

Utilization status of mangrove ecosystem services of the Ajkwa estuary, Mimika, Central Papua, Indonesia

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ABSTRACT

The capacity of the Ajkwa mangrove ecosystem in Mimika, Central Papua, Indonesia to provide benefits through ecosystem services is important to investigate due to the intensive interactions between economic developments and this ecosystem. This study aimed to identify the types and capacities of the Ajkwa mangrove ecosystem services and assess their utilization status. Data were collected through quantitative measurements of ecosystem services across five ecosystem compartments: mature mangroves, young mangroves, water bodies, sediment accretion areas, and swamps. These data were complemented by interviews with local communities throughout the Ajkwa estuary. Comparison between available ecosystem services and their utilization showed that provisioning services (such as fishes, crustaceans, molluscs, fruits, boars, etc.) were dominated by mature mangroves (36.4%) and water bodies (32.7%), while young mangroves contributed the least (3.6%). Cultural ecosystem services remained underutilized, with utilization levels below 50% of their estimated capacity. In contrast, regulating and maintenance services functioned at near-optimal levels, approaching 100% of their capacity, and were primarily associated with mature mangroves. These services included nutrient and organic matter retention, coastal protection from erosion, carbon sequestration and storage, nursery, feeding, and spawning habitats for marine biota, and sediment trapping. The relatively low utilization of ecosystem services by local communities was mainly attributed to traditional livelihood practices and limited technology. As mature mangroves exhibited the highest ecosystem service capacity, management efforts should prioritize expanding mature mangrove areas through restoration and planting in sediment accretion zones while protecting existing mature mangrove forests from degradation and disturbance.

1. Introduction

Studies on mangrove ecosystem services and their dynamics remain relatively limited in Indonesia and, to date, have not been conducted

along the southern coast of Papua, including the Ajkwa Estuary. As a matter of fact, understanding the capacity of mangrove ecosystems to provide ecosystem services is essential and of importance, particularly in relation to their interactions with human activities, where humans act

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2352-4855/© 2026 Elsevier B.V. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

both as drivers of ecosystem change and as beneficiaries of ecosystem services. Nevertheless, numerous studies have examined mangrove ecosystems from ecological and ecosystem-service perspectives in various areas outside Indonesia. For example, studies conducted in Malaysia by Chen et al. (2024), in Ghana, West Africa, by Jayson-Quashigah et al. (2025), and in China by Lee et al. (2025) have demonstrated that mangrove ecosystems are highly productive tropical coastal ecosystems that play significant ecological and economic roles. Consequently, they are of considerable importance not only for biodiversity conservation and ecosystem functioning but also for the livelihoods of surrounding human communities.

Other studies resulted that mangrove ecosystems provide a wide range of ecological and economic services that benefit both the mangrove habitat itself and adjacent terrestrial and marine environments (Tasneem and Ahsan, 2024; Analuddin et al., 2025; van Zanten et al., 2025). These services include the provision of aquatic food resources such as fish, shrimp, bivalves, and crabs; timber and fuelwood for construction materials and charcoal production; economic resources for local communities (Chen et al., 2024); opportunities for shrimp and crab aquaculture (Amien et al., 2025); and various non-timber products, including honey and fruits. Mangroves also support tourism, education, and scientific research activities. In addition, mangrove ecosystems provide essential regulating and supporting services, including nursery, feeding, and spawning habitats for marine biota; coastal protection against erosion; substrate stabilization; sediment and pollutant retention; carbon sequestration and storage; and the export of organic matter and food resources to adjacent coastal and marine ecosystems (Lovell et al., 2025; Bimrah et al., 2022; Ali et al., 2025; Humber et al., 2024).

In Indonesia, mangrove ecosystems occur in nearly in all estuarine areas and are increasingly exposed to significant environmental threats. In general, mangrove ecosystems face both global and local threats, including climate change, upstream deforestation, and conversion to alternative land uses. Mangrove conversion is a particularly critical issue on Java Island, where extensive land-use change has resulted in substantial mangrove loss (Arifanti et al., 2022).

In contrast, mangrove ecosystems in eastern Indonesia, including those in Mimika Regency, Central Papua Province, remain in relatively better condition, largely due to lower levels of economic development and reduced anthropogenic pressures (Arifanti et al., 2022; Kasihiw et al., 2023, 2024). The Ajkwa Estuary, located along the coast of Mimika Regency, has been included within the environmental management area of a mining company since 1998. Traditionally, the mangrove ecosystem of the Ajkwa Estuary has served as an important source of livelihood for local communities, providing a variety of natural resources that support their daily subsistence and economic activities.

However, mining activities in the upstream portion of the watershed have introduced environmental challenges that may affect the capacity of the Ajkwa mangrove ecosystem to provide services to both human communities and the surrounding environment. One of the major threats is the high rate of sedimentation occurring in the area, which has altered sediment characteristics and hydro-oceanographic processes within the estuary. These changes have, to some extent, influenced the distribution, structure, and development of mangrove vegetation throughout the estuarine system (Setyadi et al., 2021a).

Given the dynamic nature of the Ajkwa mangrove ecosystem and its interactions with economic activities in the surrounding area, its capacity to provide ecosystem services may be affected, making it an important subject for investigation. One key aspect that warrants assessment is the identification and evaluation of the ecosystem services provided by the mangrove ecosystem, as well as the status of their availability relative to their utilization by local communities. To date, such an assessment has not been conducted in the Ajkwa Estuary.

The central research question of this study is what ecosystem services are provided by the mangrove ecosystem of the Ajkwa Estuary, including their types, capacities, and utilization status. Addressing this question is essential for developing a scientific basis for the sustainable

management of the mangrove ecosystem in the future. The findings are expected to contribute to evidence-based decision-making and support the formulation of effective mangrove management strategies in the study area.

Accordingly, this study aimed to: (1) identify the ecosystem services provided by the mangrove ecosystem in the Ajkwa Estuary, Mimika Regency, Central Papua, Indonesia; (2) assess the capacity of these ecosystem services; and (3) elucidate the utilization status of mangrove ecosystem services in the Ajkwa Estuary.

2. Materials and methods

2.1. Study area

The study area was the Ajkwa Estuary, located on the southern coast of Mimika Regency, Central Papua Province, Indonesia (Fig. 1). The study site was located at the lower end of the Ajkwa Estuary, directly facing the relatively shallow waters but biologically productive of the Arafura Sea. Along the coastal area of the study area, there are some river mouths highly affected by the incoming riverine turbid water. The incoming rivers carry land-derived sediment, which flocculates on encountering saline water and, in combination with coastal processes, causes sedimentation in the estuaries (Setyadi et al., 2021b). Several reports have shown that the lower end of the estuary predominantly contains mangrove ecosystem possessing a tree density of 767–1345 tree ha⁻¹ with an average canopy height of 39 m. The dominant mangrove species in the upper region include *Rhizophora apiculata* and *Bruguiera gymnorhiza*, while the lower region consists of *Avicennia marina* and *Sonneratia alba* (Setyadi et al., 2021a). Mangrove ecosystem in this area has been utilized by local inhabitant as their source of foods and their other daily needs such as for source of materials (Setyadi et al., 2021b). To facilitate ecosystem service assessment of this study, the Ajkwa mangrove ecosystem was divided into five ecological compartments: mature mangrove area, young mangrove area (mangrove vegetation less than 1 m height), swamp area, new land (sedimented area) and waters (canals and estuary). These 5 compartments were used as the primary units of analysis for identifying ecosystem services and quantifying the capacity of the Ajkwa mangrove ecosystem to generate and sustain those services.

The study was conducted in the period between 2019 and 2023.

2.2. Data collection

Data collection was conducted through several approaches, namely (1) field measurements and samplings of some environmental parameters, (2) interviews with local people who lived in their traditional villages and utilize resources of the Ajkwa mangrove ecosystem, and (3) secondary data from various studies conducted in the area. The data collected consisted of data and information on services provided by ecosystems (which were mainly mangrove ecosystem and their associated biota and resources), and their relative magnitude or volume.

Mangrove ecosystem of the study area was divided into five compartments: mature mangrove area, young mangrove area (mangrove vegetation less than 1 m height), swamp area, new land (sedimented area) and waters (canals and estuary) (Fig. 2).

Data on ecosystem services of the mangrove ecosystem collected in the study area were based on the CICES category (Haines-Young and Potschin, 2018), namely provisioning, regulation and maintenance, and cultural services (Table 1).

2.2.1. Provisioning services data

Data on provisioning services were composed of both secondary and primary data. The primary data were ecological datasets collected by the PTFI's monitoring programs (PTFI, 2020), consisting of information on fish communities. In addition, data on the utilization of goods from the mangrove ecosystem were collected in the form of primary data,

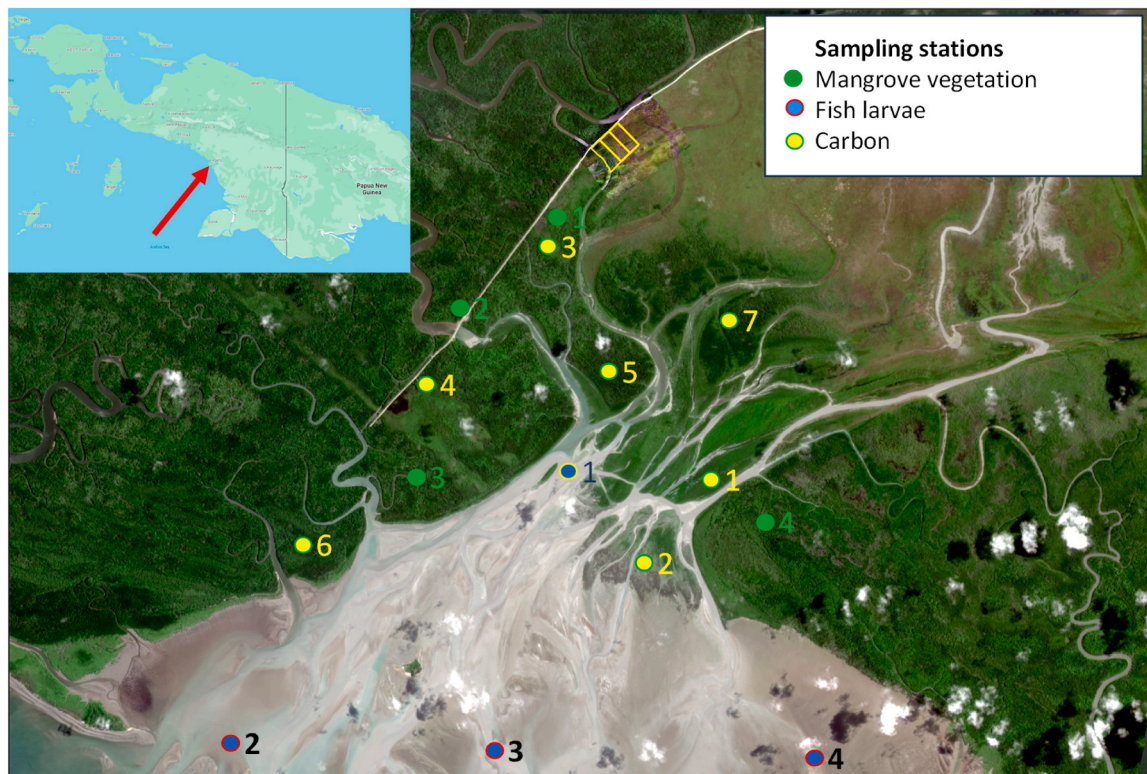


Fig. 1. Study area and measurement stations in the Ajkwa Estuary, Papua (satellite imagery is owned by PTFI and specially analysed for this study).

through an intense interview with local fishers and people in the local markets, specifically on the confirmation of the products gained from the mangrove ecosystems that were used for their food and materials. Local markets that were surveyed included Gorong-Gorong, Pasar Baru Sentral Timika, Pasar Lama Koperapoka, Tipuka Village, and Ayuka Village. Data on fish species were also confirmed by secondary data taken from PTFI's monitoring results on fish communities of the estuary (PTFI, 2020). Besides volume data of each of provisioning service goods, field survey was conducted by collecting relative magnitude of volume of each of the goods by classing them into 5 classes of levels (scores): (1) very low; (2) low; (3) moderate; (4) high and (5) very high. Scores data of each goods of provisioning service were collected through in depth interview to the local community collectors. Total of respondents from the local people who are collectors of provisioning service goods are 236 collectors. In the interview, each respondent was asked to provide answers regarding the availability and utilization level/class of a particular provisioning service. Interview was conducted in Indonesian language mixed with local dialect and accompanied by mining company persons as interpreter. Indonesian language is commonly spoken by local people of Ajkwa.

2.2.2. Regulation and maintenance services data

Data that were categorized as regulation and maintenance services were services provided by the mangrove ecosystem in the form of regulatory and maintenance services for environmental functioning. In CICES criteria (Haines-Young and Potschin, 2018), data belonging to this category were datasets on indirect services, such as mangrove ecosystem functions as nursery ground for marine biota larvae, carbon storage, and prevention of coastline against abrasion, storm, and surge. This category of information were collected through interviews with the community and data collected from routine monitoring carried out by PTFI as well as direct primary measurements at the study area.

Data on fish larvae as representation of mangrove service as nursery ground, were collected through samplings by using a fish-larvae net (mesh size of 100 micron) at four stations consisting one station of water

channels inside the mangrove forest and three in the marine sides of the estuary (Fig. 1). At each sampling point, as much as 100 L of water were filtered through fish-larvae net, following Kelso et al. (2012) method. The filtered water containing fish larvae were preserved by formaldehyde solution (4%) and brought to the main laboratory for identification and density counting.

Mangrove species and density field observation were conducted at four stations which able to cover spatial variability of the mangrove communities (Fig. 1). The observation sites were at west dyke (St. 1), outside of west dyke (St.2), Yamaima (St. 3) and Pasir Hitam (St. 4). Station 1 represents the condition of mangroves in the upper part of estuary area and affected by mining activities, station 2 represents the condition of mangroves outside the dyke which is an area not directly affected by mining activities, and stations 3 and 4 are in the lower Ajkwa estuary area which is more exposed to sea tides and affected by mining activities. Species identification and density observation were conducted at each observation site by applying 100 m² transect plot with three replications in each of the plot, following Noor et al. (1999) and Giesen et al. (2007). Carbon storage capacity of the ecosystems was estimated through Allometric method as suggested for above ground biomass by Dharmawan and Siregar (2008) for *Avicennia marina*, Vinh et al. (2019) for *Rhizophora apiculata*, Fromard et al. (1998) for *Rhizophora mucronata*, Clough and Scott (1989) for *Rhizophora stylosa*, Hanh et al. (2016) for *Sonneratia caseolaris* and Komiyama et al. (2005) for other (common) species. The below-ground biomass were estimated for *Avicennia marina* (Komiyama et al., 2008), *Rhizophora stylosa* (Gevana and Im, 2016), *Sonneratia caseolaris* (Hanh et al., 2016), and other species using common equations (Komiyama et al., 2005) as shown in Indrayani et al. (2021). Mangrove vegetation data collected from mangrove vegetation analysis were used in calculating the carbon content of each category: the old/mature mangrove community, the medium-age mangrove community and the young mangrove community. Scores for regulation and maintenance ecosystem service category were collected through in depth interview with local communities from the villages of Gorong-Gorong, Pasar Baru Sentral Timika, Pasar Lama

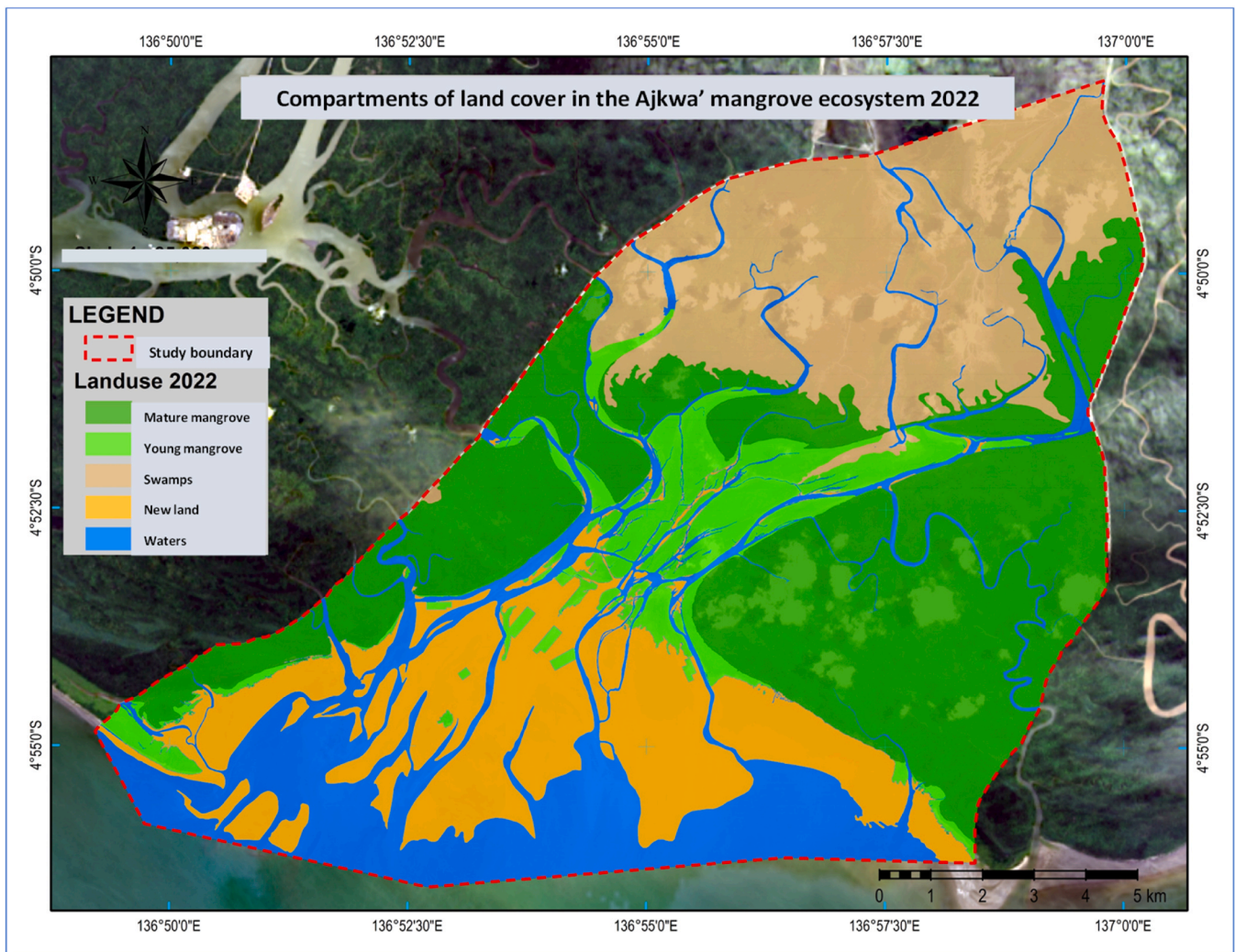


Fig. 2. Compartments in the Ajkwa's Estuary: mature mangrove, young mangrove, swamps, new land and waters. Data were spatially analysed based on satellite imagery owned by PTFL.

Koperapoka, Tipuka Village, and Ayuka Village. Each of the village is represented by Chief of Tribe, their deputies and members of communities as well as sellers in the traditional market (total 186 respondents). In the interview, each respondent was asked to provide answers regarding the availability and utilization level/class of a regulation and maintenance service, which was classed into five classes (scores), namely: (1) very low; (2) low; (3) moderate; (4) high and (5) very high.

2.2.3. Cultural services data

Cultural services data were datasets related to mangrove ecosystem services in terms of providing cultural services, such as tourism areas, education, and research activities. At present, ecosystem services at the study area in the form of tourist attractions had not been carried out. However, the estuary had been utilized as a place for studies and researches.

2.3. Data analysis

Based on the criteria developed by Burkhard et al. (2012), the calculated scores data were grouped into supply and demand services categories. Subsequently, the data were analyzed to obtain the classification of the relative magnitude score of each type of ecosystem service based on the criteria developed. Analysis was carried out using matrixes called the matrix of capacity (supply), demand, and budget of mangrove

ecosystem services. The matrix of capacity showed the relative magnitude of ecosystem services availability, the matrix of demand showed the relative magnitude of ecosystem services utilized by local communities, and the matrix of the budget was balanced between resource availability and its actual utilization by communities. In each of matrix, mangrove ecosystem service relative magnitude was analyzed based on each compartment namely (1) mature mangrove area; (2) young mangrove area; (3) swamp area; (4) new land area and (5) waters.

2.3.1. Matrix of capacity (supply) of mangrove ecosystem services

The assessment of the capacity matrix was carried out to determine the potential of mangrove resources that could be utilized by humans in the study area. This assessment was obtained from literature studies, and the author's observations as well as information obtained in the field. The capacity matrix described the existing supply of mangrove benefits for each type of utilization. Assessment of the capacity matrix ranged between 1 and 5, which indicated the level of capacity of ecosystem services. The magnitude of the capacity level for each service was based on the available data, such as the abundance of marine biota (fishes, crustaceans, and molluscs), the estuary sediment and water quality, fish larvae density, mangrove density, and wildlife animals found in the study area. In addition to quantitative data derived from regular and routine monitoring of PTFL, the classification process used qualitative insights gathered from interviews with local residents. These interviews

Table 1

Types of data collected based on ecosystem service categories identified by the Ajkwa's mangrove area, grouped according to the Common International Classification of Ecosystem Services (CICES) v5.1 (Haines-Young and Potschin, 2018)(<http://cices.eu/>).

Division	Group	Class	Class Type	Categories	Source of Data
Provisioning					
Nutrition	Biomass	Wild animals and their outputs	Animals by amount, type	Fisheries (Food)	Local fish market surveys and fish monitoring report PTFI 2021-2022
		Wild animals and their outputs	Animals by amount, type	Crustacea (Food)	Local fish market surveys and interview with local people
		Wild animals and their outputs	Animals by amount, type	Mollusks (Food)	Local fish market surveys and interview with local people
		Wild animals and their outputs	Animals by amount, type	Birds	Local fish market surveys and interview with local people
		Wild animals and their outputs	Animals by amount, type	Crocodiles, snakes and lizards	Local fish market surveys and interview with local people
		Wild animals and their outputs	Animals by amount, type	Honey	Local fish market surveys and interview with local people
		Wild animals and their outputs	Animals by amount, type	Wood	Local fish market surveys and interview with local people
Regulation & Maintenance					
Mediation of flows	Mass flows	Mass stabilization and control of erosion rates	By reduction in risk, area protected	Protection from Erosion/facilitating sedimentation	Secondary data
Maintenance of physical, chemical, biological conditions	Lifecycle maintenance, habitat and gene pool protection	Maintaining nursery populations and habitats	By amount and source	Nursery ground	Fish Larvae Samplings
	Soil formation and composition	Decomposition and fixing processes	By amount, concentration or climatic parameter	Carbon deposit	Carbon storage estimation
Cultural					
	Intellectual and representative interactions	Entertainment	Ecotourism and recreation		
		Education and research	Education and research		Number of research conducted in the area

results were cross checked by data obtained through local market surveys.

2.3.2. Matrix of demand for mangrove ecosystem services

The evaluation of the demand matrix was performed to find out the mangrove ecosystem services that had been utilized (existing utilization) by the community. The assessment was based on the results of the interviews during market surveys with a range of scores between 1 and 5, which indicated the level of utilization. Participant answers to questions about the use of mangrove ecosystems used a Likert's scale of 1 (very low), 2 (low), 3 (moderate), 4 (high), and 5 (very high). Likert's scale analysis was applied as recommended by Likert (1932) and Olsson (2022). Subsequently, the answers were grouped and categorized into 5 classes (scores) with the interval for each class measured by the criteria, as shown in Table 2.

2.3.3. Budget (availability) matrix of mangrove ecosystem services

The assessment of the availability matrix was carried out to analyze the balance between the potential and existing utilization of the services. Through the budget (availability) matrix, the types of ecosystem

services with high, moderate, and low utilization, and those that were not utilized could be identified. The matrix rating was obtained from the result of reducing the supply matrix and the demand matrix. The range of matrix values was between -5 – 5 , which indicated the level of availability of ecosystem services. Scores between -5 and -1 showed the rate of utilization of mangrove ecosystem services, which exceeded availability. When the value was 0, it indicated that the utilization rate was balanced with its potential and utilization. Meanwhile, a positive

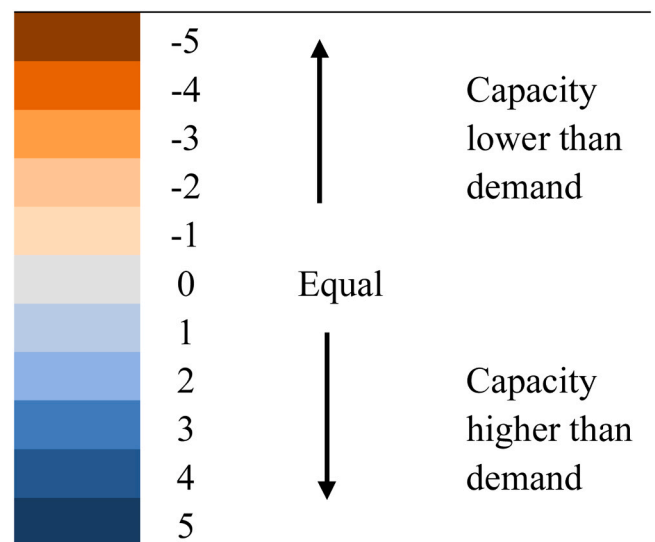


Fig. 3. Budget (availability) matrix analysis criteria in the classification of ecosystem service (Burkhard et al., 2012).

Table 2

Assessment criteria for capacity and demand category of mangrove ecosystem service.

Class range	Score	Category
1.00–1.80	1	Very Low
1.81–2.60	2	Low
2.61–3.40	3	Moderate
3.41–4.20	4	High
4.21–5.00	5	Very High

Source: Burkhard et al. (2012)

value between 1 and 5 indicated that utilization of services was still below the available capacity, as shown in Fig. 3.

3. Results and discussion

3.1. Results

3.1.1. Brief description of mangrove community in the Ajkwa Estuary

The mangrove ecosystem in the Ajkwa Estuary is located on muddy substrate that spread down to the river mouth. It is recorded that the study area comprised a total of 23 species of mangrove (Table 3), including *Avicennia alba*, *Avicennia lanata*, *Bruguiera gymnorhiza*, *Bruguiera parviflora*, *Bruguiera sexangula*, *Campostemon schultzei*, *Cerbera manghas*, *Ceriops tagal*, *Heritiera littoralis*, *Homonoia javensis*, *Inocarpus sp.*, *Lumnitzera littorea*, *Nypa fruticans*, *Rhizophora mucronata*, *Rhizophora apiculata*, *Rhizophora mangle*, *Rhizophora stylosa*, *Sonneratia caseolaris*, *Sonneratia alba*, *Stemonurus javanicus*, *Xylocarpus granatum*, and *Xylocarpus moluccensis*. This indicates that mangroves in the study area were relatively heterogeneous with the distribution of mangrove species found to spread across each observation plots.

3.1.2. Utilization of natural resources by the community

The social-ecological system in the study area was greatly influenced by the presence of the community. Concerning the location of the Ajkwa Estuary, there were at least 4 areas of customary control, based on traditional land tenure. The communities at the location were indigenous community with a level of control that had been passed down from generation to generation traditionally and customarily. They live in the villages that are in the form of traditional settlements, with housing and health support provided by the mining company and government. There is no written territorial land ownership or official agrarian law. They live under local customary law of order and led by a tribal chief. The study area was the traditional regions of Koperapoka-Nawiri, Nayaro, and Ayuka-Tipuka. The area of customary control over natural resources in the Ajkwa Estuary was the northwest area of the estuary, which was the

region controlled by the community from Koperapoka-Nawiri community, the northeast area was controlled by the Nayaro community, and the southern area (lower estuary) was controlled by the Ayuka-Tipuka indigenous community (Fig. 4).

The level of technology in utilizing the mangrove ecosystem and its related resources was still in the simple and traditional category. Utilization of natural resources was dominated by hunting systems using traditional equipment. The harvested goods in the form of food are sold in the local traditional market near Timika town. Provisioning goods are utilized at the subsistence rather than commercial level. The system for preserving harvested products had not been widely applied to communities in the study area.

3.1.3. Mangrove ecosystem service

Based on field observation and interviews with local communities through market surveys, a total of 61 ecosystem services were identified, consisting of 47 provisioning, 11 regulation and maintenance, and 2 cultural services in the Ajkwa Estuary (Tables 5–7).

3.1.3.1. Provisioning service. The provisioning service of the mangrove ecosystem of Ajkwa Estuary was in the form of food, containing of fish, bivalves, crustaceans, fruits, vegetables, mammals, and birds. Data on provisioning services were divided into 2 types, namely datasets on potential and existing provisioning services. Volume of fish catches (as potential service) are shown in Figs. 5 and 6. Photos of meats and fishes sold in the local markets which are taken from Ajkwa's mangrove ecosystem are shown in Fig. 7.

3.1.3.2. Regulation and maintenance service. Ecosystem services belonging to the Regulation and Maintenance Service category were in the form of regulation, support, and maintenance provided by the mangrove ecosystem to both natural and human systems in and around the mangrove area. Compared to the provisioning ecosystem services category which was visible, data on ecosystem services from this category was difficult to differentiate between potential and existing. Primary data that could be used included datasets on estuary sedimentation and accretion rates, the ability of mangrove sediments to store contaminants, the ability of the mangrove ecosystem to reduce waves and abrasion, provide spawning, feeding and nursery ground habitat, and store carbon.

Another well-known ecosystem service provided by the mangrove ecosystem was spawning and nursery areas for various larvae and juveniles of marine biota. One of these important roles was shown in Fig. 8, which revealed the number of groups of marine biota larvae found in the mangrove area. This indicated that the marine fish were in the mangrove area during the larvae and juveniles growth phase, showing the essential role of Ajkwa mangrove as an important nursery ground area.

One of the important services of the mangrove ecosystem, in the form of regulation and maintenance services, is its ability to store carbon. From the results of calculations using species-based allometric methods (please see Methods chapter) the values of carbon deposits stored as plant biomass (both for above and below ground) were presented in Table 4.

3.1.3.3. Cultural service. Cultural services in the study area were in the form of providing a location for tourism, education and research. Potentially, the Ajkwa mangrove area had great potential as a location for ecotourism, through objects in the form of mangrove ecosystems and its various biotic community associations. In addition, the mangrove area in the Ajkwa Estuary was also an ideal region for carrying out education and research. As part of natural ecosystem education, the Ajkwa mangrove ecosystem was an area that was capable of serving these purposes. The results showed that more than 10 investigations had been

Table 3
Mangrove vegetation species composition in the Ajkwa Estuary (PTFI, 2020).

No	Sites of observation	Species	Family
1	West Dyke (St. 1)	<i>Rhizophora apiculata</i>	Rhizophoraceae
		<i>Rhizophora mangle</i>	Rhizophoraceae
		<i>Campostemon schultzei</i>	Malvaceae
2	Outside of west dyke (St. 2)	<i>Bruguiera sexangula</i>	Rhizophoraceae
		<i>Cerbera manghas</i>	Apocynaceae
		<i>Diospyros sp.</i>	Ebenaceae
		<i>Diospyros maritima</i>	Ebenaceae
		<i>Stemonoporus sp.</i>	Dipterocarpaceae
		<i>Intsia bijuga</i>	Fabaceae
		<i>Aglaia odorata</i>	Meliaceae
		<i>Heritiera littoralis</i>	Malvaceae
		<i>Homonoia javensis</i>	Euphorbiaceae
		<i>Syzygium sp.</i>	Myrtaceae
		<i>Stemonurus javanicus</i>	Stemonuraceae
		<i>Sterculia sp.</i>	Malvaceae
		<i>Xylocarpus granatum</i>	Meliaceae
3	Yamaima (St.3)	<i>Inocarpus sp.</i>	Fabaceae
		<i>Rhizophora apiculata</i>	Rhizophoraceae
		<i>Rhizophora mangle</i>	Rhizophoraceae
		<i>Bruguiera gymnorhiza</i>	Rhizophoraceae
		<i>Heritiera littoralis</i>	Malvaceae
		<i>Xylocarpus granatum</i>	Meliaceae
		<i>Limonia littoralis</i>	Rutaceae
		<i>Avicennia lanata</i>	Achantaceae
		<i>Avicennia alba</i>	Achantaceae
		<i>Rhizophora stylosa</i>	Rhizophoraceae
4	Pasir Hitam Aijkwa (St.4)	<i>Rhizophora apiculata</i>	Rhizophoraceae
		<i>Nypa fruticans</i>	Arecaceae
		<i>Hibiscus tiliaceus</i>	Malvaceae
		<i>Sonneratia caseolaris</i>	Lythraceae
		<i>Sonneratia alba</i>	Lythraceae
		<i>Sonneratia alba</i>	Lythraceae

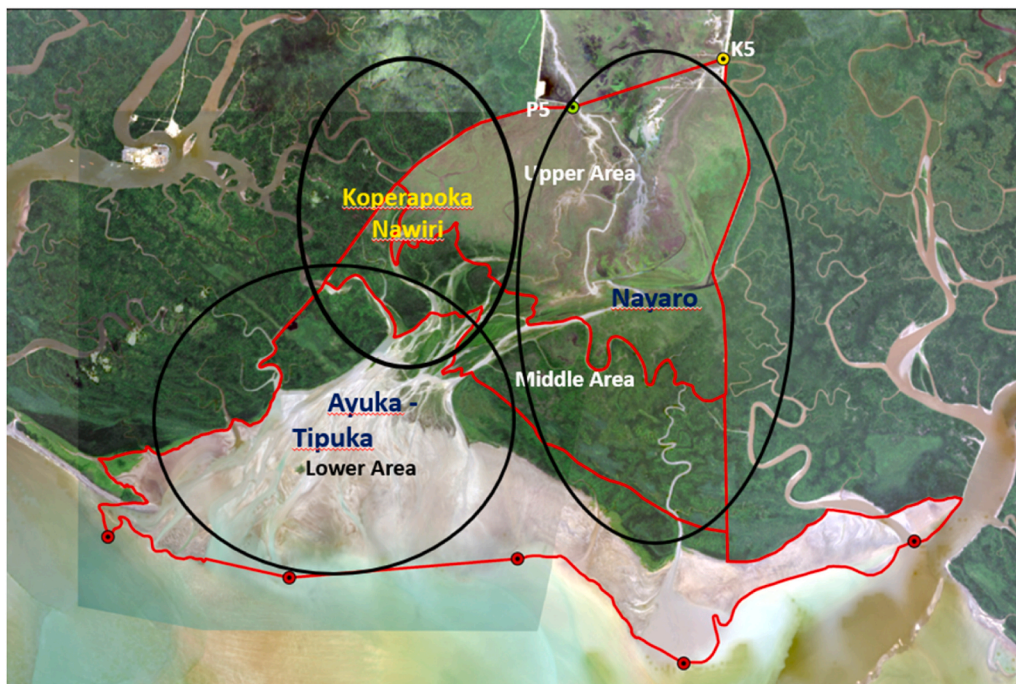


Fig. 4. Sketch of the area of utilization of mangrove ecosystem resources by the local community at the Ajkwa's Estuary location. Black oval lines are imaginary area of customary resource utilization ownership of each village. There is no official legal document of customary area resource utilization ownership.

Table 4
Carbon storage capacity at several class of mangrove communities in the study area.

No. of station	Class of mangrove ecosystem	Species dominant	Location	Carbon storage (ton CO ₂ /ha)
1	Young mangrove	<i>Rhizophora mucronata</i>	Ajkwa river mouth	20.06
2	Young mangrove	<i>Sonneratia caseolaris</i>	Pasir Hitam	66.93
3	Medium mangrove	<i>Rhizophora apiculata</i>	Close to west dyke	117.01
4	Medium age mangrove	<i>Campostemon schultzei</i>	Close to west dyke	75.74
5	Old mangrove	<i>Rhizophora mucronata</i>	Middle estuary	728.68
6	Old mangrove	<i>Rhizophora mucronata</i>	Middle estuary	778.34
7	Old mangrove	<i>Bruguiera parviflora</i> , <i>Rhizophora apiculata</i>	Middle – lower estuary	986.54

conducted in the mangrove ecosystem of the Ajkwa Estuary and some of them were part of the final stage of educational programs.

3.1.4. The balance between potential and actual utilization of mangrove ecosystem services in the Ajkwa Estuary

In the following paragraph, the relative magnitude of each category of mangrove ecosystem in the study area was presented in a comparison format between potential capacity, existing utilization, and availability status (budget) using the Burkhard et al. (2012) method.

3.1.4.1. Matrix of the capacity of the Ajkwa Estuary mangrove ecosystem services. A matrix of the capacity of mangrove ecosystem services in the Ajkwa Estuary was developed to analyse the magnitude of products and services that were potentially provided by local communities, as shown in Table 5. In the matrix, different colours showed varying levels of a class of availabilities. The mangrove ecosystem of the Ajkwa Estuary

potentially provide a high volume of ecosystem services, covering provisioning, regulation and maintenance, and cultural services.

The distribution of potential mangrove ecosystem services for all categories showed a relatively high score ranging between 4 and 5, both in the categories of provisioning, regulation and maintenance, and cultural services. Depending on their origin, mangrove ecosystem services could be provided from the water column, basic substrate, roots, and trees.

For the provisioning services, the high potential was identified in the form of fruits, wood, leaves, fish larvae, adult fish, shrimp, crabs, lizards, crocodiles, ant nests, and wild boars. Meanwhile, from the category of regulation and maintenance services, mangrove ecosystems provided services as sea wave breakers, carbon storage, oxygen producers, nursery ground, feeding ground, spawning ground, exporter of organic matter to the open sea, and habitat for a variety of wildlife. In the category of cultural services, the Ajkwa mangrove estuary ecosystem provides place for ecological tourism, education, and research.

3.1.4.2. Matrix of demand for mangrove ecosystem service of the Ajkwa estuary. Compared to the supply (capacity) matrix, the demand matrix contained the categories and types of existing environmental services provided by the mangrove ecosystem in the Ajkwa Estuary. The services of the mangrove ecosystem were those that had been and were currently being felt by the people around the location. Categories and types of existing services (demand) are presented in Table 6. For all categories and types of environmental services, scores were given based on the results of interviews with communities that used mangrove ecosystem services. In this table, the provisioning services category was generally still of low value and was lower compared to the magnitude in the capacity matrix. For local communities, a relatively large type of provision of environmental services was the use of fish, shrimp, crabs, wild boars, *Nypa* leaves and ant nests. Meanwhile, the use of birds, clams and lizards was still very low.

For the regulation and maintenance category, these types of services were relatively large despite the unawareness of the provision of environmental services indirectly for their lives. An example of these types of environmental services was that the mangrove ecosystem area served as

Table 5

Matrix of capacity of ecosystem service of Ajkwa's Mangrove Estuary.

No	Ecosystem Service	Mature Mangrove	Young Mangrove	Swamp	New land	Waters
	Provisioning					
	Fish and mussels					
1	<i>Rastrelliger Sp.</i>					5
2	<i>Chana Sp.</i>			5		5
3	<i>Clarias Sp.</i>			4		4
4	<i>Oreochromis niloticus</i>			5		5
5	<i>Oreochromis mossambicus</i>			5		5
6	<i>Plotosus sp.</i>					4
7	<i>Lates calcarifer</i>					5
8	<i>Lutjanus sp.</i>					4
9	<i>Scomberomorus sp.</i>					3
10	<i>Penaeus merguensis</i>					5
11	<i>Scylla serrata</i>					5
12	Pelecypoda	5	5		5	
13	Mussels (<i>Telescopium</i>)	5	5		5	
14	<i>Terapon sp.</i>					4
15	<i>Brama sp.</i>					4
16	<i>Dasyatis sp.</i>					3
17	<i>Rachycentron canadum</i>					3
18	<i>Chanos sp.</i>					3
19	<i>Lutjanus papuensis</i>					3
	Mammals, reptiles and birds					
20	<i>Sus sp.</i> (Wild boar)	5				
21	<i>Casuaris sp.</i> (Kasuari)	5				
22	<i>Dasyuroides sp.</i>	3				
23	<i>Palanger sp.</i> (Kuskus)	3				
24	Snakes	3				
25	<i>Apodemus sp.</i>	3				
26	<i>Crocodylus sp.</i>	3				
27	<i>Varanus sp.</i> (lizard)	4				
28	<i>Macrocephalon sp.</i> (Maleo)	5				
	Fruits and vegetables					
29	<i>Musa sp.</i> (Banana)	5				
30	Banana leaf	5				
31	Banana blossom	5				
32	Coconut	5				
33	<i>Artocarpus sp.</i> (Jerk fruit)	4				
34	<i>Gentum gnemon</i> (Ganemo)	5				
35	<i>Manihot sp.</i> (Casava)	5				
36	Daun Pakis	5				
37	<i>Ipomoea aquatica</i>			5		5
38	Sweet potato (<i>Ipomoea batatas</i>)			4		
39	<i>Colocasia sp.</i> (Talas)			4		
40	<i>Annona muricata</i> (Sirsak)			5		
41	<i>Leucaena leucocephala</i> (Petai Cina)			5		
42	<i>Pandanus sp.</i> (Daun pandan)			3		
43	<i>Carica papaya</i> (Pepaya)			2		
44	Papaya leaf			2		
45	<i>Pigafetta sp.</i> (Sagu)			5		
46	<i>Myrmecodia sp.</i> (Sarang semut)	2				
47	<i>Nypa leaf</i>	4				
	Regulation and Maintenance					
1	Wave breaker	5			3	3
2	Sediment trap	5	4	4	4	3
3	Coastal protector against storm and surge	5	4	3	4	
4	Carbon storage	5	4	3	2	2
5	Pollutant absorber	5	3	4	3	3
6	Oxygen producers	5	3	3	1	1
7	Nursery ground	5	2	3	1	4
8	Feeding ground	5	2	3	3	3
9	Spawning ground	5	2	3	2	3
10	Organics export	5	2	3	2	2
11	Wildlife habitat	5	2	3	1	3
	Cultural Service					
1	Tourism	5	5	4	4	3
2	Research and education	5	5	5	5	5

Notes:

	0	: No capacity
	1	: Very low capacity
	2	: Low capacity
	3	: Moderate capacity
	4	: High capacity
	5	: Very high capacity

Table 6

Matrix of demand of mangrove ecosystem service of Ajkwa's estuary.

No	Ecosystem Service	Mature Mangrove	Young Mangrove	Swamp	New land	Waters
	Provisioning					
	Fish and mussels					
1	<i>Rastrelliger Sp.</i>					4
2	<i>Chana Sp.</i>			3		4
3	<i>Clarias Sp.</i>			3		3
4	<i>Oreochromis niloticus</i>			3		3
5	<i>Oreochromis mossambicus</i>			3		4
6	<i>Plotosus sp.</i>					3
7	<i>Lates calcarifer</i>					4
8	<i>Lutjanus sp.</i>					3
9	<i>Scomberomorus sp.</i>					2
10	<i>Penaeus merguensis</i>					4
11	<i>Scylla serrata</i>					4
12	Pelecypoda	4	4		4	
13	Mussels (<i>Telescopium</i>)	3	3		3	
14	<i>Terapon sp.</i>					2
15	<i>Brama sp.</i>					2
16	<i>Dasyatis sp.</i>					1
17	<i>Rachycentron canadum</i>					1
18	<i>Chanos sp.</i>					1
19	<i>Lutjanus papuensis</i>					2
	Mammals, reptiles and birds					
20	<i>Sus sp.</i> (Wild boar)	4				
21	<i>Casuarius sp.</i> (Kasuari)	3				
22	<i>Dasyuroides sp.</i>	1				
23	<i>Palanger sp.</i> (Kuskus)	1				
24	<i>Snakes</i>	1				
25	<i>Apodemus sp.</i>	2				
26	<i>Crocodilus sp.</i> (crocodile)	1				
27	<i>Varanus sp.</i> (lizard)	2				
28	<i>Macrocephalon sp.</i> (Maleo)	3				
	Fruits and vegetables					
29	<i>Musa sp.</i> (Banana)	3				
30	Banana leaf	4				
31	Banana blossom	3				
32	Coconut	3				
33	<i>Artocarpus sp.</i> (Jerk fruit)	3				
34	<i>Gentum gnemon</i> (Ganemo)	4				
35	<i>Manihot sp.</i> (Casava)	3				
36	Daun Pakis	4				
37	<i>Ipomoea aquatica</i>			4		4
38	Sweet potato (<i>Ipomoea batatas</i>)			3		
39	<i>Colocasia sp.</i> (Talas)			2		
40	<i>Annona muricata</i> (Sirsak)			1		
41	<i>Leucaena leucocephala</i> (Petai Cina)			1		
42	<i>Pandanus sp.</i> (Daun pandan)			2		
43	<i>Carica papaya</i> (Pepaya)			1		
44	Papaya Leaf			1		
45	<i>Pigafetta sp.</i> (Sagu)			3		
46	<i>Myrmecodia sp.</i> (Sarang semut)	1				
47	<i>Nypa</i> leaf	3				
	Regulation and maintenance services					
1	Wave breaker	5			3	3
2	Sediment trap	5	4	4	4	3
3	Coastal protector against storm and surge	5	4	3	4	
4	Carbon deposit	5	4	3	2	2
5	Pollutant absorber	5	3	4	3	3
6	Oxygen producers	5	3	3	1	1
7	Nursery ground	5	2	3	1	4
8	Feeding ground	5	2	3	3	3
9	Spawning ground	5	2	3	2	3
10	Organics export	5	2	3	2	2
11	Wildlife habitat	5	2	3	1	3
	Cultural Service					
1	Tourism	0	0	0	0	0
2	Research and education	3	3	2	2	1

Notes :

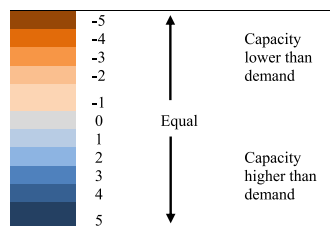
0	: No demand
1	: Very low demand
2	: Low demand
3	: Moderate demand
4	: High demand
5	: Very high demand

Table 7

Matrix of availability (budget) of mangrove ecosystem service of Ajkwa Estuary.

No	Ecosystem Service	Mature Mangrove	Young Mangrove	Swamp	New land	Waters
Provisioning						
Fish and mussels						
1	<i>Rastrelliger Sp.</i>					1
2	<i>Chana Sp.</i>			2		1
3	<i>Clarias Sp.</i>			1		3
4	<i>Oreochromis niloticus</i>			2		2
5	<i>Oreochromis mossambicus</i>			2		1
6	<i>Plotosus sp.</i>					1
7	<i>Lates calcarifer</i>					1
8	<i>Lutjanus sp.</i>					1
9	<i>Scomberomorus sp.</i>					1
10	<i>Penaeus merguensis</i>					1
11	<i>Scylla serrata</i>					1
12	Pelecypoda	1	1		1	
13	Mussels (<i>Telescopium</i>)	2	2		2	
14	<i>Terapon sp.</i>					2
15	<i>Brama sp.</i>					2
16	<i>Dasyatis sp.</i>					2
17	<i>Rachycentron canadum</i>					2
18	<i>Chanos chanos sp.</i>					2
19	<i>Lutjanus papuensis</i>					1
Mammals, reptiles and birds						
20	<i>Sus sp.</i> (Wild boar)	1				
21	<i>Casuaris sp.</i> (Kasuari)	2				
22	<i>Dasyuroides sp.</i>	2				
23	<i>Palanger sp.</i> (Kuskus)	2				
24	Snakes	2				
25	<i>Apodemus sp.</i> (Tikus hutan)	1				
26	<i>Crocodylus sp.</i> (crocodile)	2				
27	<i>Varanus sp.</i> (lizard)	2				
28	<i>Macrocephalon sp.</i> (Maleo)	2				
Fruits and vegetables						
29	<i>Musa sp.</i> (Banana)	2				
30	Banana leaf	1				
31	Banana Blossom	2				
32	Coconut	2				
33	<i>Artocarpus sp.</i> (Jerk fruit)	1				
34	<i>Gentum gnemon</i> (Ganemo)	1				
35	<i>Manihot sp.</i> (Casava)	2				
36	Daun Pakis	1				
37	<i>Ipomoea aquatica</i>			1		4
38	Sweet potato (<i>Ipomoea batatas</i>)			1		
39	<i>Colocasia sp.</i> (Talas)			2		
40	<i>Ammon muricata</i> (Sirsak)			4		
41	<i>Leucaena leucocephala</i> (Petai Cina)			4		
42	<i>Pandanus sp.</i> (Daun pandan)			1		
43	<i>Carica papaya</i> (Pepaya)			1		
44	Papaya Leaf			1		
45	<i>Pigafetta sp.</i> (Sagu)			2		
46	<i>Myrmecodia sp.</i> (Sarang Semut)	1				
47	<i>Nypa leaf</i>	1				
Regulation and maintenance services						
1	Wave breaker	0			0	0
2	Sediment trap	0	0	0	0	0
3	Coastal protector against storm and surge	0	0	0	0	
4	Carbon deposit	0	0	0	0	0
5	Pollutant absorber	0	0	0	0	0
6	Oxygen producers	0	0	0	0	0
7	Nursery ground	0	0	0	0	0
8	Feeding ground	0	0	0	0	0
9	Spawning ground	0	0	0	0	0
10	Organics export	0	0	0	0	0
11	Wildlife habitat	0	0	0	0	0
Cultural Service						
1	Tourism	5	5	4	4	3
2	Research and education	2	2	3	3	4

Notes:



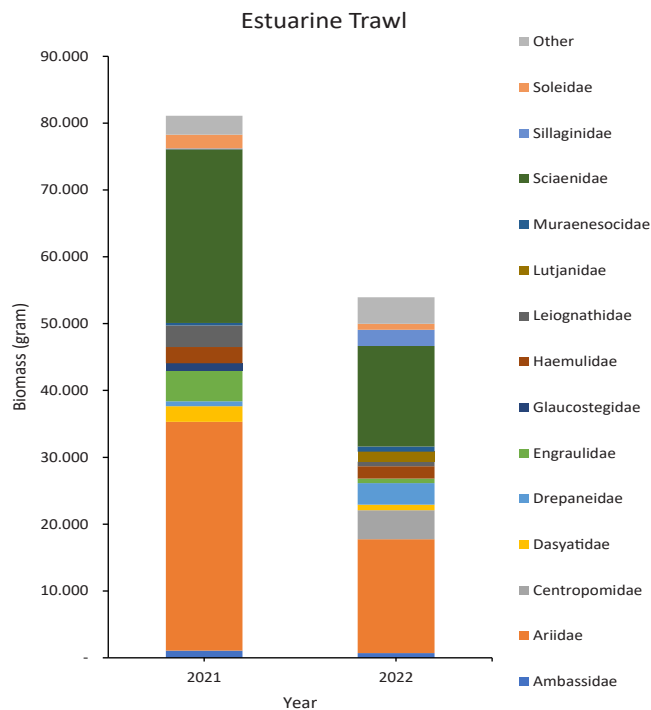


Fig. 5. Fish family distribution caught by Trawl in Ajkwa Estuary (Biomass per volume trawled - gram/825 m³) (PTFI, 2020).

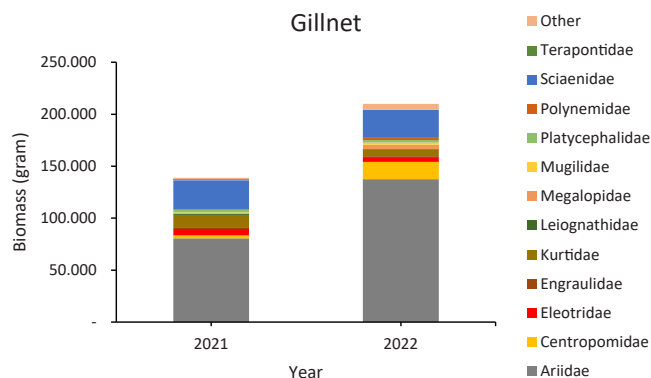


Fig. 6. Fish family distribution caught by Gillnet in Ajkwa Estuary (Biomass per gillnet area trapped - gram/200 m²) (PTFI, 2020).

a nursery, feeding, and spawning ground for various marine biota. In the water areas within the mangrove ecosystem, various types of fish larvae were found. As a sediment trap, the mangrove ecosystem area at the study location played a very important role, as indicated by the increasing growth of new land in the Ajkwa Estuary, which was formed due to mud sedimentation. The mangrove ecosystem area also served as a carbon and nutrient stores. Monitoring data on sediment quality, namely, the carbon content and nutrients in the sediment showed relatively high values. This indicated that sediment in the mangrove ecosystem area provided ecosystem services in the form of trapping carbon and nutrients.

In the culture category, these types of environmental services were still very low for ecological tourism, but relatively high for education, study and research services. The mangrove ecosystem area in the study area had long been used as research and education area.

3.1.4.3. Matrix of budget (availability) of mangrove ecosystem service in the Ajkwa Estuary. Matrix of availability (budget) shows the balance of

availability of particular ecosystem services and was calculated by reducing the capacity value by the demand value. These findings showed the availability status of services, whether deficit or surplus. When the value is positive, it indicates that community's demand for environmental services do not exceed the stock. Meanwhile, when the value is negative, it indicates that demand for a type of ecosystem services exceed the available capacity. In a case where the score was zero (0), it shows that the demand for a type of service exhibits a balance between availability and demand by people.

In Table 7, the values in the availability matrix were positive, indicating that the availability of ecosystem services had not been utilized optimally by the community, particularly for the provisioning and culture ecosystem services categories. Meanwhile, for the category of regulation and maintenance, the availability of services had been maximally used by the human system in the study area. The people in the study area did not realize that their services had benefited from this category.

Some of the mangrove ecosystem services that had been utilized optimally by local communities included fish, crabs, shrimp, shellfish, ant nests, wild boar (provisioning category), all ecosystem services from the regulation and maintenance category, and services provided places for education and research (cultural services).

Table 8 and Fig. 9A shows total number of services, which is the sum up of all identified services without considering its scores. Fig. 9B shows the total of service's scores, which is sum up of score of the all identified services. Fig. 9C shows the mean of service's scores.

In term of number of services (Table 8 and Fig. 9A), the highest number of provisioning service was observed at mangrove compartment as much as 20 services, while the lowest number was observed at the new land compartment as much as 2 services. The highest number of regulation and maintenance service was observed at the new land and mature mangrove compartments, with a total value of 11 services. For cultural service, all compartments had relatively low value of 2 service.

Sum up of service scores is shown in Fig. 9B, showing mature mangrove compartment has the highest value, both for provisioning, regulation and maintenance service categories. The lowest of this variable is observed in cultural category of service, in all of types of compartments: mature mangrove, young mangrove, new land, waters and swamps.

In terms of the mean service score (Fig. 9C), the highest average score of ecosystem service was observed at the mature mangrove compartment for regulation and maintenance service, while the lowest was obtained at the new land compartment for cultural services. From all of the variables, it indicates that the mature mangrove compartment in the Ajkwa mangrove ecosystem provided the highest number of services and its score. The waters compartment of the mangrove ecosystem was the second-highest habitat and provided both the number and scores of ecosystem services. On average, the compartment of swamps provided the lowest in number and score of ecosystem service. These findings highlight the critical role of mature mangrove compartments in the Ajkwa mangrove ecosystem as the primary providers of ecosystem services and provide a scientific basis for future management strategies in the study area. Such strategies should prioritize expanding and maintaining the largest possible extent of mature mangrove stands while minimizing degradation and damage to existing mature mangrove forests.

3.2. Discussion

The results indicated that three major categories of ecosystem services are present within the study area. The first category comprises provisioning services, including timber, food resources such as fish, crustaceans, molluscs, mammals, marsupials, fruits, and vegetables, which are primarily utilized through direct extraction and consumption by local communities. Local residents depend on a wide range of products derived from mangroves and associated habitats to meet their daily



Fig. 7. Photos of some food (meats, fishes and fruits) harvested by local community sold in local markets. From left to right of the upper graphs: wild boar (*Sus* sp.) meats, common snakehead fish (*Chana* sp.) and catfish (*Clarias* sp.). Middle graphs: mangrove crab (*Scylla serrata*), Spanish mackerel (*Scomberomorus* sp.) and barramundi (*Lates* sp.). Lower graphs: Banana (*Musa* sp.), vegetables (banana leaves, jerk fruit, *Ipomoea* sp.) and banana blossom.

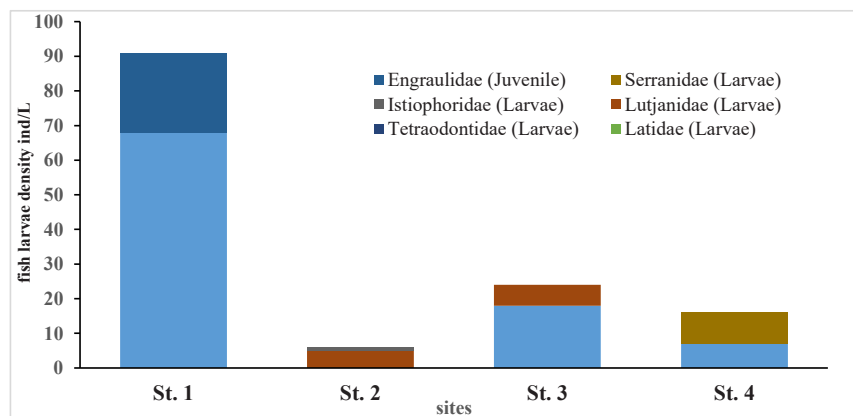


Fig. 8. Fish larvae and juvenile density in the study area as type of regulation and maintenance ecosystem service provided by the Ajkwa mangrove ecosystem. Stations position refers to stations of larvae shown in Fig. 1.

subsistence and livelihood needs.

The second category consists of regulating and maintenance services, including sea wave attenuation, sediment trapping, coastal protection against storms and surges, carbon storage, pollutant absorption, oxygen production, nursery grounds, feeding grounds, spawning grounds, organic matter export, and wildlife habitat provision. Specifically for

service of soil formation able to cover of around 50% of the total regulating service. Although these services are largely intangible and not directly perceived by local communities, they generate substantial long-term ecological and socio-economic benefits.

The third category is cultural ecosystem services, encompassing tourism, spiritual values, and research opportunities. The provision and

Table 8

Comparison in number of ecosystem services between compartments in the Ajkwa's mangrove ecosystem.

Variables	Mangrove Compartments				
	Mature mangrove	Young mangrove	Swamp	New sedimented land	Waters
Number of provisioning service	20	2	13	2	18
Number of regulating and maintenance service	11	10	10	11	10
Number of cultural service	2	2	2	2	2
Total number	33	14	25	15	30

utilization of these services remain relatively limited in the study area, largely due to its remote location and distance from major urban centers. Nevertheless, despite their non-material nature, demand for cultural ecosystem services has shown increasing trends, particularly through the growing popularity of non-consumptive activities such as bird-watching and other nature-based recreational pursuits.

In relation to the ecosystem services of the Ajkwa mangrove ecosystem, the following paragraphs discuss in detail, the ecological processes operating within the study area that affect the ecosystem's capacity to provide services, together with a detailed discussion of the characteristics, functions, and specific attributes of each ecosystem service category.

The southern coast of the Indonesian part of the New Guinea Island, including the Ajkwa Estuary, was subjected to the process of natural sedimentation, causing the region to be dominated by the muddy substrate, which was suitable for mangrove ecosystems. The sedimentation rate in this area was relatively high, as reported by Setyadi et al. (2021b) showing a value of 18.5–25.4 mm year⁻¹ or 1.88–2.98 g cm⁻² year⁻¹, with elevation changes of 8.4–12.3 mm year⁻¹. Consequently, the Ajkwa Estuary continued to experience an increase due to the high rate of sedimentation. Concerning mangrove habitat, the Ajkwa Estuary and its surroundings were very suitable habitats for mangrove (Setyadi et al., 2021a). They stated that the Ajkwa Estuary mangrove ecosystem had high species diversity, accommodating more than 43 plant species from 27 major components and 16 minor components, belonging to 17 families.

Data shown in Brunskill et al. (2004) and Setyadi et al. (2021b) show that there was an increase in sedimentation rate in the period between 2004 and 2021, from 4.5 to 7.5 kg dry wt m⁻² yr⁻¹ calculated by Brunskill et al. (2004) elevated to 18.8 kg dry m⁻² yr⁻¹ calculated by Setyadi et al. (2021b). The increase is likely to be due to a combination of natural causes and anthropogenic process in the upland area of the watershed. However, in its relation to mangrove habitat development, sedimentation in the estuary may cause accretion that provides new areas for mangrove establishment.

The utilization level of natural resources as provisioning services of the mangrove ecosystem by the community was still relatively low. This was because apart from the relatively low human population, there were still traditional and small-scale efforts to utilize natural resources in this area. The utilization by local communities was generally on a small scale for their own household needs and as a good source of protein. The low rate of utilization of living resources among communities in the study area was largely due to the conservation values held by the Papuan traditional people. These findings were consistent with several studies, including Nurhidayah et al. (2023), Tebaiy et al. (2015) and Tebaiy and Manuputty (2016), who had extensively investigated conservative values in the use of coastal natural resources of Papuan indigenous

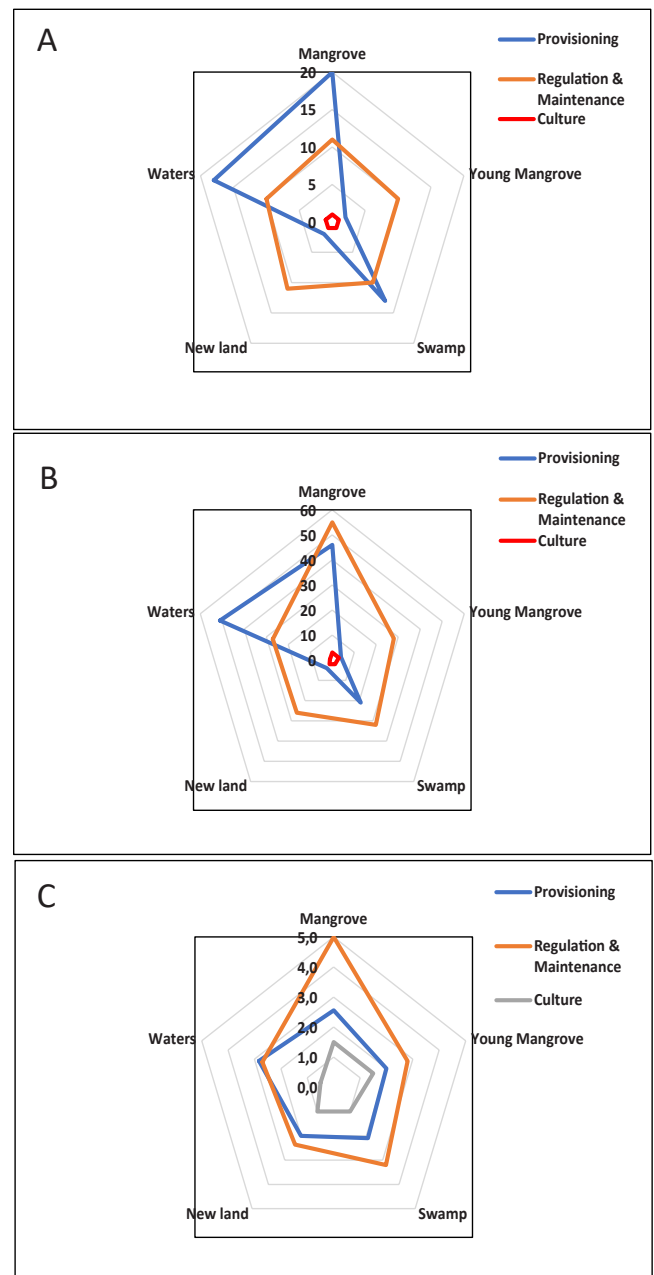


Fig. 9. Comparison between compartments of the mangrove ecosystem in terms of the actual (demand) of total number of ecosystem services (upper graph - A), the total score of ecosystem services (middle graph - B) and mean of the score of ecosystem services (lower graph - C) at all ecosystem service categories.

communities. The community in the study area utilized natural resources, specifically as a form of provisioning services, such as various fishery products, fruits, plants, and other food products from the Ajkwa mangrove ecosystem on an artisanal scale. The products obtained were sold directly to the market on the same day after leaving enough for the family's needs. This typically happened because the community had not practiced food storage technology for preserved food. From a conservation perspective, customary patterns and systems were essential and could prevent excessive exploitation of natural resources in mangrove ecosystem.

Regulation and maintenance ecosystem services category of the mangrove ecosystem in the study area showed effective utilization, specifically in terms of providing habitat, nursery ground, spawning and

feeding ground, trapping sediment, storing carbon, exporting organics to the high seas, and other various ecological roles. As a sediment trap, this function was effective with evidence of the increasing development of emergent land in estuaries. The new sedimentary land was then colonized by mangrove seeds and developed into a mangrove island colony. Until now, it had been recorded that in the period between 1999 and 2020, sedimentary land appeared in the lower estuary covering an area of 1005 ha (PTFI, 2020), which was currently inhabited by new young mangrove vegetation. Previous studies also stated that there had been a formation of new lands due to high sedimentation processes, which was the result of the role of mangrove as sediment traps (Setyadi et al., 2022). Massive root systems combined with various physical oceanographic conditions caused the mangrove ecosystem to always act as a sediment trap and could increase land area in an estuary (Karimi et al., 2022; Chen et al., 2025; Zeng et al., 2026). Several studies had been conducted regarding the high rate of addition of new land in mangrove estuaries. For example, Shearman (2010) conducted a study in the Purari Delta of Papua New Guinea, which had a fast rate of addition of land, accounting for $43 \text{ m}^2 \text{ year}^{-1}$. The ability of the mangrove ecosystem to increase land area was used as a basis for managing impacts in the form of sinking coastal areas due to rising sea levels and climate change, as stated by Zhang et al., (2025) and Jorquera et al. (2025).

Along with its role as a sediment trap, the mangrove ecosystem in the Ajkwa Lower Estuary also provided services for protecting the coastline from wave and wind energy, which made the Ajkwa lower estuary beach safe from abrasion and scouring. The role of the mangrove ecosystem as a coastal protector was a service provided by the Ajkwa mangrove ecosystem, which was consistent with its function as a sediment trap for developing new lands. Studies regarding the addition of new land (accretion) in the Ajkwa Estuary were carried out by Setyadi et al. (2021b). The results showed the essential role of the mangrove ecosystem services of the Ajkwa Estuary in the form of supporting and maintenance service categories (Spalding et al., 2014). The function of mangrove as a barrier to coastal abrasion had also been carried out in various locations, including Rembang, and Central Java (Indarsih and Masruri, 2021). Other studies had explored the role of mangrove ecosystems on several coasts, such as in China, India and other countries (Zeng et al., 2026; Kazemi et al., 2021; Paul et al., 2024; Sunkur et al., 2023).

As a provider of nursery ground areas, the Ajkwa Estuary mangrove ecosystem had a great service by providing habitat for fish larvae and juveniles. Large numbers of small and pelagic marine fish spent their larvae and juvenile period in the mangrove ecosystem. In their adult stage, the fish moved to the open sea and became economically important commodities caught by fishermen in the Arafura Sea. A strong correlation between high fisheries production in the shallower part of the Arafura Sea and the mangrove ecosystem along the southern coast of Papua Island was observed by Tirtadanu et al. (2022), emphasizing the significant ecological role of the mangrove ecosystem for fisheries economics. As a nursery ground area, the Ajkwa mangrove area also served as a spawning ground where many mature gonads marine biota could be found. Another regulation ecosystem service was that the region provided habitat for various types of marine and terrestrial biota, facilitating organics transport within and inter ecosystems. Fish larvae sampling in this study shows that there were larvae from several groups of marine fish, namely the families of Engraulidae, Istiophoridae, Seranidae, Lutjanidae, Latidae, and Eleotridae. The appearances of fish larvae indicates that mangrove able to provide habitat for nursery ground for marine fish larvae and juveniles. Similar findings were also obtained by El-Regal and Ibrahim (2014) and Mohammed-Geba et al. (2025) who examined the role of mangrove ecosystems as nursery ground areas for economically important fish for coral reef fisheries in the Red Sea. Laegdsgaard and Johnson (1995) and Bradley et al. (2024) examined the significant role of the mangrove ecosystem in Australia. This important ecological function was also observed by several other studies, including von Hammerstein et al. (2024), and Rahman et al.

(2020). Studies conducted by Moore and Reynolds (1982), Milton and Chenery (2005) and Munpholsri et al. (2025) revealed that estuaries in the southern coast of New Guinea Island (Indonesian Papua and Papua New Guinea) is important habitat for nursery ground of Barramundi (*Lates calcarifer*) larvae. They spawn in the more saline water of the Arafura Sea (more than 30 PSU salinity) and enter the coastal waters during their larvae period and spend their larvae period in mangrove ecosystem.

Another mangrove ecosystem service provided by the mangrove ecosystem in the Ajkwa Estuary was carbon storage. This type of service was important, specifically with the issue of the reduction of carbon released into the atmosphere. The values ranged from 20.06 tons of $\text{CO}_2 \text{ ha}^{-1}$ in young mangrove ecosystems to 986.54 tons of $\text{CO}_2 \text{ ha}^{-1}$ in mature mangrove community. Young mangrove areas occupied the new land areas resulting from sedimentation of the estuary. Meanwhile, old mangrove were natural mangrove regions consisting of old vegetation and had existed in the study area for hundreds of years. The results showed that the Ajkwa mangrove area was important in providing ecosystem services, such as carbon storage. When compared with other mangrove ecosystems obtained from literature studies, Ajkwa mangrove ecosystem was relatively higher. This was particularly true when compared with the results of a study conducted by Rahmat et al. (2022) in the Rembang mangrove area, Central Java, which had a carbon storage value of 193.47 tons ha^{-1} . The values obtained in this study were higher compared to Pangestika et al. (2023) at Ayah Beach, Central Java, with a carbon sediment storage of 7.50 tons ha^{-1} and Pelawi et al. (2024) in their study at mangrove ecosystem in Indramayu's coastal area of West Java province as much as 18.33 tons ha^{-1} . The role of carbon storage in mangrove sediments was relatively significant as estimated by Alongi (2014). The study showed that although mangrove only occupied an area of approximately 0.5% of all global coasts, they played a role in storing carbon up to 10%-15% or the equivalent of the total 24 TgC y^{-1} and were capable of exporting 10–11% particulate terrestrial carbon to the ocean.

Special attention was given to cultural services, which included tourism, education, and research provided by the Ajkwa Estuary mangrove ecosystem. In terms of tourism services, considering that the location was a remote area with difficult access, this made it difficult for the mangrove estuary area to be developed as an ecotourism location. The potential targets of visitors were likely limited to only the residents of Timika City. Other potential activities that could be developed in this region were in the form of education-tourism development for school students, specifically elementary and middle school students in the Timika area, the capital city of Mimika Regency, and its surroundings. For education, study and research services, the mangrove area of the Ajkwa Estuary had been used quite well, specifically for various researches carried out by mining companies, and also to facilitate university students in completing their final assignments through findings on the mangrove ecosystem in the Ajkwa Estuary.

The low utilization level of mangrove ecosystem services by the local community in the study area had two meanings and consequences. Firstly, as a provisioning entity, mangrove ecosystem in the Ajkwa Estuary had not been optimally utilized by the community. This could be seen from the low utilization of existing services, specifically provisioning (fisheries products) and cultural services. Secondly, from conservation perspective, such a surplus condition was a favourable situation, indicating that the availability of provisioning and cultural resources was not threatened and would make it easier to manage its sustainability in the future. The situation could be different if the ecosystem services utilization budget was already in deficit and negative status, indicating a deficit in the availability of goods caused by high demand for utilization. The condition of surplus availability in the Ajkwa Estuary was caused by the low human population, leading to low demand for resources. The use of goods from provisioning services was still at a subsistence and artisanal level and not yet on a large economic scale.

Based on the status of utilization of mangrove ecosystem services in the Ajkwa Estuary which is still far below the level of potential availability, future management directions are focused on increasing the utilization of ecosystem services, especially provisioning services, by considering aspects of their carrying capacity. Taking into account that the current level of utilization is still at the traditional and subsistence level, government intervention is needed in the form of providing access to technology for communities holding traditional rights in the Ajkwa Estuary. Apart from access to technology in the form of fishing gear and boats, it is also in the form of the availability of fish handling facilities, such as the availability of ice. A better handling process of fisheries catch is needed to maintain its quality so that it can maintain the selling price on the market.

For further management of the mangrove ecosystem in the study area, by considering that the highest ecosystem service is provided by mature mangrove compartment, thus the strategy for further management is focused to increase the area (compartment) of mature mangroves. Increasing the area of mature mangrove can be conducted by applying three strategies, namely: (1) increasing the area of new land (resulted from sedimentation processes); (2) planting mangroves in the new land area and (3) maintenance of young mangroves so that they can continue to grow and become mature mangroves. It is expected that, gradually the existing new land and young mangrove areas will be developed into mature mangroves. At the time when this study was conducted, the study area consisted of 6213.9 Ha of mature mangrove, 1677.1 Ha of young mangrove and 3193.8 Ha new land (result of sedimentation). With the 3 strategies set out above, it is expected that in the next 20 or 30 years, new land will be changed into young mangroves and then finally into mature mangroves, while areas that are currently young mangroves is expected to be converted into mature mangroves.

Increasing new sedimented areas in the estuary can be conducted by applying various engineering applications, resulting as much as possible new land area for mangrove habitat. Existing areas of young mangrove need to be protected and maintained, so that young mangrove plants can grow and develop into mature mangroves. Based on the land use map, it is calculated as large as 3193.8 Ha of new land can be targeted as mangrove planting sites. Engineering measures can be applied in the area in order to get new sedimented land for new mangrove habitat. Maintenance of young mangrove areas as well as mangrove planting programs in new sedimented lands are needed to be implemented in the Ajkwa Estuary. These recommended possible efforts are needed to be implemented, aimed to improve mangrove ecosystem services in the Ajkwa Estuary and deliver benefits to both the environment and humans in the area.

4. Conclusion

The current study elucidates the mangrove ecosystem services capacity and utilization status in Ajkwa estuary, Mimika, Indonesia. Huge ecosystem services comprising 47 provisioning, 11 regulation and maintenance, and 2 cultural services were identified in this estuary. Among the ecosystem mangrove compartments, mature mangroves and water bodies exhibited the greatest ecosystem service capacity, providing 33 and 30 ecosystem services, respectively. In comparison, young mangroves and newly sedimented lands provided only 14 and 15 ecosystem services, respectively. Comparative analysis between availability status and existing utilization of ecosystem services showed that provisioning and cultural services were still in surplus condition, meaning that the utilization status is below its capacity, that mostly due to the relatively low human population in the surrounding area and its low economic activity. The traditional local communities with their conservative values behaviour had a low level of economic utilization. In terms of ecosystem services of the regulation and maintenance type, all services had been utilized, specifically by natural systems. Consequently, the benefits of the ecological function of the Ajkwa Estuary mangrove had been observed for the study area, through roles as a

nursery ground for marine biota, spawning and feeding ground for biota marine and terrestrial, high wave absorbers, sediment traps, and carbon deposit. Based on these findings, a special approach was needed by all stakeholders engaged in managing the mangrove ecosystem area to preserve the availability of ecosystem services. To improve mangrove ecosystem service in the Ajkwa Estuary, recommended further management strategy is by setting up programs on mangrove planting in the new sedimentation lands and to maintain young mangrove area grow as mature mangrove ecosystem as well as ensuring the long-term conservation of mature mangrove stands and protecting them from degradation and damage.

Declaration of Generative AI and AI-assisted technologies in the writing process

There is no AI tool used in the writing of this manuscript.

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Declaration of Competing Interest

We declare that there is no conflict of interest related to this research and publication.

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Data availability

Data will be made available on request.

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SURAT PENUGASAN TENAGA PENDIDIK

Nomor : 002-III/03.1-F/III/2026
SEMESTER GENAP TAHUN AKADEMIK 2025/2026

Nama	: Dr. Daisy Radnawati, S.T., M.Si.	Status Pegawai	: Tetap
NIK/ NIDN/ NIDK	: 0313126802	Program Studi	: Arsitektur Lanskap
Jabatan Akademik	: Lektor		

Bidang	Perincian Kegiatan	Tempat	Jam	Kredit (SKS)	Hari
I. PENDIDIKAN & PENGAJARAN	1. Pengajaran di kelas termasuk laboratorium				
	1. Ekologi Lanskap	E2	13.00 - 14.40	1,5	Selasa
	2. Studio Perancangan Lanskap 3	E1	09.00 - 11.40	2	Rabu
	3. Manajemen Proyek	Studio	11.00 - 12.40	2	Selasa
	4. Studio Perancangan Lanskap 5	Studio	13.00 - 15.40	3	Rabu
	5. Lanskap Perkotaan	E2	10.00 - 11.40	2	Kamis
	2. Pembimbing				
	1. Seminar				
	2. Kerja Praktek				
	3. Tugas Akhir/Tesis				
	4. Pembimbing Akademik			1	
	3. Penguji				
	1. Tugas Akhir/Tesis			1	
	2. Kerja Praktek				
II. PENELITIAN	4. Tugas Tambahan				
	1. Penelitian Ilmiah				
	2. Penulisan Karya Ilmiah			1	
	3. Penulisan Diklat Kuliah				
III. PENGABDIAN PADA MASYARAKAT	4. Menerjemahkan Buku Kuliah				
	5. Pengembangan Program Kuliah Kurikulum				
	6. Pengembangan Bahan Ajar				
	1. Menduduki jabatan di Pemerintahan				
	2. Pengembangan Hasil Pendidikan dan Penelitian				
IV. PENUNJANG	3. Memberikan penyuluhan/pelatihan/penataran/ceramah			1	
	4. Memberikan Pelayanan Kepada Masyarakat				
	5. Menulis karya Pengmas yang tidak dipublikasikan				
	6. Pengelolaan Jurnal Ilmiah				
	1. Menjadi anggota/panitia pada badan/lembaga suatu PT				
	2. Menjadi anggota Badan Lembaga Pemerintah				
	3. Menjadi anggota organisasi profesi			1	
	4. Mewakili PT/lembaga pemerintah, duduk dalam panitia antar lembaga				
	5. Menjadi anggota delegasi nasional ke pertemuan internasional				
	6. Berperan serta Aktif dalam pertemuan ilmiah/seminar				
	7. Anggota dalam tim layanan pendidikan				
Jumlah Total				15,5	

Kepada yang bersangkutan akan diberikan gaji/honorarium sesuai dengan peraturan penggajian yang berlaku di Institut Sains dan Teknologi Nasional. Penugasan ini berlaku dari tanggal 09 Maret 2026 sampai dengan 04 Juli 2026

Tembusan :

1. Wakil Rektor 1 - ISTN
2. Wakil Rektor 2 - ISTN
3. Ka. Biro Sumber Daya Manusia - ISTN
4. Arsip



Jakarta, 09 Maret 2026
Dean FSTT

Dr. Ir. Iqbal Wardana Abyoto, M.T.
NIDN. 0311086903