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Review

Nypa-based land uses and ecosystem services in the tropics: A review

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ABSTRACT

This study reviewed the state-of-the-art knowledge on *Nypa fruticans*-based (hereafter *Nypa*-based) land use along with the corresponding ecosystem services that contribute to the wellbeing of mangrove-dependent communities (MDCs) in the tropics. In relation to the land uses, *Nypa*'s ecosystem service valuation, restoration potential and threats were also explored. *Nypa*-based land uses documented in tropical countries since the last century include, Natural *Nypa* Forests (NNF), *Nypa* Plantations (NP), *Nypa*-Aquaculture Systems (NAS), and *Nypa*-Agriculture Systems (NAgS). Even though land use-specific variations were found in distribution, abundance, and ecosystem services provided, it appears that there is the great overlap of reported ecosystem services regardless of *Nypa* land use. The provisioning ecosystem services of *Nypa* have been made use of at the subsistence level by man for millennia. These especially include its use as a source of food, fuel, and fiber. *Nypa* is unique among the many mangroves as being about the only one that has significantly been developed for commercial exploitation beyond the typical destructive harvest for wood and charcoal as seen in most other mangroves. Our review presents new research that has made important inroads in exploring *Nypa*'s yet untapped commercial potential for livelihood provisioning for poor MDCs. Building further on these pioneering results holds major promise for the development of new sustainable livelihood opportunities for MDCs. The review also shows that *Nypa* provides substantial supporting, regulating and cultural services. These services have been rarely studied, and *Nypa*'s contribution to the wellbeing of MDCs are therefore not well-acknowledged. Our review also suggests that at the landscape level, *Nypa* also holds major promise as a way to rapidly sequester atmospheric carbon dioxide, protect coastal areas from weather extremes, rehabilitate abandoned aquaculture ponds and transform aquaculture towards greater sustainability. Therefore, we recommend further intensification of *Nypa*-based land uses in conjunction with the further development of value-added *Nypa* products for livelihood support, as well as basic research on the ecological niche-specific suitability of *Nypa*-based land uses, and their associated ecosystem services.

1. Introduction

Mangroves are found across the tropics and up into temperate regions, usually forming natural mangrove forests along the coast, where they provide a multitude of ecosystem services to the mangrove dependent communities (MDCs). They occur in more than 100 tropical and sub-tropical countries and cover roughly 152,000 km^2 in total surface. This amounts to less than 1 % of worldwide tropical forests, and 0.4 % of total worldwide forest cover (Van Lavieren et al., 2012). Even so, worldwide, 1.5 billion people from largely poor coastal communities depend on non-timber forest products that these forests yield (Shanley et al., 2016). Notwithstanding the worldwide growing awareness of the

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practically irreplaceable ecosystem and economic value of mangrove forests, their deforestation continues, albeit at a somewhat lower pace this century than in the latter 20th century (Feller et al., 2017). The root causes for the continuing mangrove deforestation are largely economic whereby these forests are converted to alternative land uses to produce (generally low value), unsustainable, commodity products for the global market (Richards and Friess, 2016) and to the overriding benefit of multinational companies. In this new "neo-imperialism" (Boussebaa and Morgan, 2014), the host country destroys its critical ecosystems and the livelihoods of its coastal peoples in return for short-term economic gains. Therefore, there is an urgent need to solve the economic challenges of tropical MDCs but without destroying the remaining mangroves and even reversing the process and bringing mangroves back (e.g., Debrot et al., 2022). This can only be achieved by focusing more effort on developing the wide array of subsistence-level mangrove non-timber forest products (NTFPs) for local value-added production (Debrot et al., 2020). In this regard, the global trend towards bioeconomy, represents a major new opportunity (Weiss et al., 2020).

One of the most important species with this potential is *Nypa fruticans* Wurmb also known as the "mangrove palm" or "*golpata*" in both Bangladesh (Rahman et al., 2020) and India (Chakraborty, 2019). The species is widely used throughout Southeast Asia but foremostly at the subsistence or local level (Islam et al., 2020b). Hossain and Islam (2015) point to the importance of *Nypa* for coastal Bangladesh and its presumed but largely unrealized potential for export. Joshi et al. (2006) further laments the Indonesian government's lack of attention for this species in mangrove reforestation efforts for areas where the species was formerly abundant. All the while, the value of *Nypa*-based land uses to human wellbeing has been acknowledged at local to global levels for a long time already (Fong, 1992; Siddiqi, 1995). The plant is regarded as one of the keystone palms of SE Asian home gardens and agroforestry and is characterized as highly versatile to changing conditions and as being able to deliver a wide range of human-use products (Barfod et al., 2015). It is the only mangrove species for which production has already reached industrial scales in some areas for fiber materials, sugar, vinegar and/or ethanol (Hamilton and Murphy, 1988). Annual production of thatching from the Sundarbans of Bangladesh over the 20-yr period 1957 to 1977, averaged 81,600 t per year (Hamilton and Murphy, 1988), whereas more recently average annual production has been about 67,000 metric tons/ha per year (Islam et al. 2020). For the period 1976 – 1980, statistics showed increasing *Nypa* shingle production in the Philippines, with 2,978,000 pieces being commercially produced in 1980 (Hamilton and Murphy, 1988). For Cagayan, the Philippines, Taguiam et al. (2022) speak of a current vast nipa plantation of 1408.98 ha that serves as a main source of livelihood of the surrounding communities, while in the 1980s there already were large factories for vinegar and sugar production from *Nypa* (Hamilton and Murphy, 1988). Even though the species is widely being used and produced, production figures largely remain wanting. Awaltanova et al. (2013) point to its high and yet largely untapped potential because of its high coverage in the mangrove ecosystem of Indonesia while Wan Zaki et al. (2011) discuss its large economic potential for Malaysia but lament the lack of technology development for both upstream and downstream production activities.

Interest in the use of *Nypa* is increasing because of its contribution to human wellbeing in the form of diversified ecosystem services including provisioning, supporting, regulating and cultural services (Rahman and Mahmud, 2018; Cheablam and Chanklap, 2020; Islam et al., 2020a; Robertson et al., 2020). However, *Nypa*-based land use forms, and exploitation vary greatly across the tropics (Rozainah and Aslezaeim, 2010; Robertson et al., 2020). Consequently, ecosystem services obtained or obtainable and the value of the services provided by this species also vary widely among MDCs in the tropics. Therefore, in order to strengthen future mangrove restoration and conservation efforts by means of this species, it is imperative to understand its occurrence in relation to the different land use systems and ecosystem services, as well as achieve a more complete valuation of its ecosystem services.

While the species represents a largely underexploited potential for income and human wellbeing (Barfod et al., 2015), its occurrence and use in the rural landscape is declining and natural *Nypa* forests are widely under threat in SE Asia. For instance, *Nypa* forest is threatened in the Indian Sundarbans because of declining freshwater (Chakraborty, 2019) along the central south coast of Java due to clearing for other aquatic uses (Widodo et al. 2019) and has practically disappeared in some areas along the central northern coast of Java due to habitat destruction and saltwater intrusion (Damastuti et al., 2022). The species suffers over-exploitation in Cagayan, Philippines (Ame et al., 2011) and extreme deforestation in Palawan, Philippines (Fadiman, 2008). It is listed as "critically endangered" in Japan, as "endangered" in China and as "vulnerable" in Sri Lanka and Singapore (Sugai et al., 2016). The species is also known to suffer from very low genetic diversity (Jian et al., 2010), which is likely contributed to by its tendency for clonal propagation.

Notwithstanding its evident additional potential for livelihood provisioning for the MDCs, the gradually growing interest in this species and its widespread threatened state of occurrence, up to now only five mini-reviews have been available for the species. An eight-page mini-review was given by Päivöke (1983) on raw materials provided by the species, a seven-page mini-review by Hamilton and Murphy (1988) was written on the use and management of *Nypa*, a six-page mini-review by Tsuji et al. (2011) addressed the species' biology and ethnobiology, a six-page mini pre-publication review paper by Clemente (2013) highlighted promises and potentials of the species and a five-page mini-review by Hossain and Islam (2015) briefly discussed its utilization. However, since these mini-reviews, much valuable new research has been done, thereby warranting an updated review for this species.

2. *Nypa*-based land use systems in the tropics

2.1. Nypa-based land use systems

The modern natural range of distribution of this species is limited to the tropical Indo-West Pacific region, from Sri Lanka through Asia to Japan, Northern Australia and the Western Pacific islands. It has recently naturalized in Panama and Trinidad in the America's and is also present along the coasts of several countries of Central-West Africa (Moudingo et al., 2020). *Nypa* grows in brackish environments across different coastal land uses of tropical countries (Fong, 1992; Siddiqi, 1995). It is typical of the landside zone of the mangrove forest where mangroves give way to coastal lowland forest and where the predominant habitat is brackish to freshwater pools and streams. Polidoro et al. (2010) point out that exactly mangrove communities and species characteristic of the upper intertidal and upstream freshwater estuarine zones (like *Nypa* forest) are the most threatened because these are typically the first mangrove-associated areas cleared for aquaculture and agriculture (Fig. 1). For instance, Zain et al. (2014) documented how *Nypa* mangrove areas, degraded in the Mahakam Delta, where the species formerly accounted for 50 % of the mangrove coverage, were reduced from 58,000 ha in 1980 to 11,000 ha in 1999 due to land conversion for aquaculture.

The species is abundant in the coastal ecosystem of Bangladesh (Rahman and Mahmud, 2018), India (Chakraborty, 2019) and Indonesia (Mubarak et al., 2020), where the environmental conditions are favorable for its establishment and growth. Based on archaeobotanical studies, it has been suggested to have been of economic significance to man in SE Asia since at least 3400 BP (Weisskopf, 2018). As long ago as 4,000 BP, the Hindus of Indonesia extracted sugars from palms (Fox, 1977). In fact, some of the anthropogenic land uses today have specifically been developed around the presence of *Nypa*, such as in Nigeria (Nwobi et al., 2020). Researchers have explored various *Nypa*-based land use types since the last century (Berry, 1914; Fong, 1992; Siddiqi, 1995). Accordingly, we here distinguish four key types of land use forms with *Nypa*. These are (i) natural *Nypa* forest (NNF) (Berry, 1914; Fong,

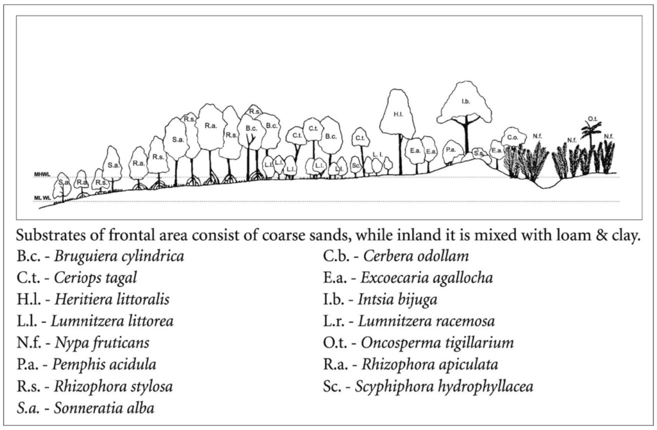

Fig. 1. Nypa is typical of the landside zone of the mangrove forest where mangroves give way to coastal lowland forest (Adapted from Giesen et al., 2007).

1992; Islam et al., 2020b; Rozainah and Aslezaeim, 2010; Ellison et al., 2010), (ii) *Nypa* plantation (NP) (Chongkhong and Puangpee, 2018), (iii) *Nypa* aquaculture systems (NAS) (Matsui et al., 2014a; Matsui et al., 2014b; Matsui et al., 2016; Rahman and Mahmud, 2018; Rahman et al., 2020), and (iv) *Nypa* agricultural systems (NAgS) (Barfod et al., 2015; Robertson et al., 2020).

Land use such as NNF is a naturally occurring system, where *Nypa* colonizes intertidal habitat with its dense root system. Due to its dense and typically massive root system, it is much better adapted to swift current conditions than other mangrove species (Giesen et al., 2007) which allows it to extend far inland along freshwater rivers and streams (Fig. 2A). A recent study also supports such occurrence patterns of *Nypa* that grows better in the upper part of the NNFs rather than in the edge of mangrove forests along the river (Widodo et al., 2020). However, it also abundantly grows along the banks of rivers, canals, and creeks in mangrove ecosystems by forming either pure or mix stand with the other mangroves (Rozainah and Aslezaeim, 2010; Satyanarayana et al., 2011; Shah et al., 2016; Mubarak et al., 2020; Widodo et al., 2020; Nawar et al., 2021). Land coverage and stand structure of *Nypa* in the NNF depend on the location-specific abiotic and biotic factors (Zakaria 2017), even if the *Nypa* zone may be up to 5 km wide (Giesen et al., 2007). According to Awaltanova et al. (2013) *Nypa* coverage amounts to almost 1/3 of the total mangrove forest cover in Indonesia.

Recognizing the potential that *Nypa* represents, man developed new land use systems (like NP, NAS, and NAgS) by integrating *Nypa* to achieve diversified ecosystem services. When exactly these anthropogenically-modified *Nypa* land use forms were first developed is difficult to retrace. However, the earliest introduction of *Nypa* to Nigeria for economic purposes was in 1906 (Saenger et al., 1983; Upkong 1995). Mangrove plantations including *Nypa* along with other mangroves in the coastal belt were initiated in the coastal areas of Bangladesh in 1966 (Iftekhar and Islam, 2004; Hossain, 2016). This means that the use of this species for anthropogenically modified, economically motivated land uses must well predate the early 20th century. Usually, NPs are established along the river or canal banks, the slopes of embankments or roads in the coastal landscape (Fig. 2B). In addition, newly accreted lands of tropical deltas in countries like Bangladesh are also suitable for establishing NPs (Miah et al., 2003; Hossain, 2016).

NAS is also a manmade land use system (Fig. 2C), which like the NP has become established in their separate suitable niches of the coastal landscape. This land use system is generally established in the degraded mangrove forest (Miah et al., 2003), shrimp ponds (Miah et al., 2003; Matsui et al., 2014b) or newly accreted coastal lands (Miah et al., 2003). It is also the case that land use systems including NAS are often established by converting the original mangrove forest. NAS is generally established following community-driven decision-making (Fong, 1992), where communities aim to restore the vegetation to optimize the ecosystem services of tropical coastal ecosystems (Fong, 1992; Miah et al., 2003; Islam et al., 2020b). In this land use form, *Nypa* is grown either on the pond dikes or dunes (the central pond platforms) or in both places, leading to more diversified ecosystem services (Ahmed et al., 2020). NAS differs from NP in terms of land coverage and stand structure to some extent as these systems are heavily managed by man. However, one of the major outcomes of NAS is that *Nypa* is typically combined with the growth of high value animal crops like shrimp, fish, crab and mollusk (Rahman and Mahmud, 2018; Rahman et al., 2020).

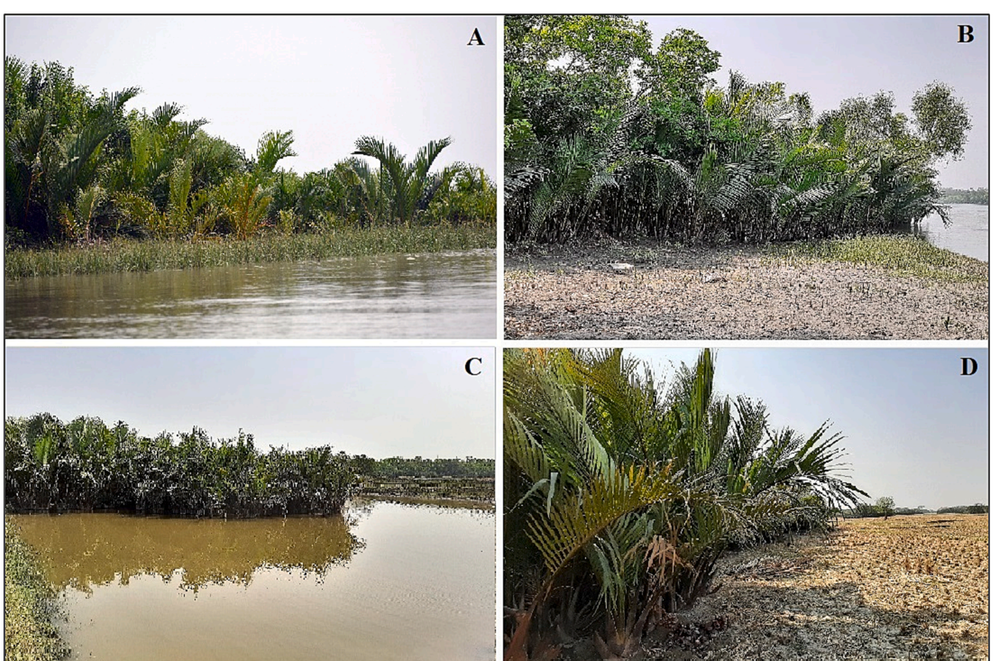

Fig. 2. Images of *Nypa*-based land use types including the (A) natural *Nypa* forest (NNF), (B) *Nypa* plantation (NP), (C) *Nypa*-aquaculture system (NAS), and (D) *Nypa*-agriculture system (NAgS) in Bangladesh.

Finally, NAgS (Fig. 2D) is also a manmade land use system developed in the agroecological niches of the coastal ecosystem (Miah et al., 2003). Agricultural land (Miah et al., 2003; Matsui et al., 2014b) or newly accreted coastal lands, and homesteads are the areas where this system is generally created (Miah et al., 2003). However, mangrove forest conversion/ degradation is also attributed to NAgS land use. Meanwhile, community driven decisions also can play a key role in the establishment of NAgS, which is very similar to NAS the system (Fong, 1992). Under this land use system, mangrove species like *Nypa* is often introduced to restore the tropical coastal ecosystem with the aim to diversify the ecosystem services (Fong, 1992; Islam et al., 2020a; Miah et al., 2003). *Nypa* grows mostly in the dikes of the agricultural lands specially along the canals that act as the source of water for agricultural practices (field observation in Bangladesh). Land coverage and stand structure of *Nypa* are quite similar to those seen in the NAS land use because both are established and managed by the human though differently from NNF and NP. Like NAS, in the case of NAgS the *Nypa* is combined with the culture of several plant crops such as rice paddy (Jamieson et al., 2017) or sugarcane (Robertson et al., 2020) to reduce the risks of economic loss by diversifying the products/ income for the MDCs.

2.2. Distribution of Nypa-based land uses

Occurrence of *Nypa* depends on site stability and tidal inundation in relation to seasonal variation. The species thrives best at relatively stable sites that experience lower tidal inundation in the wet season and no tidal inundation in the dry season (Siddiqi, 1995). *Nypa* grows well in both gaps and open spaces except for in the understory or in shady conditions (Ewel et al., 1998). In the early 19th century, it was claimed that the distribution of *Nypa* was restricted to the coastal ecosystem of tropical countries (Berry, 1914; Tsuji et al., 2016), where *Nypa* is one of the dominant mangrove species (Satyanarayana et al., 2011). In addition, the researchers explained that the origin of *Nypa* might be the Indian sub-continent since the Bay of Bengal likely played a key role in dispersing the *Nypa* seeds among the continents (FCB 1860; Mehrotra et al., 2003). Fig. 3 shows the current distribution of *Nypa* across the countries. *Nypa* is found from Australia, the Solomon Islands, and the Ryukyu Islands to Sri Lanka, Bangladesh, India and the Ganges Delta. It is also found in Myanmar, Andaman, Thailand, Cambodia, Vietnam, Maluku, Java, Borneo, Singapore, Malaysia, Philippines, Indonesia, Sumatra, Sulawesi (Dransfield et al., 2008). ***Nypa*** was first brought to the Niger Delta in West Africa in the late 19th century (Dransfield et al., 2008), and it is found in Madagascar to the eastern Indian Ocean coastline, western Cameroon, Nigeria, Ghana, New Guinea and the Bismarck Archipelago. In North America it is found in Northeastern Brazil (Lacerda et al., 1993), the Colombia/Panama border (Duke, 1991) and in Trinidad (Bacon, 2001). It is also found in Polynesia and the Mariana Islands in Micronesia (Dransfield et al., 2008).

Due to its wide environmental tolerance, *Nypa* occurs in different landscapes and land use forms established either by means of natural regeneration through seed dispersal or clonal growth (Berry, 1914) or planting (Rahman and Mahmud, 2018; Robertson et al., 2020). While the details of habitat distribution of *Nypa* in the NNF has been well documented (Ellison et al., 2010; Spalding, 2010), the current distribution of *Nypa*-based land uses has not. Fig. 4 illustrates the current global distribution of the four *Nypa*-based land use forms. NNFs are still found in all countries in which the species naturally occurs (Islam et al., 2020b; Spalding, 2010; Widodo et al., 2020; Ellison et al., 2010) as well as in Nigeria (Ellison et al., 2010). Fig. 4A shows the distribution of NNFs across the countries from Taipei in the north to Australia in the south, and from Sri Lanka in the west to Micronesia in the east. In the Americas, particularly Panama and Trinidad where it has been introduced and is behaving invasively, it only occurs in the form of forestation (Ellison et al., 2010). NP land use is found in a more limited subset of countries where it is established by the MDCs following the traditional approaches (Numbere 2019a; Nwobi et al., 2020). NP is also found in some African, countries where it has been introduced and is behaving invasively (4B) (Ellison et al., 2010). NAS (4C) is found in Indonesia, Bangladesh (Rahman and Mahmud, 2018; Rahman et al., 2020) and Thailand (Matsui et al., 2014a; Matsui et al., 2014b), whereas NAgS land use is only found in Bangladesh (Islam et al. 2020) and Australia (Robertson et al., 2020) (Fig. 4D). The reasons for these regional differences in the use of *Nypa* in different agricultural production systems are poorly understood but likely due to a combination of environmental, biological, economic, cultural, and historical factors. Therefore, understanding the distribution of *Nypa*-based land uses across its range of

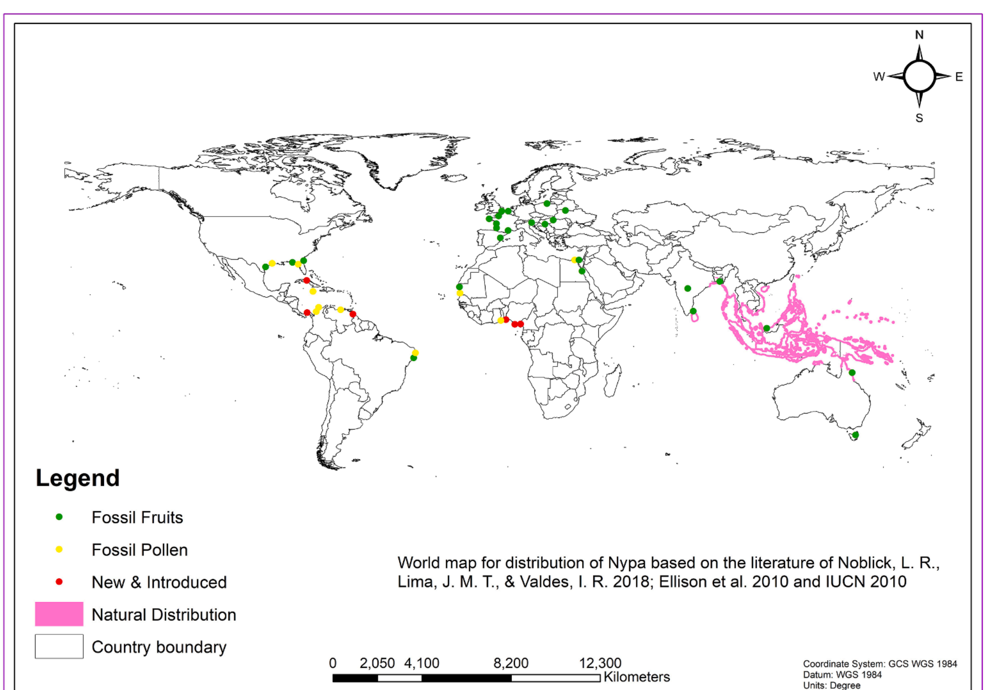

Fig. 3. Fossil and current (both introduced and natural) global distribution of *Nypa* fruticans.

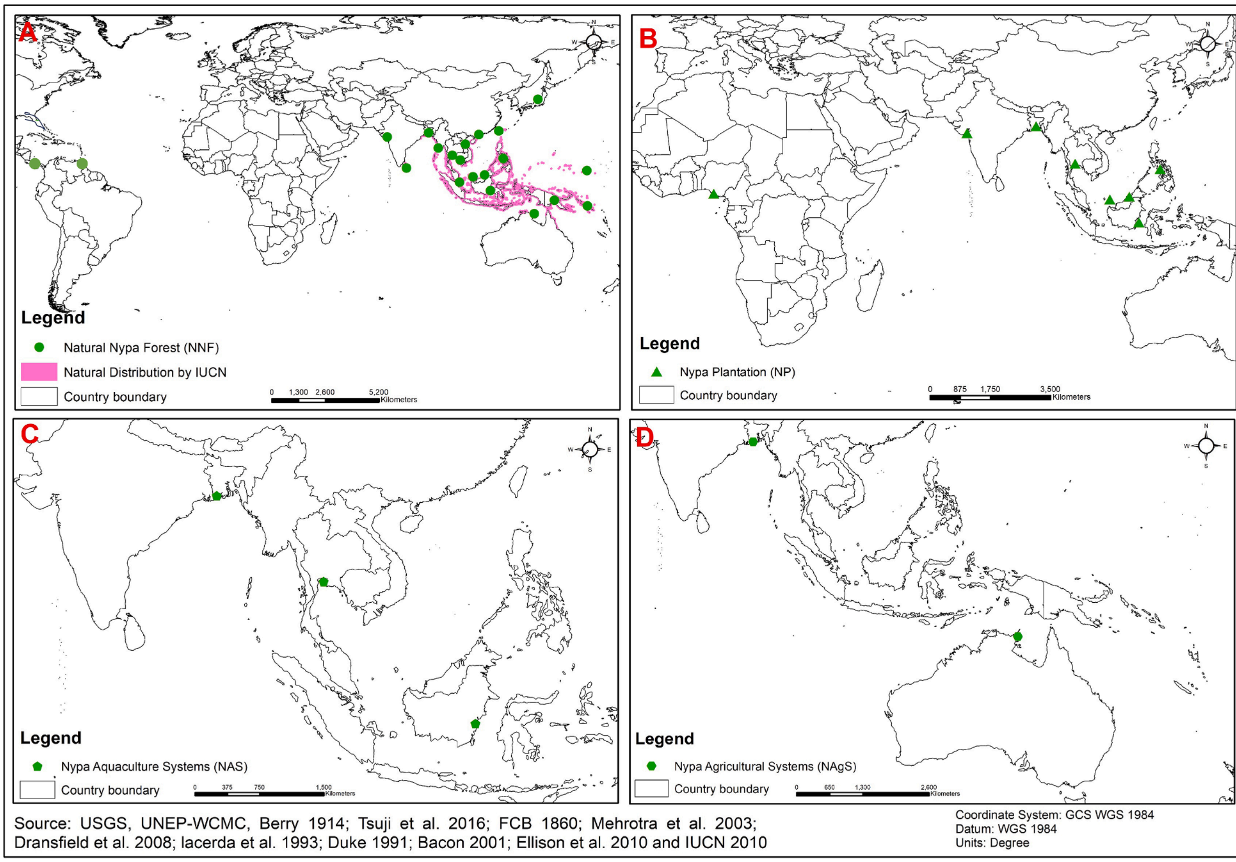

Fig. 4. Global distribution of the four distinguished *Nypa*-based land uses including NNF (A), NP (B), NAS (C), and NAgS (D) (Adapted from literature cited in subsections 2.1 and 2.2).

occurrence has the potential for opening new windows of opportunity by sharing lessons learned for the sustainable transformation of landscapes through restoration, conservation and sustainable use of *Nypa*.

2.3. Land use specific characteristics of Nypa

In mangrove ecosystems, *Nypa* preferentially grows in freshwater (Ellison et al., 2010) and higher salinity has been shown to negatively affect the establishment and growth of *Nypa* (Theerawitaya et al., 2014). However, it can also thrive in low to moderate saline and brackish coastal areas because of its remarkable adaptive capacity (Siddiqi, 1995; Theerawitaya et al., 2014). The plant is very resistant to natural stress like high salinity and anthropogenic stress such as oil pollution (Dutrieux et al., 1990). However, it has been the subject of only five studies that examined stand structure, above-ground biomass, and vegetative and floral demography (Fong, 1992; Rozainah and Aslezaeim, 2010; Carandang et al., 2009). The establishment and growth rate of *Nypa* in NP, NAS, and NAgS are comparable to in NNF (Rozainah and Aslezaeim, 2010; Robertson et al., 2020; Widodo et al., 2020). Growth rate can vary in relation to climatic, edaphic, and hydrological factors (Siddiqi, 1995; Zakaria 2017). Ecological characteristics of *Nypa* in the different land use systems discussed, have been illustrated in Table 1. The stand density of *Nypa* in NNF is substantially higher compared to the other land use types. It ranges from 1025 to 6400 plants per ha, 10–1000 plants per ha, and 106 plants per ha in the NNF (Rozainah and Aslezaeim, 2010), NP and NAS (Lestari and Noorâ, 2019), respectively. One reason for this is that thinning allows better yields of *Nypa* sap (Matsui et al. 2014) and *Nypa* leaves (Carandang et al., 2009) and because when used in conjunction with agriculture or aquaculture, by definition space is also required for the other crops. For instance, Hai and Yakupitiyage (2005) show that when combining mangroves and shrimp, excess mangrove coverage and leaf litter fall can be deleterious to shrimp production. However, abundance of *Nypa* in NNF also varies among size classes (Rozainah and Aslezaeim, 2010). Despite the fact that NAgS is a man-made system, the optimal use forms of *Nypa* have not been explored in it yet.

Land use systems, tidal inundation (Rozainah and Aslezaeim, 2010), salinity (Theerawitaya et al., 2014; Widodo et al., 2020), wave actions and management practices determine the establishment, growth, and abundance of *Nypa* in its native range (Fong, 1992). Morphological characteristics of *Nypa* like leaf type, length, and color also depend on biophysical factors like, size category (life stages), distance to the sea, soil type, pH, and salinity (Widodo et al., 2020). A demographic study on *Nypa* in NNF reported that the life stages can be categorized into four groups including seedling, juvenile, adult and mature in terms of morphological characteristics (Rozainah and Aslezaeim, 2010). The highest leaf production rates are reported for the early life stage. Leaf

Table 1
Ecological characteristics of *Nypa* as documented for different land use systems in the tropics (Extracted literature sources cited in subsection 2.3). Here, "×" indicates "not documented yet".

Characteristics	NNF	NP	NAS	NAgS
Density/ha	1025–6400	10–1000	≤106	×
Leaves per tree	4–5	×	×	4–5
Height (m)	8–13	0.4–11.5	×	×
Leaf production/palm/year	×	≤3	×	×
Leaves per ha	6538–13550	×	≤336	×
Survival (%)	×	≤28	×	×
Flowers/palm/year	1	×	×	×
Flowers/ha	×	×	×	×
Fruits/palm/year	1	×	×	×
Fruits/ha	×	×	12	×

production rates in seedling is about 3 leaves per year while in older plants it goes down to 1 leaf per year. Leaf production also varies over the site-specific conditions and the length of harvesting cycles (Carandang et al., 2009). Leaf height varies from 1 to 13 m with a curved or erect shape and varying color in the NNF (Widodo et al., 2020). Silty clay soil positively influences the growth of *Nypa*, while water parameters regulate the early-stage growth in the NNF (Zakaria et al., 2017). Similar to NNF, the height growth of the *Nypa* depends on the soil properties like compactness, water content, pH and electrical conductivity as studied in NP (Matsui et al., 2016). Accordingly, leaf heights ranging from 0.4 to 11.5 m have been reported for the *Nypa* of NP which is comparable to leaf heights in NNF (Ukpong, 1995). The leaf colors displayed include green, dark green, purple, yellow, and orange (Widodo et al., 2020). Leaf abundance varies from 6538 to 13550 (Robertson et al., 2020; Matsui et al., 2014b) to ≤ 336 per ha (Lestari and Noorâ, 2019) in NNF and NAS, respectively. Survival rates of *Nypa* have been reported only for NP amounting to ≤ 28 % at 2 years age after planting (Siddiqui 1995). Production rates of inflorescences and infructescence are 1.1 and 1.0 per palm per year, respectively in the NNF (Rozainah and Aslezaeim, 2010). *Drosophila* flies appear to be the principal pollinating agents of *Nypa* inflorescences (Panabang et al., 2017; Straarup et al., 2018). In the NAS, fruit abundance has been documented as 12 per ha by Lestari and Noorâ (2019). Mature fruits are dark brown in color and spherical in shape (Mantiquilla et al., 2018). The factors leading to all these differences imply that there remains considerable scope for research on the ecological characterization of *Nypa* in relation to the different forms of land uses in specific ecological niches.

3. Ecosystem services of *Nypa*

A considerable portion of the MDCs are deriving principal income from the ecosystem services provided by mangroves like *Nypa*. Meanwhile, subsistence services also remain in the center of MDCs' interest. According to Cheablam and Chanklap (2020), *Nypa* has the potential to serve the MDCs for generation to generation in the tropics by providing a multitude of ecosystem services (Fig. 5). Table 2 depicts the ecosystem services of *Nypa* palm parts that contribute to the wellbeing of MDCs in the tropics. MDCs are utilizing all *Nypa* parts from root to sap for their wellbeing following traditional knowledge (Udofia and Udo, 2005). Some researchers have claimed that mainly the indigenous population explored several important uses of *Nypa* following traditional extraction techniques (Hamilton and Murphy, 1988, Fong, 1992) and numerous studies have been conducted to explore the ecosystem services of *Nypa*-based land uses since the last century. Table 2 illustrates the principal documented value and identified potential of ecosystem services of *Nypa* in relation to the land uses including NNF, NP, NAS, and NAgS in the tropics. As with other mangroves, these services contribute greatly to the food security, life and livelihood of the MDC and vary based on the biophysical factors in the landscape.

3.1. Provisioning services

3.1.1. Food

Table 2 shows that all the *Nypa*-based land uses provide foods including fruit, sap and other products like vinegar, and molasses for the MDCs. Seasonal variation in yields of different *Nypa* products has been reported by Cheablam and Chanklap (2020). Fresh *Nypa* fruit can be eaten raw, as processed snacks and can be used to extract bioactive components. For example, coastal communities of Bangladesh collect fresh fruit from NP and consume it in raw or pulp form (Paul et al., 2012). In addition, the fruit (both mesocarps and endosperms) are an important source of fatty acids and phytochemicals including tannin, phenolic and flavonoid compounds (Astuti et al., 2020; Moon et al., 2020). Though it has been reported that the phytochemical content of *Nypa* fruit might vary depending on the experiments used for the identification process (Astuti et al., 2020), they are suitable for the production of low-fat confectionary products (Akpabio et al., 2007). Fruits are also a source of natural antioxidants (Sum et al., 2013; Prasad et al., 2013; Hermanto et al., 2020). In the Philippines, the farmers also make

Fig. 5. Overview of ecosystem services provided by *Nypa*. Asterisks (*) pinpoint those ecosystem services of greatest known MDC value and identified potential.

Table 2
Provisioning services with respect to *Nypa* plant parts (Adapted from the literature cited in subsection 3.1). Here, "+" indicates confirmation of the corresponding service in the literature.

Nypa plant parts	Food	Fiber	Medicine	Thatching material	Fuel	Bioethanol	Chemical extracts	Others
Root			+					+
Leaf		+	+	+	+	+	+	+
Leaf midrib		+	+	+	+	+		
Inflorescence			+				+	
Infructescence						+		
Fruit	+		+				+	+
Fruit husk		+			+		+	+
Seed					+			
Sap	+		+			+	+	

wine from the *Nypa* fruits (Langenberger et al., 2009).

Raw *Nypa* sap is a popular traditional drink among the MDCs (Chairul et al., 2020). Sap production ranges from 0.4 to 1.2 L d^{-1} per palm (Tamunaidu et al., 2013). It mainly contains water with sugars such as sucrose, glucose, and fructose (Tamunaidu and Saka, 2011; Tamunaidu et al., 2013; Phetrit et al., 2020). The sugar content of *Nypa* sap is much higher than sugar cane sap (*Saccharum officinarum*). Päivöke (1985) reported that *Nypa* sap contains 16 % weight to volume (w/v), while sugar cane contains 12 % w/v. *Nypa* sugar extract contains active chemical compounds and hence, shows antioxidant and antidiabetic effects (Sabri et al., 2019) along with approximately 2 % salt (Apirattananusorn, 2021). However, nutritional value varies among the geographical areas and/or collection locations (Saengkrajang et al., 2021). Sap is used to produce edible sugar (Päivöke, 1985; Tomomatsu et al., 1996; Radam et al., 2016; Cheablam and Chanklap, 2020), syrup (Saengkrajang et al., 2021; Apirattananusorn, 2021) and vinegar (Yusoff et al., 2015a; Yusoff et al., 2015b; Yusoff et al., 2017). Quality sap production depends on the thickness and length of the fruit stalk (Matsui et al., 2014a) and traditional knowledge (Cheablam and Chanklap, 2020). Furthermore, MDCs obtain *Nypa* sap using the traditional technique of beating and/or kicking at the base of the stalk for a few days and then cutting the stalk with a sharp knife. However, sap collection results in lower yield and is of detrimental to the *Nypa* plant. Because this technique reduces proliferation and vigor, consequently, reduces the colonizing ability of *Nypa*. Tapping *Nypa* sap required specialized skills and can also be done by both the elders and youth from MDCs to increase income (Ijeoma et al., 2015). Considering these issues with traditional harvesting techniques, Udofia and Udo (2005) emphasizes the need for the development of improved sap tapping practices to avoid damage to the plant and its overall productivity.

3.1.2. Fiber

Fibers including pulp and particles are obtained from the *Nypa* of NNF and NP (Table 3). Further, leaf fronds can be converted into pulp with cellulose content and fiber length comparable to the hardwood species (Jahan et al., 2006; Dewi et al., 2018). Though the strength properties of pulp are comparable to the non-wood pulp, yield and quality of *Nypa* pulp are judged as poor (Jahan et al., 2006). Moreover, fiber boards/ bio-composites can also be made from the leaf midribs (Ekpunobi et al., 2013). In addition, fruit husks are used in particleboard (Nurdin and Saddikin, 2019), and bio-composite (Rasidi et al., 2014; Rasidi et al., 2015; Govindan et al., 2017; Syahmie et al., 2018) production because of having suitable fiber content. Nitrophenols used in industries are highly toxic to and often accumulate in the aquatic environment. *Nypa* nanoparticles show promise for use in environmental remediation and decontamination in such cases of nitrophenol contamination. Moreover, nanoparticles having the size of 10–15 nm obtained from fruit husks also show antibacterial activity against *Bacillus cereus* (Doan et al., 2020).

3.1.3. Medicine

Nypa plant parts from the NNF, NP and NAgS are being explored for producing medicines (Table 3). MDCs used to produce folk medicines from *Nypa* plant parts. However, now a days researchers are also exploring the opportunities for application in modern medicines production. For instance, *Nypa* sap (Chairul et al., 2020), roots (Rahmatullah et al., 2010; Teo et al., 2010), young shoots (IUCN, 2011), leaves (Islam et al., 2020a; Suwardi et al., 2021), leaf midribs (Trisasiwi et al., 2019); and inflorescence (Chairul et al., 2020; Islam et al., 2020a), are explored to produce medicinal compounds. Further, *Nypa* vinegar produced from the sap shows antidiabetic effects (Yusoff et al., 2015a; Yusoff et al., 2015b; Yusoff et al., 2017).

Table 3
Ecosystem services of *Nypa*-based land uses including NNF, NP, NAS, and NAgS (Adapted from the literature cited in subsections 3.1, 3.2, 3.3 and 3.4). Here, "+" indicates confirmation of the corresponding service and "×" indicates "not documented yet" in the literature.

ES categories	Ecosystem services	NNF	NP	NAS	NAgS
Provisioning	Food	+	+	+	+
	Fiber	+	+	×	×
	Medicine	+	+	×	+
	Thatching/ fencing material	+	+	+	×
	Chemical extracts	+	+	×	×
	Fuel	+	+	×	×
	Others	+	+	×	×
Supporting	Biodiversity support	+	+	+	×
	Primary production	+	×	×	+
	Coastal protection	+	+	+	×
Regulating	Water quality	×	+	+	×
	Soil quality	×	+	+	×
	Climate regulation	+	×	×	+
	Prevent soil erosion	+	+	×	×
	Carbon sequestration	×	×	+	×
	Sediment trapping	×	+	+	×
	Salinity regulation	×	×	+	×
Cultural	Cultural value	×	×	+	×
	Education and research	+	+	+	+
	Tourism	×	+	×	×

Leaves serve as a source of medicine and are used to treat jaundice in Indonesia (Suwardi et al., 2021) and Bangladesh (Islam et al., 2020a). Because of containing dolichol, the leaves show pharmacological properties of inhibiting the growth of certain types of cancer (Istiqomah et al., 2020a; Istiqomah et al., 2020b). Leaf extract possesses pain-relieving effects (Marchione, 2011). The IUCN (2011) further mentions the potential for producing vermicide from the young shoots. *Nypa* roots are used for the preparation of folk medicines (Rahmatullah et al., 2010; Teo et al., 2010).

Anti-hyperglycemic and antinociceptive effects have been reported for the extracts obtained from leaf, leaf midrib (Reza et al., 2011) and inflorescence (Kang and Hyun, 2020). The inflorescence is used in folk medicine in tropical countries (Islam et al. 2020; Chairul et al., 2020) and is a traditional remedy against toothache and headache in coastal Bangladesh (Islam et al., 2020a). Further, Kang et al. (2020) reported the neuronal regenerative effect of extracts of inflorescence that can heal sciatic nerve injury and may be of use as a neurotherapeutic.

3.1.4. Thatching materials

Thatching materials from the *Nypa* leaf is the most common and traditional ecosystem service, while researchers confirmed that it is obtained from all the *Nypa*-based land uses (Atheull et al., 2009, 2011; Carandang et al., 2009; Islam et al., 2020b; Langenberger et al., 2009; Rahman et al., 2020). This thatching material is known as "poor man's tin-sheet" in tropical countries like Bangladesh (Miah 2003), while the researchers categorized the thatching material as an ecofriendly construction material (Umar et al., 2017; Rahman et al., 2020). Simple tools and preservation methods are used to process the leaves by hand (Umar et al., 2017) which is an important source of income for MDCs (Islam et al., 2020b). Traditionally, women principally produced the *Nypa* thatch. However, gender-oriented occupation change due to urbanization and land use change has taken place in the Palawan islands of the Philippines (Fadiman, 2008). In Bangladesh men are the primary collectors of leaves and producers of the thatch (Islam et al., 2020b). In Myanmar, tying materials are made from leaf midribs by soaking in water to remove starches and separate the fibers before cording the fibers into rope (Ono and Suzuki, 2013).

3.1.5. Chemical extracts

Among the *Nypa* plant parts, husks, inflorescences, and sap are used to produce chemical extracts. Inflorescence and husk extracts are an effective agent to inhibit the corrosion of aluminum (Satar et al., 2012). However, increasing temperature of extraction negatively affects the corrosion inhibition efficiency (Orubite-Okorosaye et al., 2007). In addition, nanoparticles from *Nypa* possess the ability to absorb nitrophenols which are persistent and highly carcinogenic compounds that accumulate in groundwater due to the degradation of commonly used pesticides (Tchieno and Tonle, 2018). *Nypa* husks are a good source of activated carbon (Dechabun et al., 2020; Taslim et al., 2021), where temperature and chemical activation methods are responsible for producing a highly porous carbon surface (Dechabun et al., 2020).

3.1.6. Fuel

MDCs mainly use the dried leaf base and leaf axes as fuelwood which is one of the most renowned traditional uses (Fong, 1992). In exception to the regular use of seeds as planting materials, some MDCs also use the seeds for fuel purposes (Yanti et al., 2020). Leaf midribs are also utilized as fuelwood (Trisasiwi et al., 2019). Dry fruit husks and seeds have calorific values of 3843 and 4093 kcal/kg, respectively. This falls within the range of the calorific value of traditional fuel pellets, indicating their potential use as biofuel (Harun et al., 2021).

3.1.7. Bioethanol

Among the land uses, NNF and NP have been investigated as the source of bioethanol production. *Nypa* sap has been shown to be a feasible resource for bioethanol production (Natarajan et al., 2012; Tamunaidu et al., 2013; Chairul et al., 2020) because of its favorable chemical composition (Phaiboonsilpa et al., 2011; Tamunaidu and Saka, 2011; Chongkhong and Puangpee, 2018; Chairul et al., 2020). Fermentation time and yeast type determine the ethanol production efficiency from the sap (Tamunaidu et al., 2013; Chairul et al., 2020), while ethanol production time ranges from 30 to 48 h (Tamunaidu et al., 2013). Even the infructescence can be used for bioethanol production (Islam et al. 2020; Chairul et al., 2020).

3.1.8. Other provisioning services

Young leaves are also used for wrapping cigarettes and cooked rice (Fong, 1992). Leaf bases and axes are used to produce fishnet floats and fishing poles, respectively (Fong, 1992). Fruits are used for roof decoration in Cameroon (Atheull et al., 2011). Dried leaf bases and axes are used for making brooms (Fong, 1992).

These provisioning services of *Nypa* supposedly do not differ among the land uses, but likely do vary in terms of total and relative value. Therefore, further studies are recommended to characterize and quantify the differing importance of the various provisioning services of the four main *Nypa*-based land use systems in the tropics. In conclusion, practically all parts of the *Nypa* plant have found some actual use or have potential as food, medicine, materials, fuel or biochemicals. *Nypa* is consistently contributing to the human wellbeing of MDCs, thanks to the multitude of provisioning services for income generation and subsistence. There is a need for planning further study and establishment of *Nypa*-based land uses for sustainable coastal zone management, improvement of household welfare, the establishment of small-scale household level industries and the creation of new employment opportunities in the tropics.

3.2. Supporting services

3.2.1. Biodiversity support

Some work from West Africa, where *Nypa* is invasive, has suggested that *Nypa* could damage fish-the mangrove fish, shrimp, and crab nursery habitat (Isebor et al., 2003; Numbere, 2018) and might generally possess lower marine macrofaunal diversity than more seawards and more saline mangrove zones (Taguiam et al., 2022). However possible, as yet no studies demonstrate conclusively that *Nypa* is a major detriment to faunal diversity compared to either native mangroves or deforested former mangrove areas (Biswas et al., 2018). For instance, Emoyoma et al. (2020) found *Nypa* to possess a similar and equally rich macrobenthos, while Rosle and Ibrahim (2017) documented high densities of the brackish black tiger shrimp in estuarine areas dominated by *Rhizophora* and *Nypa*. Baker et al. (2019) indicated the important function of freshwater estuarine areas in which *Nypa* is dominant as being of vital importance to two commercially important snapper species, namely *Lutjanus fuscescens* and *L. goldiei*. Likewise, Nguyen et al. (2020) concluded that juveniles of the snapper *L. argentimaculatus* in Vietnam were preferentially found in brackish areas dominated by *Nypa*. As *Nypa* is much more associated with freshwater than other more seawards-located, salt-tolerant mangrove species, a lower diversity of marine macrofauna in *Nypa* might fully be expected. Further, NNF supports important fungi (mainly the ascomycetes) by providing essential habitat (Hyde, 1992; Hyde and Sutton, 1992; Jones et al., 1996; Hyde et al., 1999; Pilantanapak et al., 2005; Hyde and Sarma, 2006). Fungi are found in the different *Nypa* parts including leaf, leaf veins, rachides, petiole bases, and inflorescences with varying densities (Hyde and Alias, 2000; Hyde and Sarma, 2006). However, the diversity of fungi also varies over the seasons (Pilantanapak et al., 2005). *Nypa* sap from NNF provides habitat to yeast communities that are also responsible for fermentation of the sap. Fifty-nine yeast isolates have been identified in the sap of *Nypa* from NNF that occurs in Thailand. The most common yeast species found in the *Nypa* sap are *Saccharomyces cerevisiae*, *Hanseniaspora guilliermondii*, and *Lachancea thermotolerans* (Limtong et al., 2020).

Fithria et al. (2020) point to important mangrove fisheries production along the coast of West Aceh, which was the highest direct use value of those *Nypa* dominated mangrove communities. This is evidence that *Nypa* also strongly supports the coastal biodiversity that contributes to the coastal wellbeing by supporting the livelihoods of MDCs and maintaining the ecological balance. Therefore, simple comparisons of biodiversity or faunal densities may not be appropriate or appreciative of any unique role *Nypa* may play in the integrated functioning of the mangrove ecosystems of which it forms part. So, while due to the lack of research, it remains unclear whether and how *Nypa* influences aquatic biodiversity, it forms a unique fresh to brackish mangrove ecotone habitat and probably also plays a separate and yet poorly understood role in the mangrove ecotone.

3.2.2. Primary production

Nypa in all four distinguished land use types also supports MDCs with primary production (Table 3). Robertson et al. (2020) recently found that NNF has among the mid to highest above ground annual net primary production levels (ANPP) along with the highest levels of litter production compared to other mangrove forests. This indicates that it contributes crucially to the carbon budgets of coastal systems. The ANPP of NAgS is comparable to the ANPP of NNF, whereas ANPP tends to increase with increasing latitude up to a certain degree. For example, ANP increases from Papua New Guinea to Australia (Robertson et al., 2020). Furthermore, an increase of above ground biomass (ABG) shows a similar tendency to increase in ANPP. Biomass of *Nypa* has been reported as 22 tons/ha in the NNF (Zuhrizal et al., 2021), while comparable AGB has been reported for NAgS (Robertson et al., 2020). These also vary with the land use systems, successional stages, water discharge and length of the dry period (Robertson et al., 2020).

3.2.3. Coastal protection by wave attenuation

Nypa has the potential to protect the coast by reducing wave impact, where the leaves have been found to play a vital role. Ismail et al. (2012) found that wave attenuation in the Malaysian *Nypa* forest to be correlated to leaf volume. Wave attenuation increases with increasing leaf volume and decreases with increasing water level. Moreover, the species, as is the case with many other palms, can withstand winds of up to 250 km/h (Sen, 2021) and forms the first line of defense in the Indian Sundarbans. However, poor understanding of supporting services provided by *Nypa* in different land use types is evident (Table 3). This indicates the need for further research to characterize the land use specific supporting services of *Nypa*. La et al. (2015) studied the efficacy of wave attenuation in *Rhizophora apiculata* and *Nypa* stands and found that both species were able to strongly dissipate wave energy and therefore have a high potential for use in riverbank protection. Hussain et al. (2012) further found wave reduction efficiency is related to frond volume, and is around 48 % over the first 5 m distance inside the forest.

3.3. Regulating services

The regulating services of *Nypa* in relation to the land use systems are shown in Table 3. Regardless of land use, *Nypa* provides coastal regulating services for climate, soil erosion, water quality (Wankasi and Tarawou, 2008; Syauqiah 2020; Adowei and Abia, 2016), soil quality, salinity (Rahman and Mahmud, 2018), carbon sequestration (Rahman and Mahmud, 2018), and sediment trapping (Fadiman, 2008). Regulation of microclimate might facilitate the growth of crops in NAS and NAgS by acting as a buffer to minimize the exposure to supra-optimal temperature and UV radiation both of which can restrict growth. While some work has been done to document the regulating services provided by *Nypa*, clearly further research is needed to completely understand the regulating services it provides in different land use systems.

3.3.1. Bioremediation

Nypa leaves can be used as a source of activated carbon because the cellulose content is around 29 %. Accordingly, leaf powder has the potential for absorbing and removing Fe and Mn from solution and has prospects for use in water purification (Syauqiah et al., 2020). *Nypa* leaf extracts in hydrochloric acid media inhibit the corrosion of mild steel sheet (Orubite and Oforka, 2004; Orubite-Okorosaye et al., 2007) and aluminum (Satar et al., 2012). Moreover, *Nypa* absorbs the heavy metals like Pb^{2+} and Cu^{2+} ions from the wastewater under favorable pH conditions (Wankasi and Tarawou, 2008) and thus aside from the previously discussed potential for nitrophenol clean-up, clearly has additional potential for soil and water quality regulation and remediation (Table 3).

3.3.2. Carbon sequestration

Barrientos & Apolonio, (2017) studied soil carbon storage in a few mangrove plots and described how a plot dominated by *Rhizophora* had a carbon storage of about 77 tons C ha^{-1} (282.43 tons CO_2 ha^{-1}). Whereas a plot dominated by *Nypa* had a carbon content of 56.12 tons C ha^{-1} (205.95 tons CO_2 ha^{-1}). Their results suggest that among mangroves, *Nypa* did not accumulate the most carbon. However, their study was based on very few plots. Isnaini et al. (2020) document dry biomass densities for the mangroves *Sonneratia alba* and *Nypa* as being 0,74 tons/ha and 11,65 tons/ha respectively, and their carbon accumulations as being 0,35 tons/ha and 5,47 ton/ha, respectively. These results thus suggest that *Nypa* may be among the mangroves that can best absorb and store carbon (Table 3). Finally, the low values of carbon storage indicated for *Nypa* by Hilmi et al (2017) is because of only counting above ground biomass in multispecies mangrove forests in which *Nypa* was only a minor component of the vegetation. Hence, there is a wide disparity between studies for the calculated potential for carbon storage by *Nypa*. In part, these are due to differences in the methods used and in part due to local differences. In a larger study of carbon stocks, Arifanti (2017) determined carbon storage levels of woody mangroves, *Nypa* stands and abandoned shrimp ponds as being 1023 ± 87 Mg C/ha, 982 ± 51 Mg C/ha and 499 ± 56 Mg C/ha, respectively). So, notwithstanding some different results from different studies, the potential for carbon sequestration at a landscape level in this fast-growing palm should be of great value for carbon sequestration in light of urgently needed climate adaptation. This potential should be further studied and developed.

3.3.3. Sea level rise mitigation and rehabilitating ponds back to land

Culver et al. (2015) show how *Nypa*-dominated mangrove forests have been well able to migrate and maintain themselves in the face of sea level rise in the prehistoric and historical past. Handley et al. (2011) further find evidence for the expansion of *Nypa* forests to coincide with global warming. *Nypa* in particular has been shown to be able to rapidly build useful land in deserted ponds based on its production of decay-resistant fodder (Bamroongrusa and Purintavarakul, 2006). The species thus appears to be well able to cope with rapid rates of sea level rise. This, combined with its high rate of accumulation of organic carbon in soils and concomitant ability to elevate the surface levels of soils suggests that the species is ideal for use in sea level mitigation and shrimp pond rehabilitation back to useful emerged land coverage (Table 3). The land use carbon footprint of shrimp production is very high and ranges from 2250 to 4874 kg CO_2 per kg of shrimp when produced in ponds converted from mangroves (Arifanti, 2017). Hence there is a high premium on converting abandoned ponds back to land using mangroves like *Nypa* which at the same time fulfill numerous other ecosystem functions (as already discussed). However, the species will likely only be of use in areas dominated by fresh to moderately brackish conditions as it requires high input of freshwater to thrive (Giesen et al., 2007).

3.3.4. Enhanced aquaculture sustainability

With increasing global temperatures in shallow-water ponds in the tropics, water temperatures often exceed levels that allow healthy fish and shrimp production and exacerbate vulnerability to disease (Reverter et al., 2020). Shade provided by vegetation in and around a waterbody like the pond attracts fish and is used by fish for various reasons (e.g. Helfman, 1981) and can help reduce lethal exposure of cultured fish and/or shrimp to excessive heat (Epaphras et al., 2007; Johnson, 2004). Vegetation inside a pond can also provide shelter for molting shrimp, during which time they are vulnerable to cannibalism by conspecifics (Abdussamad and Thampy, 1994; Gopalakrishnan and Parida, 2005), and thus enhance shrimp survival. Recent work further shows the role of mangroves in serving as a potential food source for shrimps inside ponds (Alam et al., 2021; Alam et al., 2022). While *Nypa* is generally excluded from studies into mangrove functioning (e.g. Alam et al., 2021), due to its unique position as a mangrove palm, it remains unclear whether its leaf litter can serve as a significant food input to the pond as with other mangroves (Table 3). However, actinomycete bacteria isolated from the sediment root zone have been found to have the potential to improve the feed quality in aquaculture systems (Yanti et al., 2020). Earlier, Ama-Abasi and Umorem (2013) compared the decomposition of *Rhizophora racemosa* and *Nypa* and concluded that nutrient contents and decomposition rate in the two species were comparable. Even though its value in pond nutrition remains unclear and debatable, it still may serve a number of the mentioned aquaculture-associated pond functions to the benefit of shrimp or fish culture. In addition, it happens to be one of the mangrove species favored by Bangladesh farmers because of its many other uses in the household economy of MDCs (Rahman et al., 2020). Hence it can certainly play a larger role than at present in enhancing aquaculture in terms of environmental and economic resilience.

3.4. Cultural services

Like the other services, *Nypa* provides cultural services for the MDCs in the tropics (Table 3). Such cultural values for *Nypa* have only been confirmed for NAS (Rahman and Mahmud, 2018). Meanwhile, all the *Nypa*-based land uses have been explored to understand the opportunities for education and research, and tourism. The latter can be a major opportunity for the MDCs to improve their livelihoods but has so far only been reported for the NP landscape (Fadiman, 2008; Rahman and Mahmud, 2018). The highest tourism-related cultural services from *Nypa* might be expected from NNF but still remains to be studied.

4. Land use specific valuation of *Nypas*' ecosystem services

Valuation of ecosystem services in the restoration and conservation of mangroves is a recent innovation in the field of assessing the value of mangroves to human wellbeing (Miah 2003). Accordingly, researchers have assessed the economic value of *Nypa*'s ecosystem services under different land use systems (Table 4). Economic valuation depends on the availability of knowledge, data and scientific attention dedicated to a species. For example, lack of knowledge about processing technologies and relatively lower scientific attention are partly responsible for *Nypa* often not being considered as an economic crop (Hermanto et al., 2020). This problem is hardly unique to *Nypa* but common to other often invisible, undervalued and under-appreciated natural resources such as most non-timber forest products (Debrot et al., 2020) and even artisanal fisheries (Guggisberg et al., 2022). The economic value of *Nypa* leaves from NNF has been economically assessed as a contribution to the livelihoods of MDCs in coastal Bangladesh (Islam et al., 2020b). While *Nypa* leaf collection generates attractive income for the MDCs of the Sundarbans, it is most useful as a supplementary income generating activity because of its seasonal nature (Islam et al., 2020b). However, also local infrastructure, threats, market price and access to capital greatly affect the income of leaf collectors from the Sundarbans (Islam et al., 2020b). Cheablam and Chanklap (2020) more broadly assessed the value of *Nypa*'s economic value by including molasses, syrup, granulated sugar, vinegar, and thatching material in their study for Thailand's NP where MDCs generate 90–130 US$ per day by producing sugar. Finally, in Indonesia, the value of *Nypa* sap from NP has also been evaluated as raw material for bioethanol production (Hidayat, 2018). Hence, all analyses so far available have only considered a limited subset of provisioning services in the economic valuation of *Nypa*. Not surprisingly such limited valuations by design fail to quantify the true importance of the different *Nypa* land use systems (Rahman and Mahmud, 2018). Hence, there is a clear need for further research before the value of *Nypa*'s ecosystem services in NNFs, NP and NAgS land uses can be more fully appreciated. This review also revealed that there are no valuations yet of the ecosystem services of *Nypa* from NAgS (Table 4).

Table 4
Studies on ecosystem services valuation for *Nypa* in relation to *Nypa*-based land uses.

Valuation of Ess	Country	Land uses	Reference
Leaf collection as livelihood strategy	Bangladesh	NNF	Islam et al., 2020b
Nypa products for contributing to quality of life	Thailand	NP	Cheablam and Chanklap, 2020
Sap as raw material for bioethanol production	Indonesia	NP	Hidayat, 2018
Ecosystem services of *Nypa*	Bangladesh	NAS	Rahman and Mahmud, 2018
Income from sap production as food	Bangladesh	NP	Miah et al., 2003

5. Restoration

Restoration of coastal ecosystems in different mangrove land use scenarios has been a common effort across the tropics since the last century, and *Nypa* has been one of the key species. Because *Nypa* is a mangrove palm that has the ability to quickly colonize under suitable circumstances even if highly petroleum polluted (Akpan et al., 2020) or deforested and degraded (Numbere 2019a, Eddy and Basyuni, 2020). It can be considered as a valuable ecosystem engineer, as it is capable of greatly altering ecosystems or even creating novel ecosystems in areas where it is not native (Fehr et al., 2020). It is critical to include socio-economically important species in order to muster local support for restoration efforts (Joshi 2006). Accordingly, it has been proposed to use *Nypa* for restoring the coastal ecosystem in Ghana, where restoration was deemed too slow with native species (Rubin et al., 1999). Later, Nguyen et al (2016) described a successful mixed plantation of *Nypa* and other mangrove species in Vietnam. Important challenges to integrating *Nypa* into different land use forms remain. One of these is the limited understanding of *Nypa*'s propagation techniques (Zaki et al., 2017). Partly because of its exceptional pioneering characteristics (e.g., relatively wide environmental tolerance, easy dispersal, vegetative propagation via rhizomes and firm rooting once established), it is also a potent invasive species in areas where disturbance has weakened the native mangrove stands (Dutrieux et al., 1990; Numbere 2019a, Eddy and Basyuni, 2020; Moudingo et al., 2020; Nwobi et al., 2020). Examples of such *Nypa* invasions have been reported for Indonesia (Eddy and Basyuni, 2020) and Nigeria (Ellison et al., 2010; Numbere 2019b; Nwobi et al., 2020). In Nigeria, the land cover of *Nypa* increased by about 700 % by replacing the native mangroves between 2007 and 2017 (Nwobi et al., 2020). Apart from these countries, *Nypa* plantations have been established in the coastal areas of Cameroon, Panama, Trinidad and Tobago (Ellison et al., 2010). In their recent review on the impacts of invasive species on mangrove ecosystems, Biswas et al. (2018) indicated that *Nypa* is known to modify hydrology and impede the natural regeneration of native species. However, *Nypa* invasion can be controlled by applying appropriate management techniques like leaf harvesting and/ or sap tapping (Okugbo et al., 2012; Ijeoma et al., 2015). These management techniques of *Nypa* purportedly reduce the vigor of *Nypa* and quell its invasive characteristics. However, for this to be effective, harvest needs to minimally cover costs and generate income, and this is only possible once suitable harvest methods, processing and marketing are developed in the tropics.

6. Threats to *Nypa*-based land uses

Today, both natural phenomena (such as droughts due to climate change) and anthropogenic activities (deforestation and river diversion) are acting as consistent threats to the wider spread of *Nypa*-based land uses, ultimately limiting the scope for *Nypa*-based land uses to deliver a multitude of ecosystem services in the tropics (Fadiman, 2008; Chowdhury et al., 2016; Cheablam and Chanklap, 2020; Fawzi and Husna 2021). Even though IUCN categorizes *Nypa* as a "least concern" species, a worldwide decline of 20 % global areal coverage for this species in mangrove forests has been documented (Ellison et al., 2010). Meanwhile, the coverage of *Nypa* and the *Nypa*-based land uses continue to decline. Threats to *Nypa*-based land uses are several (Table 5). *Nypa* is threatened due to coastal development interventions, over-exploitation, climate change, aquaculture expansion, increasing salinity due to groundwater extraction and river diversion, sea level rise, wave action, pollution, and natural disasters in the NNF across the tropics. For example, *Nypa* has almost disappeared in the Indian Sundarbans due to a combination of reduced freshwater flow, increasing salinity and sea level rise (Ellison et al., 2010; Chowdhury et al., 2016). Like the *Nypa* in several other tropical countries, *Nypa* in Thailand is largely threatened by natural disasters such as drought and insect pest infestations (Cheablam and Chanklap, 2020). In many cases inland *Nypa* forest migration is not feasible due to the presence of other mangrove species or because the freshwater areas in which *Nypa* especially thrives have been usurped for agriculture or urbanization (Widodo et al., 2020). The continued destruction of *Nypa* in the NNF of Indonesia continues to occur due to continued coastal development towards meeting the demand of ever-increasing population growth (Widodo et al., 2020). Expansion of aquaculture practice is also a leading threat to the NNF in Indonesia (Fawzi and Husna, 2021), while outbreaks of fire facilitated by drought are also becoming more and more of a threat (Mubarak et al., 2020).

Nypa in NP faces many similar anthropogenic and natural threats as seen in NNF (Fadiman, 2008; Rubin et al., 1999) In NPs, the *Nypa* are threatened because of costal development activities, over exploitation, aquaculture, and agricultural expansions, increasing salinity and natural disasters (Table 5). Nevertheless, as can be seen in Table 5, *Nypa* of NPs is relatively less vulnerable to several categories of threats than that of NNFs. Even so, *Nypa* in the NP setting remains extremely vulnerable compared to the *Nypa* associated with NAS and NagS. We believe this may be due to the fact that in both of the latter systems *Nypa* has a more-or-less understood and locally supported role to play in the production system. This not only guarantees their inclusion but only at low densities that simultaneously make them less vulnerable to natural epidemics.

Almost no information is actually available about the threats that are affecting the *Nypa* in the NAS and NAgS land use systems (Table 5). One major threat to *Nypa* in NAgS systems appears to be from the agricultural expansion itself by which the NAgS is supplanted by agricultural systems without *Nypa* (Robertson et al., 2020). The threats to *Nypa* in the different land use scenarios seem to clearly differ but are poorly understood. Much work is needed to better understand the factors that need to be addressed in order to reduce threats and make better use of the many promises associated with expanded *Nypa* land use.

7. Way forward

Many others have emphasized the benefits for sustainable management, cultivation and utilization of *Nypa* for the advancement of sustainable environmental, social, and economic development. Coastal ecosystem and ecosystem services are indispensable for human existence, and *Nypa*-based land uses contribute in this considerably. However, the lack of past scientific and commercial development attention translates into the current paucity of knowledge on critical aspects of production and value-added consumer products for *Nypa* all the while

Table 5
Nypa-based land use specific threats to *Nypa* in the tropics (Adapted from the literature cited in section 6). Here "+" indicates confirmation of the corresponding threats and "×" indicates "not documented yet" in the literature.

Threats	NNF	NP	NAS	NagS
Coastal development activities	+	+	×	×
Overexploitation	+	+	×	×
Agricultural expansion	+	+	×	+
Aquaculture expansion	+	+	×	×
Climate change	+	×	×	×
Increasing salinity	+	+	×	×
Erosion	×	+	×	×
Insect attack	×	+	×	×
Pollution	+	×	×	×
Sea level rise	+	×	×	×
Natural disaster	+	+	×	×
Fire	+	×	×	×

ecosystem valuation for *Nypa*-based land uses remains in its infancy. The distribution of *Nypa*-based land uses has been especially poorly studied, where remote sensing could be a useful tool to explore and monitor the land uses for future reference. The lack of land use specific information on the biology, growth, and production of *Nypa* creates additional barriers for restoration and conservation. Accordingly, major research on land use specific fundamental biology of *Nypa* is needed to better understand the effects of hydrology and edaphic factors on *Nypa* production.

Each part of *Nypa*, from root to seed of the *Nypa* is already serving MDCs throughout much of the tropical Pacific and Indian oceans by contributing to household income and subsistence. However, successful market development for *Nypa* products depends on the development of appropriate production and processing technology and a proper understanding of the value chain and these are key areas for further research. This review emphasizes the great potential benefits of more widely establishing *Nypa*-based land uses in suitable coastal areas following local level planning. However, monoculture of mangrove species in the NP, NAS and NagS land use settings may be vulnerable to disease or insect infestation and ultimately lead to degradation of coastal ecosystem services. To overcome such problems of monoculture, it would be better to combine *Nypa* with other mangroves like *Sonneratia species*, *Avicennia species*, *Rhizophora species*, and *Heritiera* species to establish *Nypa*-based multi-species mangrove land uses, where it is appropriate. Even the integration of other lesser-known palm species, such as the more salt-tolerant sugar date palm *Phoenix sylvestris,* could solve disadvantages related to *Nypa* monoculture. In order to promote such effective *Nypa*-based land uses, further research is imperative. In addition, to ensure the sustainability of these *Nypa*-based land uses, improvement of harvesting techniques followed by research focusing on sustainability and technology transfer among the MDCs are a prerequisite. Research on alternative uses of palms that already play an important role in home gardens and agroforestry systems across the SE Asian region is suggested. A better understanding of the carbon sequestration potential of *Nypa*-based land uses might be useful in facilitating or promoting the adoption of *Nypa* restoration and use in local to regional level planning processes. In addition, a better understanding of the value of the ecosystem services of *Nypa* in relation to different land use options is poorly understood as these have only been explored for the NAS setting.

Assessments of land use specific threats to *Nypa*, especially for land uses like NAS and NagS would be supportive for landscape level planning and decision-making processes and are also recommended for further research. Overall, in areas with low to moderate salinity, the transformation of the agricultural systems towards *Nypa*-based land uses would be a suitable option for building resilience through sustainable transformation at a landscape level. Local level planning with necessary incentives, such as payment for ecosystem services (PES) for *Nypa* rehabilitation as a nature-based solution, might be a practical way to restore and conserve such a precious species and simultaneously alleviate poverty by securing livelihoods for the MDCs in the coastal areas of tropical countries.

8. Conclusion

We here collate and review substantial progress that has been made in terms of research and development on different aspects of *Nypa* biology and *Nypa*-based land uses over the last few decades. Based on this review numerous avenues for valuable future research can be identified. In addition to the land uses of NNF and NP, two new land use types, namely NAS and NagS have been adopted by MDCs in the tropics. Even though the growth of *Nypa* varies between studies, growth and biomass production of *Nypa* may be fairly similar among the land uses studied. While MDCs are making use of diversified provisional ecosystem services from practically all parts of the *Nypa* plant, the differences in ecosystem services among different types of *Nypa* land use remain poorly understood. In addition, the valuation of ecosystem services of *Nypa*-based land use requires further study to assess the value of such land use and development to sustainable coastal development. However, notwithstanding major economic and ecosystem value, *Nypa*-based land uses are declining in the tropics at an alarming rate due to threats like coastal development, aquaculture, agricultural expansion, increasing salinity, and others. Therefore, this review urgently recommends stakeholders to invest in further research and development interventions to promote *Nypa*-based land uses as nature-based solutions suitable for sustainable transformation of land uses in the coastal tropics.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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