wungu*—that is now rarely found and grown. In Klaten, farmers reported seldom cultivating yams, and information on tuber crop diversity in the area was limited [pers. comm. Head of the Agricultural Office, Klaten Regency]. This is likely due to the inhabitants' preference for rice and particularly the *rojo lele* rice cultivar that dominates as the staple of choice. Nevertheless, a couple of interesting local endemics, possibly belonging to *D. esculenta*, were recorded during the field assessments: *gembili ketan* (glutinous yam), characterized by a sweet and glutinous flesh, and *kereweng*, which can be harvested twice a year. The latter is very popular in Klaten and market demand is high, with tubers reportedly usually sold out within a few hours. Of the three studied regencies in Central Java, Blora was the least interesting in terms of yam diversity, with few local cultivars recorded during field visits. Overall, in Central Java, local awareness of the decline of tuber crops remains limited.

Figure 8. Local cultivar of lesser yam (*Dioscorea esculenta*) found in Magelang, Central Java, and known locally such as *tapak celenk*, which literally means "boar's hoof print", referring to the tuber's unique shape. Source: A. Keim, BRIN, 2021.

In North Maluku, FGDs with the Agriculture Agency revealed that yams have ceased to be grown and eaten on Tidore and South Halmahera Islands. The two species mentioned by key informants during the field assessments refer to lesser yam (*Dioscorea esculenta*), known locally as *brisi*, and Asian bitter yam (*Dioscorea hispida*), known locally as *belah*, which are now only found growing in wild populations (S3). Residents regard yams as poisonous plants, fit for pig feed. They are never eaten, nor does there appear to be any cultural tradition of doing so.

3.4. Clove (Syzygium spp.*)*

3.4.1. Gaps in Active Collections

The Maluku Islands are estimated to harbor unidentified species of cloves (*Syzygium* spp.) [66]. In the late 1980s, the establishment of permanent clove germplasm collections was proposed to conserve the species' genetic diversity and to "facilitate screening programmes for disease resistance and other agronomically desirable traits" [32]. More recently, genetic sequencing data were used to study the distinctiveness of Maluku cloves [34]. This reference information can be used for further conservation and breeding efforts targeting this species. Clove is a climate-sensitive crop; it will therefore be important to identify, characterize and select the most promising wild types in terms of performance traits and adaptation to climate change.

3.4.2. Diversity Observed in Field Assessments

Cloves were not found in field assessments in Central Kalimantan. In Central Java, they were only found in Magelang. Previously cultivated in the province, clove trees had almost vanished from smallholder production systems, reportedly because they lacked commercial value. We observed, however, that clove trees were being reintroduced to farms, albeit on a limited scale, due to their increasing market value. Furthermore, in response to the economic slump imputable to the COVID-19 pandemic, entrepreneurs were returning to their ancestral homes to manage inherited productive clove farms. In doing so, they were employing pesticide-free traditional management practices, including the use of cattle manure and compost as fertilizers. However, no local cultivars were identified.

As the center of origin of many spices, the Maluku Islands remain a key region for clove cultivation. Cloves are grown and maintained by many farmers in almost all regencies of the province, occupying both small to very large land areas. Despite the widespread cultivation of the 'Zanzibar' clove variety—a cultivar introduced from Tanzania and characterized by a higher eugenol content—some local cultivars were found. In South Halmahera, Bacan Island harbors two unique clove cultivars. The first is *sibela bunga cengkeh* (literally meaning "clove flower of Sibela"), named after the location where it was found near the Mount Sibela Protected Area (Cagar Alam Gunung Sibela) in the southwestern part of the island. The second indigenous cultivar is the *cengkeh bunga mera* or "red flower clove", commonly found throughout the island. These indigenous clove cultivars were reported as threatened by illegal logging and unsustainable management practices.

3.5. Nutmeg (Myristica spp.*)*

3.5.1. Gaps in Active Collections

Similarly to cloves, the presence of nutmeg is largely restricted to the Maluku Islands out of the three study areas (S4). Several original nutmeg taxa have been known to exist in Central Kalimantan in the forested areas of Lamandau, namely *Myristica beccarii* Warb., *M. cinnamomea* King, *M. iners* Blume, *M. lowiana* King, *M. maxima* Warb. and *M. smythiesii* J. Sinclair. However, there have been no recent explorations to determine the current presence of these taxa in the area.

3.5.2. Diversity Found in Field Assessments

In Central Java, two cultivars are known to exist, the more common *Myristica fragrans* Houtt. and the endemic Javanese nutmeg (*M. teysmannii*), which is said to grow only in the wild now. However, we did not find either species during field assessments. Key informants reported that climatic conditions in Blora and Magelang were unsuitable for the species. Similarly, in Central Kalimantan, nutmeg was unknown locally, despite the evidence of original taxa in the area.

In Tidore, Maluku Islands, nutmeg has never been identified in the wild and is only known as a domesticated and cultivated tree. It is the most important crop cultivated in the foothills of Mount Kie Matabu (Mount Tidore). Seven nutmeg taxa were identified in Gurabunga as part of the field assessment (Figure 9). Five were classified as *Myristica fragrans* (although one with a noticeably elongated fruit and seed might be *M. argentea* Warb.). Striking in appearance, due to their bristly exocarps, the two remaining taxa were classified as *Myristica fatua* Houtt. The two *M. fatua* taxa can be differentiated by hair thickness, with one taxon (Figure 9A) being less hairy than the other (Figure 9B). Morphological variations in *M. fatua* were never reported prior to this study.

Figure 9. The seven nutmeg taxa (*Myristica* spp.) identified as part of our study's field assessment near Gurabunga village in Tidore. Samples of *Myristica fatua* are indicated with the letters (**A**,**B**), while other specimens belong to *Myristica fragrans*. Source: Bioversity International, 2021.

In the village of Jaya, Tidore, four taxa were reported, known locally as *pala*, *pala bulu*, *pala buah kecil* and *pala buah lonjong* (S4). We identified *pala* as *Myristica fragrans*, *pala bulu* as *M. fatua*, *pala buah kecil* as *M. succedanea* Blume and *pala buah lonjong* as *M. argentea*. These findings are in keeping with previous studies on nutmeg in the area. The presence of *M. argentea* (or Papuan nutmeg) in Maluku Islands can be traced back to the biogeographical history of the Maluku Islands that were connected to mainland New Guinea in the Pleistocene [36,67].

Just north of Tidore, on Ternate Island, we found a distinctive nutmeg cultivar characterized by a white aril/mace (Figure 10). However, the cultivar is likely *Myristica fragrans*, consistent with previous findings from the molecular characterizations of Tidore's nutmeg morphotypes. *M. fragrans*, commonly referred to as *banda* nutmeg in international trade, exhibits remarkable morphological variations, including fruits with white mace [68].

Figure 10. A distinctive nutmeg cultivar found in Ternate (probably *Myristica fragrans*) characterized by a white aril/mace. Source: Bioversity International, 2021.

The regency of South Halmahera is also rich in nutmeg diversity. Although improved cultivars (e.g., *banda* 1, *tidore* 1, *tobelo* 1, *ternate* 1 and *makian*) are most popular, there is reportedly still considerable diversity to be found, particularly on the slopes of Mount Sibela, on Bacan Island. Considered the center of origin of nutmeg and clove germplasm, Mount Sibela is a nature reserve characterized by moist tropical rainforest, with dense canopy cover; it is relatively isolated and therefore ideally suited to promoting speciation. The *mandaya* cultivar, for instance, is reported as growing in large numbers at an altitude of 900 masl. The nutmeg trees can reach a height of 30–45 m, with trunks measuring 30–80 centimetres in diameter. The tree is characterized by a reddish-brown bark (suggesting high tannin content) and the leaves are deep green, glabrous, large, wide, strong and rigid. The fruit is significantly larger than that of *M. fragrans* and is distinguished by a notably thick mesocarp. The exceptional size of *mandaya*'s fruit and the thickness of its mesocarp may indicate it as a potential new species (Figure 11). This hypothesis is supported by findings from Soenarsih et al. (2012) [67] who observed no phylogenetic resemblance of the species to *M. fragrans* and placed *mandaya* in a clade of its own. The taxon is provisionally identified as part of this study as *Myristica sibelaensis*. Unsustainable collection practices were reported to pose severe threats to the survival of the nutmeg variety *mandaya*. As its fruits are mainly harvested from wild populations, farmers felled the trees to speed up collection. Planting is typically very high density, due to lack of expertise. Overcrowding causes nutmeg trees to compete for light and nutrients, leading to the plants' weakened health and poor growth.

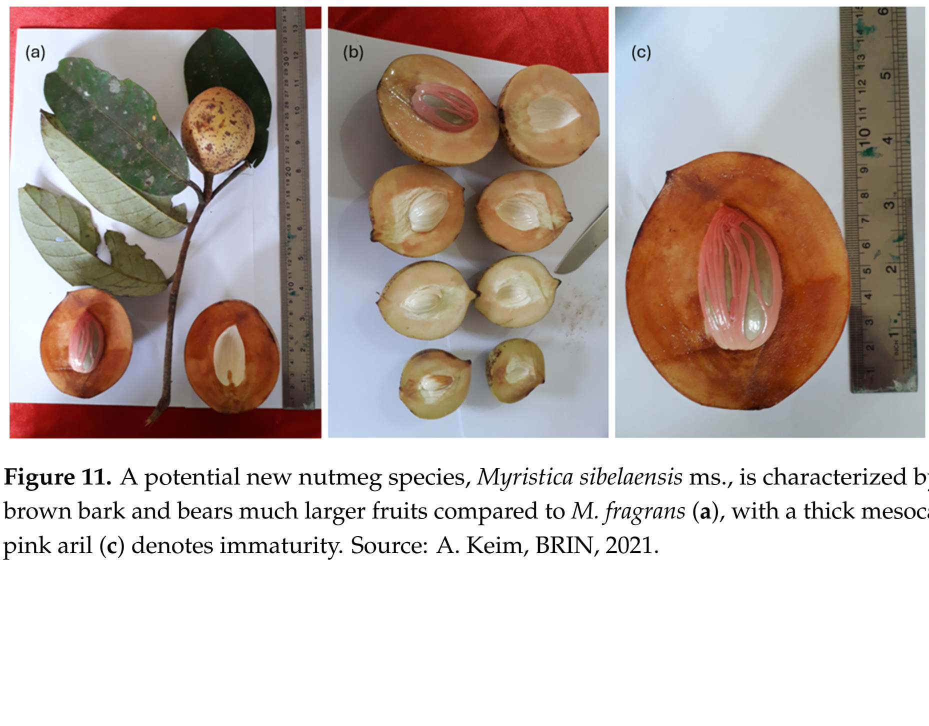

Figure 11. A potential new nutmeg species, *Myristica sibelaensis* ms., is characterized by a reddish-brown bark and bears much larger fruits compared to *M. fragrans* (**a**), with a thick mesocarp (**b**). The pink aril (**c**) denotes immaturity. Source: A. Keim, BRIN, 2021.

4. Discussion

The systematic documentation of the erosion of Indonesia's PGRFAs has yet to be undertaken. The present study shows that the country continues to have significant potential for conserving agrobiodiversity through the cultivation of local crop varieties and CWRs that are still found in farmers' fields. The findings are in line with previous studies of Indonesia as the center of diversity of rice, taros, yams, cloves and nutmegs. However, our study findings indicated that this diversity is being rapidly eroded and is scattered, cultivated and used by a limited number of predominantly traditional women and men. Despite their cultural, economic and nutritional significance, numerous barriers exist that hinder efforts to preserve these valuable genetic resources. The more prominent examples among these obstacles are outlined below.

4.1. Limited Institutional Capacity

Favorable policies and efforts targeting the ex situ conservation of PGRFAs and initiatives focusing on PGRFAs' in situ and on-farm conservation remain largely insufficient. On a positive note, Indonesia has designated institutes in charge of PGRFAs' on-farm conservation. The Assessment Institute for Agriculture Technology (AIAT) is responsible for monitoring on-farm conservation of PGRFAs [41]. The National Committee on Genetic Resources (KOMNAS SDG) has been encouraging the establishment of a Regional Committee on Genetic Resources in every province aimed at collecting and taking stock of regional PGRFAs. The Committee also coordinates stakeholders involved in in situ management, undertakes capacity building activities targeting breeders and seed growers and has established a national network on in situ management and genetic improvement to bolster in situ conservation of PGRFAs [1]. Yet, compared to the extent of Indonesia's PGRFA diversity, these efforts remain insufficient. Conservation programs often suffer from inadequate funding, lack of trained personnel and insufficient or inadequate infrastructure. This limits the ability of institutions to implement effective in situ and ex situ conservation strategies.

In Indonesia, the main mechanism for knowledge transmission to smallholder farmers is via the government's agricultural extension services, with a limited number of extension agents per province. Unfortunately, the online assessments undertaken as part of this study were unable to determine the capacity of extension services to transmit information on sustainably managing and conserving local varieties and CWRs. However, it is assumed that the knowledge shared is greater for mainstream crops. Generally, it was observed that information is lacking on the diversity of local species at both the provincial and regency level, and lack of genetic resources databases adds to the challenges of implementing conservation programs on the ground. In summary, policies and programs on the ground focus mainly on increasing production of mainstream crops and less on diversity, resilience and sustainability.

The lack of any conservation status assessment of traditional crops on-farm and the lack of reliable crop-specific production data at the national level make it difficult to quantify the decline of traditional crops [69,70]. Taro and yams lack any government-led monitoring and national statistics. Creating a national database for wild populations and local cultivars requires coordination and information sharing among the various institutions holding occurrence data, such as genebanks, herbaria, protected areas, research institutes and individual researchers. However, connections between organizations managing plant genetic resources, including CWRs, tend to be weak, and integrating the vast amounts of data across these institutions remains a considerable challenge [71]. However, efforts are underway to develop a genetic resources database that could handle future data on the target crops and other local varieties for better decision-making [72].

It is noteworthy that lack of research investments has had concrete impacts on the existing collections, namely a reduction in the national taro ex situ collections [58]. The ex situ conservation of vegetatively propagated species like taro is normally carried out in field genebanks where the plants are exposed and highly vulnerable to both abiotic and biotic stresses [25]. In the dry season, for instance, Indonesian genebanks are known to experience lack of water availability, leading to weed and pest control issues [41]. In 2010, the safety duplication rates of accessions in ex situ conservation facilities were reportedly low, with precise estimates made impossible due to lack of information and documentation by many genebanks [1]. This highlights the need for complementary in situ and on-farm conservation efforts.

To strengthen institutional capacity to conserve PGRFAs, we recommend the following:

- Promoting the development and/or inclusion of agrobiodiversity, resilience and sustainability concerns in relevant policies and programs (e.g., agriculture, environment, health, food security, tourism and education, for example, via public procurement).
- Collecting and analyzing data for the target species (and other agrobiodiversity of importance) and disseminating the data among relevant stakeholders and policymakers.
- Encouraging relevant government agencies to collect data and produce statistics on local agrobiodiversity.
- Developing new training materials, increasing the capacity of extension agents on the sustainable and resilient production of the target crops and exploring digital and private extension services.
- Setting up demonstration plots for farmers and providing training in extension services.

4.2. Changing Dietary Preferences

Across Indonesia, diets are shifting away from complex carbohydrates, fruits, legumes and vegetables towards more Western-style foods and the consumption of simple carbohydrates, fats and animal foods, particularly in younger generations [73]. Micronutrient deficiencies are on the rise among all age groups [74], undernutrition and overnutrition coexist in the same population [75] and limited progress has been made in reducing the impact of diet-related, non-communicable diseases [76]. As well as affecting the health of many Indonesians, the nutrition transition has contributed to neglecting traditional foods in diets, further undermining conservation efforts, as was also observed during the field assessments.

Taro, for example, has been gradually replaced by improved and exotic taro varieties, such as the Taiwan cultivar, or other starchy staples such as rice, maize, cassava and sweet potato [77,78]. Already more than 20 years ago, the Indonesian Institute of Sciences (LIPI) observed how rice was preferred over taro as a staple food, with rice being perceived as more prestigious by a sizable proportion of the population [79]. In the taro-growing centers of Indonesia—especially in Java, where taro is still grown as a cash crop, albeit to a limited extent—commercially superior varieties had already replaced local cultivars in 2010 [57]. Changes in food preferences and consumption patterns have especially driven yams into agricultural neglect with only pockets of smallholder farmers growing the species for cultural reasons [64]. Already in 2016, data from the Merauke Regency in Papua province revealed that the farm area allocated to growing local yams was significantly lower than the area devoted to taro and sweet potato cultivation [65]. Yams hold significant cultural value and are often used in weddings and in traditional ceremonies, for example, in Papua [28,65,80], but their widespread use as an ingredient is sometimes limited by the presence of anti-nutrients [81].

Where roots and tubers are still consumed, they are increasingly used to prepare unhealthy snacks that do not contribute to optimal health goals. In all three target provinces, fried taro and yam chips were by far the most prominent snack consumed. In Central Java, for example, the Sakinah Women Farmers and Wives Association produces chips from Asian bitter yam *gadung* (*Dioscorea hispida*). "Kripik gadung" or "gadung" chips are popular and considered premium chips in Java, and sometimes the price per kilogram is higher than chips made from introduced tuber crops such as potatoes (*Solanum tuberosum* L.) and sweet potatoes (*Ipomoea batatas* (L.) Lam.). In Maluku, nutmeg fruits are processed to make sweets and syrup rather than eaten raw.

Studies in Indonesia have shown household dietary diversity to be directly related to changes in production diversity at the household level [82]. In the case of tubers, for example, the probability that a household consumes the crop increases by 44% if produced by the household itself. This result is of particular importance given that tubers represent a good and cheap source of dietary energy and dietary fiber, while containing important micronutrients as well as antioxidative, hypoglycemic, antimicrobial and immunomodulatory properties. Like other crops, there is a large intra-species and inter-species variation in nutritional value depending on variety, location, soil type and agricultural practices. Although the Ministry of Health has issued dietary guidelines for the Indonesian population, they do not account for the country's diverse dietary practices among its more than 700 ethnic groups. There is a need for more tailored dietary guidelines that incorporate the use of traditional foods within healthy ethnic dietary practices and detailed studies of how they affect health status [83].

To maintain and encourage the consumption of traditional and local PGRFAs, we recommend the following:

- Assessing and describing the nutritional and health benefits of target species (and varieties therein) and disseminating the findings widely to stakeholders.
- Enhancing capacities for healthy processing and handling of the target crops, including developing and disseminating small-scale technologies (e.g., technology for nutmeg value chains, including pulp).
- Undertaking policy advocacy to systematically use local products made from target crops for meetings, events and gifts within the local government institutions, private sector and community.
- Supporting and scaling out school meal programs that incorporate local crops.

4.3. Economic Pressures and Market Barriers

Farmers often face economic pressures to shift from cultivation of traditional or local cultivars to more commercially viable crops. The lack of immediate financial incentives for growing diverse local varieties discourages farmers from maintaining these crops, leading to a decline in diversity. Our findings of the declining popularity of local rice varieties are in line with studies showing how farmers prefer to grow improved rice varieties due to their higher market value, shorter growing cycle and higher yields compared to their traditional counterparts [44]. Nevertheless, with increasing demand for organic rice, particularly from urban consumers, some farmer groups and cooperatives in Central Java commercialize organically grown local rice varieties such as *mentik wangi*, *mentik susu*, *rojo lele*, *sintanur* and *lembayung* [84].

Traditional taro cultivars are outcompeted by Japanese taro (*Colocasia esculenta* var. *antiquorum* (Schott) F.T. Hubb. & Rehder), known locally as *talas jepang*. This variety (known as "satoimo"), introduced from China and Japan, has a higher market value than local cultivars due to its high productivity and export value [85]. Farmers interviewed in this study in Central Java indicated their preference for planting only good quality and marketable cultivars such as *keladi putih*, *wangi* and *udang* to meet market demand. Without historical data for taro production and future market projections, producers and traders are unlikely to see economic potential in this crop. This negative feedback loop may be reinforcing the low visibility of taro, confirming it as an orphan crop [70]. An additional challenge is the lack of food processing capacity and technologies in the target provinces. Small-scale home industries—mostly run by women—are prevalent throughout the region and have the potential for growth and benefits from increased capacity and technical support.

To foster economic benefits from the use of PGRFAs, we recommend the following:

- Ensuring fair and stable prices for farmers along the value chain, including through developing producer organizations.
- Developing markets for and scaling up the production of successful products, and developing innovative and healthy food or health products and markets for them.
- Exploring new uses of waste and byproducts (e.g., compost production).

4.4. Habitat Loss, Land Degradation and Overexploitation

Rapid deforestation and the conversion of agricultural lands to commercial plantations or urban areas have significantly reduced the natural habitats where diverse local varieties thrive. Among the studied species and provinces, these threats particularly affect CWRs of all species, as well as traditional and local cultivars of cloves and nutmegs in North Maluku. For cloves, production pressures have resulted in unsustainable production practices and land degradation and deepen the productivity decline, despite increases in the land devoted to clove cultivation [33,86]. The same holds true for nutmeg [38]. Male nutmeg trees, which do not bear fruits, are reportedly "frequently cut down to reach an approximate ratio of ten females to one male... with detrimental effects on population panmixia" [87]. The one surviving nutmeg species in Central Java, *Myristica teysmannii* Miq. [88], is listed as endangered in the IUCN Red List of threatened species [89]. In the last assessment, carried out in 2018, its population was considered severely fragmented, due to the continuing decline in area, extent and quality of habitat. Threats to its survival included urbanization, logging and land clearance due to the expansion of agriculture and livestock farming. At the time, the author called for the enactment of conservation actions and further research [89].

Both clove and nutmeg are sensitive to climate change. Pests and diseases and extreme weather events such as droughts and excessive rains affect clove growth and flowering [90,91]. Nutmeg production is projected to be affected by an increase in the number of wet days, heavy rainfall, mean temperature above the optimum temperature range (25–26 °C), heatwaves and protracted warm spells [92]. Ongoing habitat loss and degradation and consequent decline in the available genetic pool affect the species' ability to adapt to the changing environment and threaten the survival of many traditional cultivars.

To help address unsustainable use and climate-related threats to PGRFAs, we recommend the following:

- Identifying and addressing reasons behind unsustainable harvesting practices in wild and semi-wild populations and training farmers in sustainably managing and conserving local varieties.
- Collecting CWR data and conserving natural forest areas and other relevant habitats.
- Building stakeholder capacity to select new resilient varieties for climate change adaptation and raising awareness of the linkages between biodiversity conservation, adaptation and breeding resources.

4.5. Cultural and Knowledge Erosion and Gender Barriers

The traditional and gender-specific knowledge of *Masyarakat Adat* and local communities regarding the utilization and management of valuable autochthonous plant resources is insufficiently documented. The preservation of this culturally specific knowledge is under threat due to cultural shifts and younger-generation migration from rural areas to cities in pursuit of education and job opportunities. The exact number of unique and culturally distinctive food systems practiced by *Masyarakat Adat* in Indonesia remains unknown, necessitating further intercultural research. The evidence gathered indicates that the abundance and diversity of edible wild, semi-domesticated and domesticated resources used by *Masyarakat Adat* and local communities far exceed those found in other agri-food systems. In Java, for instance, indigenous varieties endure thanks to the continuous on-farm planting and conservation of the Badui and Samin communities, for ritual and medicinal purposes. Similarly, in Lamandau, local knowledge on planting local rice varieties in steep or slopy areas is maintained by traditional leaders via a knowledge management system called 'Kelompok Adat'. In Seruyan, most rural residents can differentiate local rice varieties based on color, shape, height and other morphological features. In Kapuas, local rice varieties, including glutinous rice, are used for several religious festivals including for medicinal rituals. These findings align with similar evidence from research conducted since 2008 by the United Nations Food and Agriculture Organization (FAO) in collaboration with

Bioversity International and McGill University [93], examining various indigenous peoples' food systems worldwide.

Unsustainable practices are intensified by the loss of traditional and religious conservation practices. For example, in the past, the Tabaru people on the island of Halmahera took a 'sasi' (literally 'oath') or offering of trees to gain the protection of God, which ensured that plantations of several tree species—including nutmeg and cloves—were protected, owned and managed by the community and the dividends shared. The practice is gradually disappearing, particularly among younger farmers who consider it "outdated and ancient" [94].

Women are important players in preserving agrobiodiversity in Indonesia, yet this role is poorly recognized. In Central Java, women are responsible for cultivating taro and yam, as well as engaging in food processing activities like preparing chips and cakes. In Maluku, women are experts in identifying nutmeg and clove cultivars and are actively involved in selecting which cultivars to plant. Despite the importance of their contribution, women's ability to participate in and benefit from local agrobiodiversity management is constrained by their lack of access to extension services, community-level decision-making processes and credit to develop new products and markets. Bridging this gap is doubly important as women are typically responsible for household spending and dietary choices. Thus, building women's capacity to produce, market and prepare a broader range of nutritious local and indigenous foods can spur improved nutrition security and economic prosperity within individual households and communities alike.

Although many gender-responsive policies exist, they are not effectively implemented at the local level due to capacity gaps.

To overcome cultural, gender and knowledge barriers to conserving and using PGRFAs, we recommend the following:

- Establishing participatory frameworks that actively involve local communities in generating knowledge and decision-making processes around PGRFA conservation.
- Documenting traditional knowledge and uses, including by women, and promoting knowledge exchange between scientists and customary communities (i.e., traditional and indigenous groups).
- Disseminating information on the benefits of these crops, including among youth.
- Organizing awareness-raising campaigns and/or information events.
- Developing a gender-responsive communications and outreach strategy for conserving and sustainably using PGRFAs.

4.6. Study Limitations

Our study is descriptive and does not address the lack of systematic documentation of Indonesia's vast PGRFAs or their genetic erosion. Rather, it provides a snapshot of the diversity of five key crops with food security and market importance currently found across provinces with distinct socioecological contexts. It also describes the key drivers of genetic erosion—including climate change, habitat loss and destruction, and adoption of new/commercial varieties—in the selected sites. The varietal diversity observed and documented by our study reflects the selection of the study sites and key informants. We sought to integrate this observation data with extensive stakeholder consultations conducted with over 200 participants in national and provincial consultation workshops, and a two-step validation process where the findings of both the initial literature review and the field assessments were validated and refined separately with experts. The study was also carried out during the COVID-19 pandemic, which restricted some field activities and prevented field visits in Central Kalimantan, suggesting that the study's estimates of varietal diversity are conservative, and the actual diversity and conservation value of Indonesia's PGRFAs are likely higher. Despite the lack of field assessment in Central Kalimantan, by far the highest varietal diversity of rice was documented in that province, indicating that the stakeholder consultations were effective in uncovering the diversity. It is hoped that this study serves as impetus for finally initiating systematic assessments of Indonesia's vast PGRFAs and the threats driving their erosion.

5. Conclusions and Recommendations

As described, conserving these five priority species of Indonesia's unique biodiversity, with the potential to support food and nutrition security, faces significant challenges spanning from environmental and socioeconomic pressures to knowledge gaps and policy challenges. Addressing these barriers requires coordinated efforts involving evidence-based policy reform and investments in conservation and sustainable agriculture, while providing economic incentives and building the multi-level capacity of conservation actors. Ex situ and in situ/on-farm conservation methods are complementary and play essential roles in preserving plant genetic resources. Ex situ conservation, through genebanks and seed collections, safeguards genetic material and ensures its availability for research and restoration efforts. In contrast, in situ and on-farm conservation maintain genetic diversity in natural environments and farming systems, allowing species to adapt to evolving conditions. Investing in both approaches is crucial to ensure a comprehensive strategy for conserving biodiversity, enhancing ecosystem resilience and securing the genetic resources needed for future agricultural innovation.

Our findings and recommendations, based on extensive stakeholder consultations, highlight the potential solutions to overcome the obstacles to conserving, valuing and sustainably using these five key species among Indonesia's extraordinary PGRFAs and putting the conservation of these invisible treasures on stronger footing.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su16229824/s1, Table S1: Diversity of rice growing in the target provinces; Table S2: Diversity of taro growing in the target provinces; Table S3: Diversity of yams growing in the target provinces; Table S4: Diversity of nutmeg growing in the target provinces. Table S5: Summary of key gaps and barriers and recommendations for improving the conservation and use of target crops by thematic area.

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