

A critical review of peatland ecosystem services research in Indonesia: Uncovering knowledge gaps and research needs

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Abstract

Peatlands provide a broad range of ecosystem services (ES) that are critical to ecosystem regulating and human well-being. However, anthropogenic activities threaten their existence, leading to degradation, destruction, and loss of these ecosystems. To effectively convey the value of peatlands, it is important to share knowledge on the ES they provide. This review aims to provide an overview of the ES provided by peatlands in Indonesia. We undertook a critical review of articles published on Scopus, ScienceDirect, and Google Scholar to investigate various aspects of peatland ES. Our examination encompassed data types, valuation methods, modes of assessment, ecosystem services categories, study site scale, temporal patterns, purposes of publication, and study limitations related to peatland ES. From a set of 1,115 potentially relevant papers, 45 were selected for analysis. Our findings showed that ES studies are heavily concentrated on the Kalimantan and Sumatra islands, with most studies focused on specific provinces such as Central Kalimantan and Riau. The most commonly used data type, method, and mode of assessment were secondary data, look-up tables, and economic valuation, respectively. Provisioning services were the most frequently studied ES category, followed by regulating services, supporting services, and cultural services. However, gaps persist, including limited data, understanding, and long-term sustainability consideration. Future research should address these gaps by focusing on underrepresented peatland ecosystems, integrating diverse approaches, and considering global peatland issues.



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1. Introduction

Indonesia possesses a high level of diversity and complexity in its ecosystems, which are linked and interdependent. As of 2013, it has been discovered that there are 74 types of ecosystems in Indonesia (Kartawinata 2013). One of the most significant ecosystems is peatland, which Indonesia has a vast area of, making it the fourth country with the largest peatland area in the world after Canada, Russia, and the USA (Ministry of Environmental and Forestry Republic of Indonesia 2019). Indonesia has 14.91 million hectares of peatland, with 6.44 million hectares (43%) located in Sumatra, 4.78 million hectares (32%) in Kalimantan, and 3.69 million hectares (25%) on the Papua islands (Anda et al. 2021). Peatlands supply a wide range of ecosystem services (ES), such as

providing food, fiber, water, and genetic resources. Peatlands also sustain biodiversity, primary production, and nutrient cycling, as well as sociocultural uses like recreation and education (Reed et al. 2014; Bonn et al. 2016; Wichmann et al. 2016).

Despite playing a critical role in providing essential ES, peatlands are under threat due to anthropogenic activities, leading to degradation, destruction, and loss of these ecosystems (Dohong et al. 2017; Hergoualc'h et al. 2018; Mishra et al. 2021). Anthropogenic activities have caused a significant decline in the provision of ES that are crucial for the well-being of surrounding communities and environmental sustainability. Despite the recognition of the importance of peatlands in providing essential ES, there is limited and partial information and understanding of the specific services provided by peatlands in Indonesia. Therefore, it is essential to improve our understanding of the ES provided by peatlands in Indonesia and their current status, considering the ongoing threats of degradation and loss due to anthropogenic activities. Understanding the ES provided by peatlands in Indonesia is crucial for developing effective management strategies that will ensure the continued provision of these services.

The number of articles related to the literature review of ES has been increasing in Indonesia. (Firdaus et al. 2022) provided a comprehensive review of ES on a national scale. There is also a considerable amount of literature focused on the regional scope and specific aspects. For instance, (Sofian et al. 2019) conducted a literature review on ES and mangrove management, while (Lourdes et al. 2021) undertook a systematic review of urban ES research in Southeast Asia. Abas et al. (2020) analyzed interactions and relationships between ecotourism and its services in Southeast Asia. Ayompe et al. (2021) investigated the positive and negative impacts of palm oil production on ES and human well-being in Africa, Asia, and Latin America.

Despite the large number of studies examining ES literature reviews, the literature review of peatland ES in Indonesia remains relatively unknown. In particular, critical reviews and analyses of peatland ES research in Indonesia are lacking. Such a review is imperative to provide valuable insights into the current state of research on peatland ES at the national level, as well as to identify the most prevalent research gaps. Conducting such a study could also help researchers identify which ES have received the least and most attention, the challenges encountered by researchers, and the research gaps that require further investigation. Therefore, this study aims to achieve the following objectives: (1) to provide an overview of the current status of research on peatland ES in Indonesia; (2) to identify the ES that have been most and least studied in peatlands; and (3) to identify knowledge gaps that require further research to improve understanding of peatland ES in Indonesia.

2. Methods

2.1. Data collection

Following the steps outlined by (Templier and Paré 2015), we conducted a literature review. As discussed in the introduction chapter, we formulated a problem statement that served as our guide. This statement helped us determine the type of information we needed, guided our search for relevant literature, and

informed our subsequent analysis. To conduct our search, we focused on internationally recognized databases, including Scopus, ScienceDirect, and Google Scholar. We used the following keyword search string: ((Peatland(s) OR Wetland(s) OR Peat Swamp OR Peat Swamp Forest OR Lowland) AND (Ecosystem Service OR Economic Valuation OR Economic Value) AND (Indonesia)). This search string was applied to the title, abstract, and keyword filters within the research database, and we extracted all results. The summary of the steps is depicted in Fig. 1.

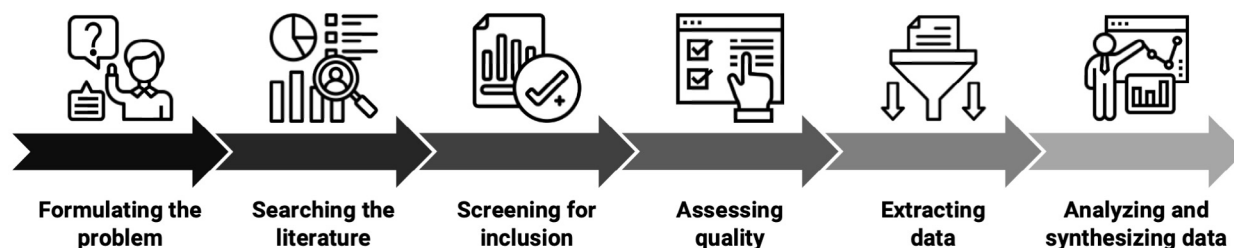


Figure 1. Steps involved in conducting a review article.

We conducted the literature search in two stages. Initially, we screened titles, abstracts, and keywords, resulting in the identification of 1,115 potentially relevant papers. These papers were evaluated based on predefined criteria, including the presence of specific keywords, publication type (only peer-reviewed journal articles and book chapters), language (Indonesian and English), and addressing at least one ecosystem service type. From this screening, 750 papers were selected for the next screening. During this stage, three additional criteria were applied: avoiding duplicate articles, ensuring accessibility (open access), and excluding review papers and meta-analyses. After this process, 432 articles were eligible for abstract reading. These papers were excluded if they didn't explicitly mention or assess ecosystem services or focused solely on environmental issues unrelated to peatlands or ecosystem services. Subsequently, 120 articles directly related to ecosystem services were identified and deemed suitable for full-text reading. Through careful full-text reading, we removed duplicated papers and articles lacking clear ecosystem service assessment methods. Ultimately, 45 articles met all the study criteria and were included in our analysis (Suppl. material 1).

Data related to the criteria were extracted from the 45 articles identified during the screening process. We recorded information about the general characteristics of the study, modified from the criteria analysis suggested by (Neu-garten et al. 2018; Mengist et al. 2020; Rau et al. 2020). These criteria include year of publication, geographical distribution, data type, assessment method, mode of assessment, valuation method, types of ES, number of ES assessed, study site scale, temporal patterns, purposes of publication, and study limitations (Suppl. material 2). Finally, data related to each selected article was extracted into an Excel spreadsheet for further processing. The categorization step involved classifying and processing the extracted data for further analysis, which was presented using various types of charts.

The concept of ES type originates from global classification system (Millennium Ecosystem Assessment 2005), which categorizes ES into four distinct

groups: provisioning, regulating, cultural, and supporting services. Each ES type has its indicators, provisioning services provide tangible outputs like food, water, and energy derived from natural resources. Conversely, regulating services encompass natural processes such as carbon and greenhouse gas sequestration, water purification, and disaster prevention. Supporting services, on the other hand, represent the fundamental ecological processes necessary for ecosystem function and maintenance, including habitat provision and biodiversity protection. Finally, cultural services encompass the non-material benefits derived from nature, including spiritual enrichment, ecotourism/recreation, and educational experiences (Suppl. material 2).

2.2. Data analysis

In this study, we used descriptive statistics as the primary method for analyzing the data that was collected. Descriptive statistics helped us to summarize and present the data in a clear and concise manner. We organized the data based on the number of articles for each criterion to provide a better understanding of the trends and patterns found in the literature. To accomplish this, we used Microsoft Excel, a popular data analysis tool, which allowed us to create various charts and graphs that effectively summarized the results. In addition to Excel, we also utilized QGIS, a geospatial data analysis tool, to map the study sites or geographic locations mentioned in the articles. This helped us to gain a better understanding of the distribution and frequency of research in different regions of Indonesia. Furthermore, we utilized Flourish, a data visualization tool, to create interactive and visually appealing graphics that effectively conveyed our findings to the audience.

3. Results

The total number of articles published on the topic between 2010 and 2023 was 45, with an average of three articles per year. In 2010 and 2012, only one article was published each year (Fig. 2). In 2014, there was a significant increase with four articles published, which accounted for 8.89% of the total number of articles. The following year, 2015, recorded the highest number of publications, with seven articles (15.56%) published. The number of articles slightly decreased in 2016 and 2017, with five articles (11.11%) published each year. In 2018, the number of publications decreased significantly to one article (2.22%), but increased again in 2019 with four articles (8.89%). In 2020, there was a further increase with eight articles published (17.78%), before stabilizing in 2021 with five articles (11.11%). For the last year, 2022, and the current year, 2023, two articles (4.44%) were published each year.

The studies included in the review were conducted in 16 provinces, with Central Kalimantan having the highest number of articles on peatland ES, totalling 17 articles (37.78%). This was followed by Riau with 16 articles (35.56%), South Sumatra with seven articles (15.56%), and West Kalimantan with six articles (13.33%). The remaining regions had a relatively smaller number of articles, with some regions having only one article available (2.22%). The broad geographical coverage of the studies indicates that the review covers a wide range of regions in Indonesia (Fig. 3).

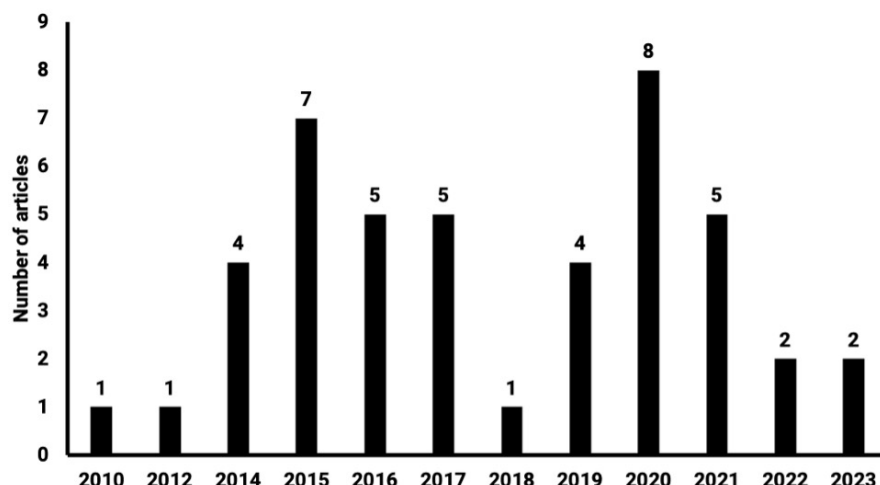


Figure 2. The number of articles published from 2010 to 2023.

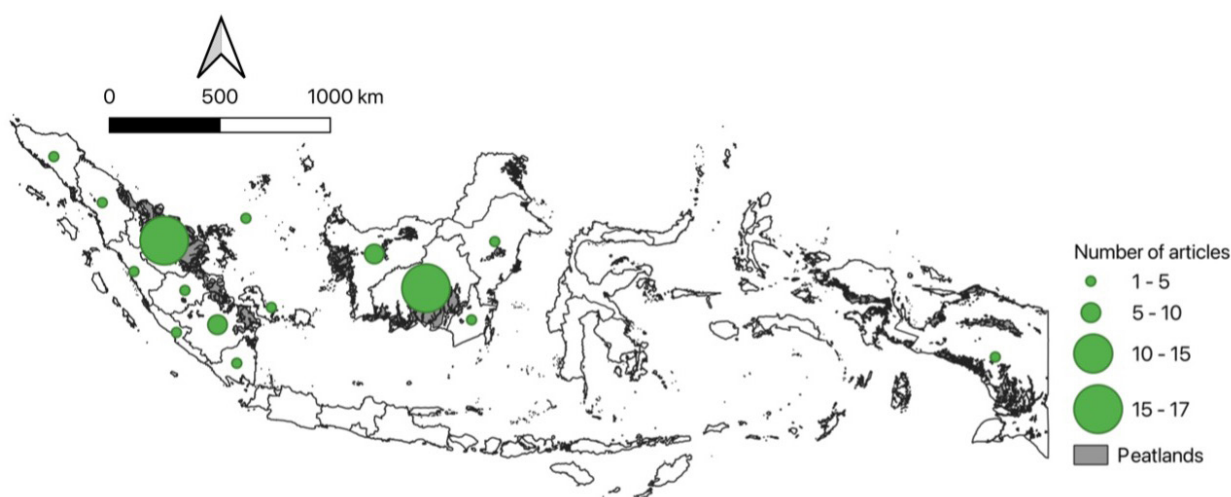


Figure 3. A map displays the geographical distribution of the selected articles.

3.1. Data types, methods, and mode of assessment

The most commonly utilized data type in selected articles is secondary data, which is used in 44 articles. This finding indicates that many researchers rely on pre-existing datasets rather than conducting their own data collection. The use of secondary data was found to be more common compared to other types of data. Two main purposes of secondary data were identified: first, as the main data source, as demonstrated in a study by (Ulya et al. 2014a) who used the benefit transfer method to estimate the economic value of carbon in Merang Kepayang, South Sumatra Province. The benefit transfer method relies on secondary data and is used to estimate non-market economic values by transferring available information from previous studies (Masiero et al. 2019). Second, secondary data were used to answer new research questions or to provide alternative perspectives on the original research question of a previous study. For instance, (Martono et al. 2018) used secondary data to construct research

questions and support their findings regarding the estimation of the non-use value of peatland in Siak Regency, Riau Province.

Field samples/observations are the second most commonly used data type, with a frequency of 33 articles, suggesting that primary data collection in the field is still prevalent. Field samples/observations are the second most commonly used data type, providing direct and reliable measurements of ecosystem processes and the provision of ES. They are utilized to measure various ecosystem service dimensions, including biodiversity (Rahajoe et al. 2014), carbon storage (Rochmayanto et al. 2010), economic loss (Nugraha et al. 2019; Putra et al. 2020), peatland use (Zahrul Muttaqin et al. 2017), perception (Schaafsma et al. 2017), and societal role (Kilonzi et al. 2016). These dimensions are crucial determinants of ES. Furthermore, field samples/observations offer insights into the relationship between ES and human activities, such as land use, management practices, and socio-economic factors. This information is significant for comprehending the drivers of ecosystem service provision and identifying potential trade-offs between different services.

Remote sensing is the third most frequently used data type, with a frequency of 11 articles, indicating its usefulness in gathering data from hard-to-reach or study areas. Remote sensing and simulated data have been used in the least number of articles. Remote sensing is a technique used to measure both land cover and land use, which are important determinants of ES (Sumarga and Hein 2016; Rossita et al. 2021). These data can be acquired at different scales and resolutions, allowing for the analysis of ES at the patch, local, and regional levels. On the other hand, simulated data are generated using models that simulate the dynamics of ecosystems and the provision of ES. These models can be used to assess the impacts of different management scenarios, such as land use changes or carbon storage, on ES (Abram et al. 2014; Pertiwi et al. 2022).

In contrast, simulated data is the least frequently used data type, with only seven articles utilizing it. Simulated data can be used to evaluate the effectiveness of different management strategies in enhancing the provision of ES (Law et al. 2015). Although the utilization of remote sensing and simulated data is low according to our findings, numerous studies have demonstrated that remote sensing and simulated data have the potential to monitor and evaluate ES at the landscape or regional level because they are cost-effective and can provide consistent and standardized information over large areas and long periods of time (Ayanu et al. 2012; De Araujo Barbosa et al. 2015; Avtar et al. 2017). The most frequently utilized method among the selected articles was look-up tables, which appeared in 22 articles. Look-up tables are beneficial tools for organizing and quickly accessing pre-calculated data in a variety of applications. The second most frequently used method was causal relationships, utilized in 14 articles. In this review, we found that causal relationships were mainly used to explore the impact of land and forest fires on people's livelihoods (Nugraha et al. 2019; Putra et al. 2020; Rimbawan and Nur 2021; Rosyida and Sopiana 2021), the costs and benefits of peatland management (Khalwani et al. 2015; Kiely et al. 2021; Prasetyawan 2023), land use impacts (Rahajoe et al. 2014), and social networks (Kilonzi et al. 2016). Models were the third most commonly used method, appearing in ten articles. Models were used particularly for ES in spatial planning and cost-benefit analysis because

they have the ability to predict the impacts of different management scenarios on ES (Sumarga and Hein 2016; Pertiwi et al. 2022). Expert knowledge was the least commonly used method, with only three articles employing this approach. Expert knowledge refers to insights and expertise provided by individuals with specialized knowledge and experience in a particular field. In this review, we found two articles that used these methods: (Ulya et al. 2014b), who estimated the economic value of water for domestic and transportation purposes in villages around Merang Kepayang peat swamp forest, South Sumatra Province, and (Pertiwi et al. 2022), who evaluated the carbon pricing of full ES for peatland conservation in Riau Province.

Table 1. Types mode of assessment that the most commonly used in selected articles.

No.	Mode of assessment	Articles	Percent
1	Economic valuation	30	36.14
2	Quantification	13	15.66
3	Combined	13	15.66
4	Trade-offs	10	12.05
5	Qualification	9	10.84
6	Mapping and modeling	8	9.64
Total		83	100

The majority of studies focused on economic valuation—analyzing the monetary value of peatland ES—which was the most commonly used mode of assessment, with 30 articles published in the field. In this review, we found that economic valuation is not only used to calculate the monetary value of peatland ES but also to compare the economic costs and benefits of different land use and management scenarios. This helps identify the most cost-effective management strategies for enhancing ecosystem service provision (Law et al. 2015; Sumarga and Hein 2016; Pertiwi et al. 2022). Quantification and combination were each used in 13 articles, while trade-offs were used in ten articles. Qualification and mapping/modeling were used in nine and eight articles, respectively. Quantification provides a way to measure and compare the quantity of ES provided by peatlands, using standardized methods such as emergy evaluation—a method of valuation based on the total amount of energy of one kind used directly or indirectly to make a product or service—including fish biomass production, peat production, and live biomass (Simangunsong et al. 2017). Moreover, quantification is crucial as it allows us to measure the success of various management strategies in improving the provision of ES. For instance, if a strategy aims to promote sustainable management of peatlands, it is essential to quantify the actual increase in different scenarios, such as continuing with current practices, implementing conservation efforts, or gradually replacing oil palm and other crops that require drainage with crops that do not, while also incorporating forestry practices for both timber and non-timber forest production (Uda et al. 2017).

3.2. ES categories

In terms of ES indicators, we found one article that assessed 15 ES indicators—(Abram et al. 2014) explored spatially explicit perceptions of ES and land cover change in forested regions of Borneo. Two articles assessed 13 ES indicators—one regarding ES under future oil palm expansion scenarios in West Kalimantan (Sharma et al. 2019), and another by (Dommain et al. 2016) who estimated ES, degradation, and restoration of peat swamps in the Southeast Asian tropics. One article estimated 12 ES indicators, quantifying the economic value of ES in oil palm-dominated landscapes in Riau Province in Sumatra, Indonesia (Aulia et al. 2020). The rest of the selected articles assessed 2–9 ES indicators, with the majority of articles only assessing one ES indicator—17 articles (Fig. 4). The range of services varied, with four articles covering all ecosystem categories. For example, (Sharma et al. 2019) explored ES under future oil palm expansion scenarios in West Kalimantan, while (Uda et al. 2017) assessed the monetary value of peatland ES at a national level. Some articles assessed fewer than four ES categories, with 13 articles only assessing three ES categories, four articles assessing two ES categories, and half of the selected articles assessing only one ES category.

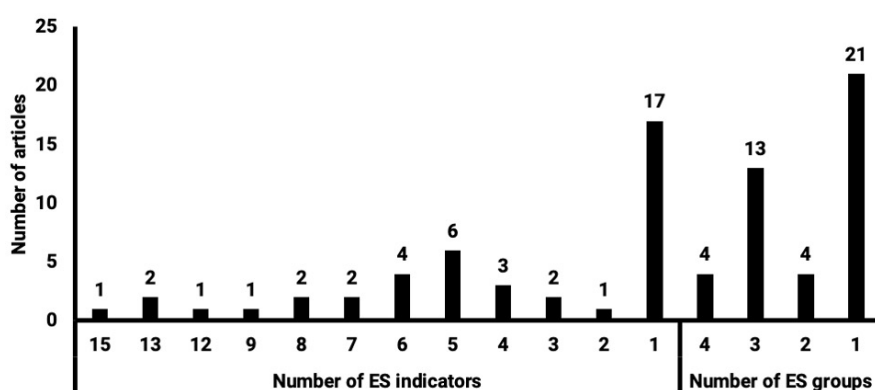


Figure 4. The number of groups and indicators of peatland ES.

Provisioning services were the most commonly discussed service, accounting for 88 indicators, followed by regulating services with about 57, supporting services with 13, and cultural services with 24. According to Fig. 8, the most frequently assessed ES from the four main categories are listed. The most studied services were food, with 20 ES indicators; carbon sequestration, with 18 ES indicators; timber and raw materials, with 17 ES indicators; recreation and fish, with nine ES indicators; provisioning for habitat, with seven ES indicators; and fire prevention, with six ES indicators. The remaining ES indicators were the least studied, with only one ES indicator (Fig. 5).

Market prices are the most commonly used valuation method, with 14 articles published in the field. Market prices are based on actual transactions in real-world markets, and therefore provide a more accurate and reliable estimate of the value of ES (De Groot et al. 2006; DEFRA 2007; Masiero et al. 2019). For example, the market price of oil palm can provide an estimate of the value of

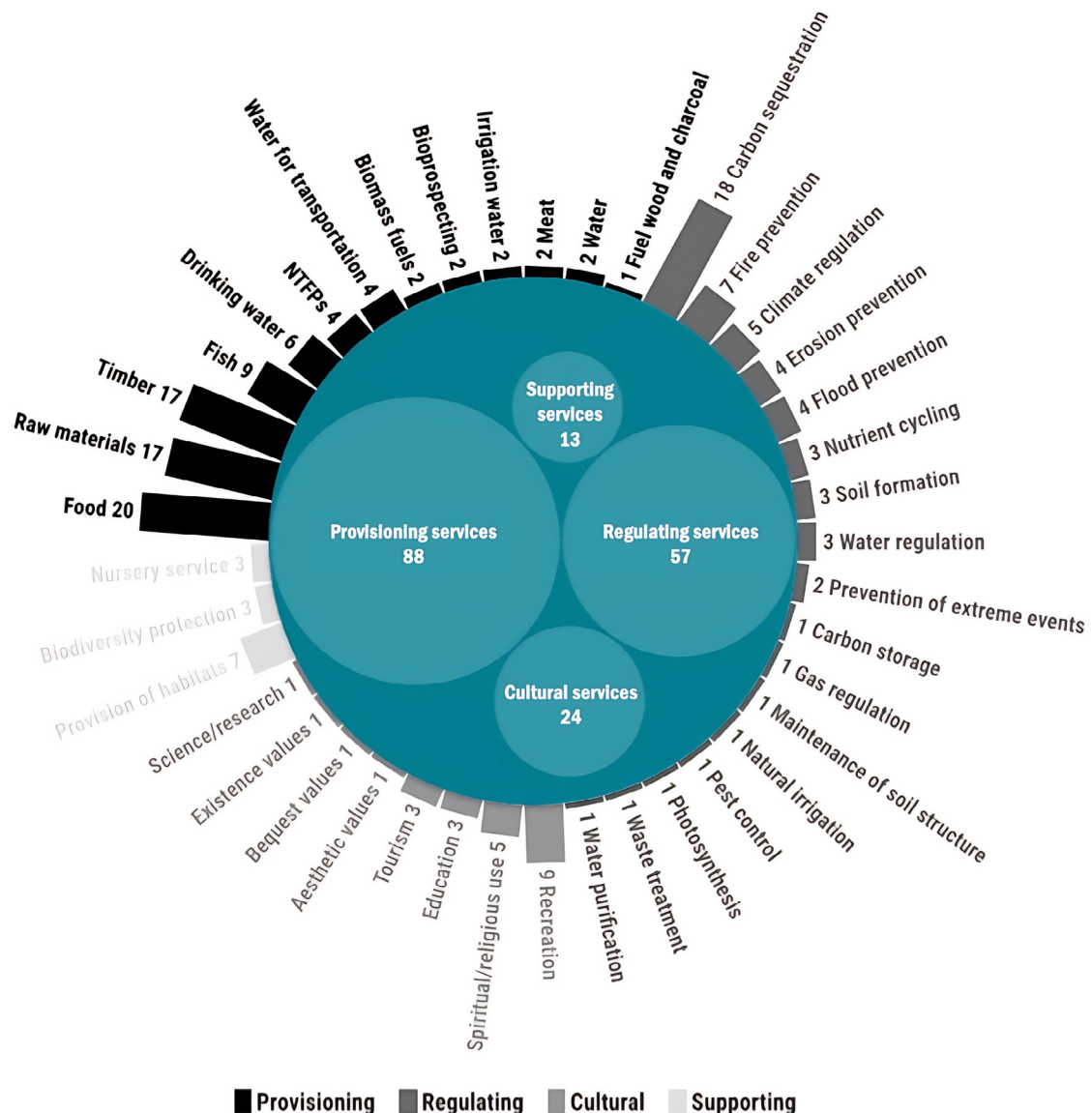


Figure 5. Most common ES investigated from the selected articles.

peatland ecosystems for oil palm production (Sumarga and Hein 2016; Aulia et al. 2020), and the market price of agricultural commodities can provide an estimate of the value of ES for agricultural production (Ulya et al. 2019). Market prices can also be used to value non-marketed ES, such as water (Roslinda and Yuliantini 2014; Ulya et al. 2019) and carbon sequestration (Rossita et al. 2021; Pertiwi et al. 2022). Contingent valuation is the second most commonly used valuation method, with eight articles published. Contingent valuation is used to estimate the economic value of non-market ES, which are services that are not traded in markets and do not have observable market prices. In this review, examples of non-market ES include conservation (Martono et al. 2018; Prasetyawan 2023), payment for ES (Ota et al. 2020), and hydrological services (Roslinda and Yuliantini 2014). Social cost carbon is used to value peatland ES regarding carbon sequestration and storage, which contribute to the mitigation of climate change impacts by reducing the amount of carbon dioxide in the

atmosphere (Rossita et al. 2021). Cost-benefit analysis and social cost of carbon have been used in six articles each. Cost-benefit analysis (CBA) is used to evaluate the costs and benefits of a project or policy decision (Hanley 2001). In this review, we found that CBA is used to value ES by comparing the economic value of the benefits provided by these services against the costs of conserving or restoring peatlands (Pertiwi et al. 2022). The other valuation methods have been used less frequently, with only one to five articles published for each of them (Fig. 6).

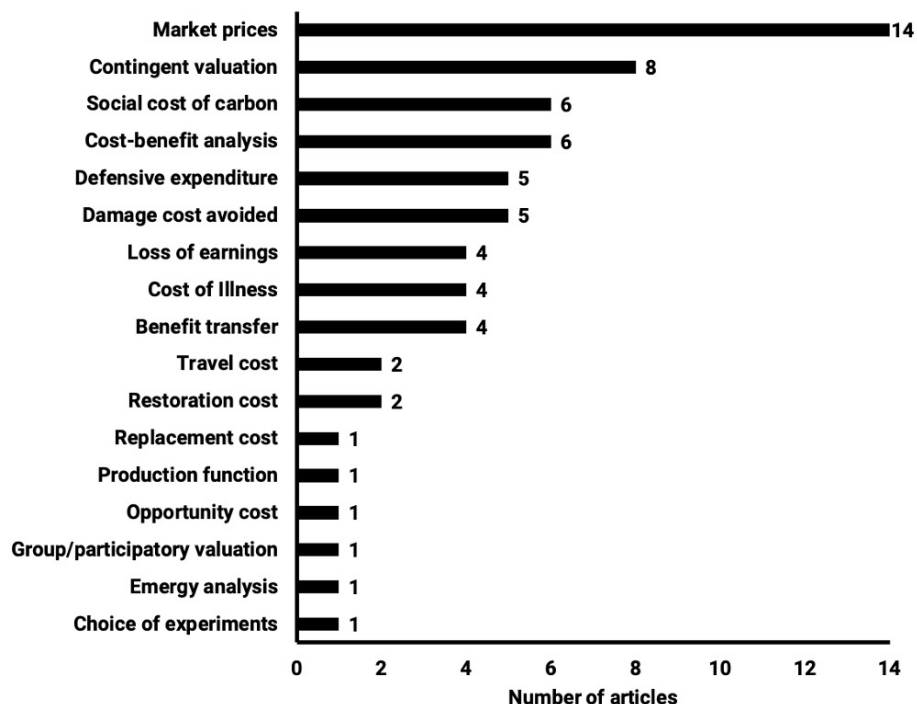


Figure 6. Valuation methods of ES.

3.3. Study site scale, temporal patterns, and purposes of publication

One article was conducted at a global scale, written by Dommain et al. (2016), which estimated ES, degradation, and restoration of peat swamps in the South-east Asian tropics. Three articles were conducted at a national scale, eight articles at a regional scale, ten articles at a local scale, and 23 articles at a patch scale. Local and patch scales were the most commonly used scales in the selected articles. Peatlands are highly location-specific and can exhibit significant variation based on factors such as peat depth, nutrient supply, climate, and flooding amplitude and period. As a result, it is necessary to study ES at the local scale to understand their true value and potential benefits. Furthermore, the majority of peatland data was available at different scales, locations, and themes. Therefore, when data is limited, researchers may need to narrow the research area, and many have focused on smaller, localized areas such as peat hydrological units (PHU), small watersheds, remnant forests, or other land use types with small areas.

The majority of the studies were conducted in non-linear patterns, with 38 articles falling into this category, while eight articles were in linear patterns, and one article in periodic patterns. ES research often follows non-linear temporal patterns because ES themselves are non-linear and exhibit temporal dynamics (Rau et al. 2018, 2020). In other words, the benefits that people derive from ecosystems can vary in both magnitude and timing. For example, the value of a forest for carbon sequestration may increase over time as the trees grow, but it may also fluctuate in response to disturbances such as wildfires or deforestation (Rochmayanto et al. 2010). Furthermore, the benefits of ES can exhibit time lags, where there is a delay between changes in the ecosystem and the resulting benefits to human well-being. For instance, the value of a restored peatland for flood control may not be fully realized until several years after the restoration is completed (Gunawan et al. 2021). The uncertainty and difficulty of ES is also considered for this reason, particularly in the face of environmental change and other disturbances. Non-linear temporal patterns help to capture this uncertainty and provide a more comprehensive understanding of the potential benefits and risks associated with ES. Lastly, conducting ES research in non-linear temporal patterns can have significant policy relevance, as it helps to inform decisions about ecosystem management and conservation that take into account the complex and dynamic nature of ES.

Most of the studies, comprising 43, had the main purpose of knowledge generation, while 13 articles had the purpose of supporting public/policy. Studies with the main purpose of management site and funding/investment were small (Fig. 7). The primary goal is to better understand the value and benefits that people derive from ecosystems, and to develop a more comprehensive and

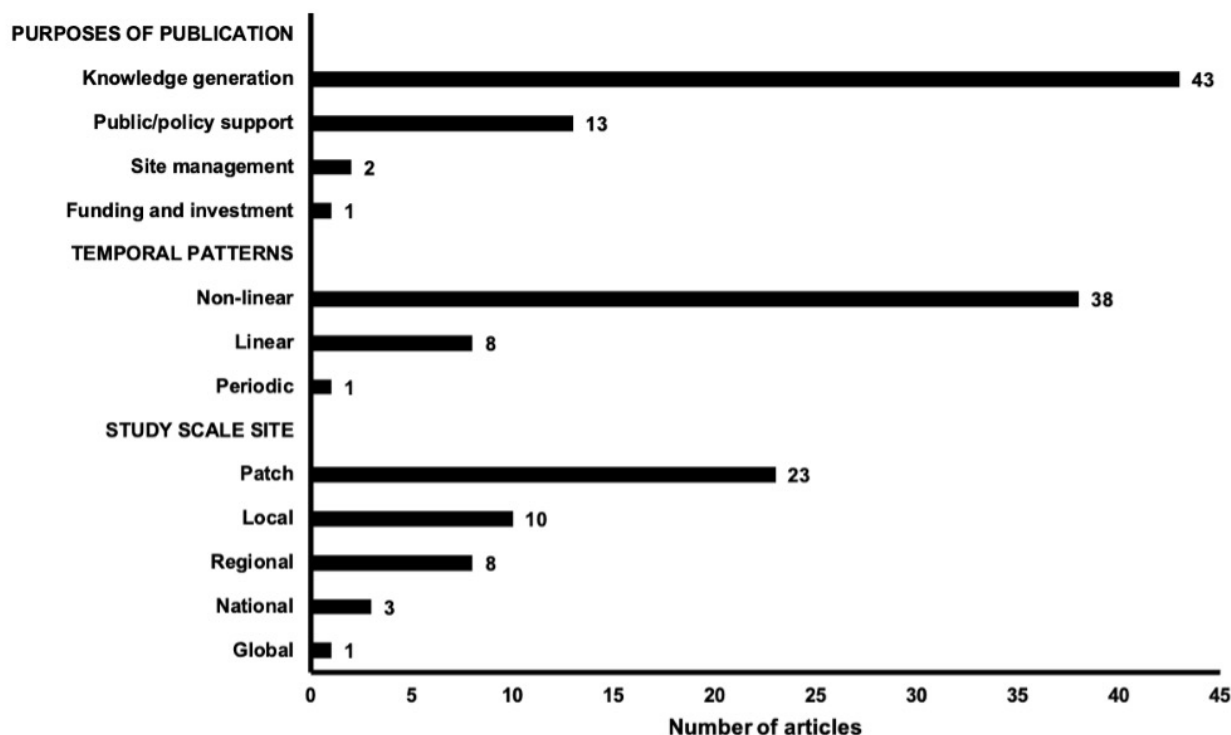


Figure 7. Category of selected studies based on their study scale, temporal patterns, and purposes of publication.

nuanced understanding of the relationships between human societies and the natural world. There are several reasons why knowledge generation is the main purpose of ES research. First, it advances scientific understanding. ES research is an important area of scientific inquiry that seeks to improve our understanding of the complex and interconnected relationships between ecosystems and human well-being. By generating new knowledge and insights, ES research can contribute to the development of new scientific theories and models that better capture the complex dynamics of natural systems. Second, it informs policy and decision-making. The knowledge generated through ES research can inform policy and decision-making at multiple levels, from local land-use decisions to global environmental treaties. By providing policymakers and decision-makers with a more comprehensive and nuanced understanding of the value and benefits of ES, ES research can help guide more effective and sustainable management of natural resources. Lastly, it enhances public awareness and engagement. ES research can also contribute to public awareness and engagement on issues related to the environment and natural resource management. By communicating the value and benefits of ES to a wider audience, ES research can help build support for conservation and restoration efforts.

3.4. Study limitations

The review identified a wide range of limitations that hinder the accurate valuation, quantification, and mapping of various peatland ES, which in turn affects the practical application of management strategies aimed at preserving peatland ecosystems. These limitations were grouped into seven categories. The first limitation was limited data availability, which was mentioned in 16 articles. Limited data availability is a significant limitation in ES research due to the complexity and variability of ecosystems, as well as the diversity of human uses and values associated with them. There are several factors that can contribute to limited data availability in ES research. Firstly, the lack of monitoring programs can make it challenging to collect reliable data on the provision and distribution of ES, especially in developing countries or remote areas. Secondly, even when monitoring programs exist, there may be gaps or inconsistencies in the data collected, such as missing data for certain locations or time periods or different monitoring methods used in different locations. Thirdly, limited resources required for ES research, including funding, equipment, and trained personnel, may be scarce in developing countries or areas with limited infrastructure. Lastly, the complexity and variability of ecosystems, which can be influenced by a wide range of factors, including natural processes, human activities, and climate change, can make it challenging to collect comprehensive and reliable data on ES. In addition, there are other limitations to ES research. One of them is the difficulty in quantifying ES, such as cultural services, due to the complex and diverse ways people interact with nature. Cultural services cannot be explained as a direct benefit to people, making it challenging to fully understand their value and benefits. Lastly, the lack of standardized methodologies for valuing ES can lead to inconsistencies in research and make it challenging to compare results across studies. The second major limitation was uncertainty and complexity, which was mentioned in seven articles. The

third and fourth limitations were the difficulty in quantifying ES and spatial and temporal variability, which were mentioned in six articles, as shown in Table 2.

Table 2. The group of study limitations in peatland ES studies which stated in selected articles.

No.	Study limitations	Articles	Percent
1	Limited data availability	16	34.78
2	Uncertainty and complexity	7	15.22
3	Difficulty in quantifying ES	6	13.04
4	Spatial and temporal variability	6	13.04
5	Lack of standardized methodologies	4	8.70
6	Trade-offs and synergies	4	8.70
7	Ethical concerns	3	6.52
	Total	46	100

4. Discussion

This study aims to explore the articles published in the last 13 years regarding the ES provided by peatlands in Indonesia to advance our knowledge of the specific services provided by peatlands in the country, which is important given the limited and partial information available. The review identified 45 articles related to peatland ES in Indonesia.

The analysis revealed a slowly increasing trend in research on peatland ES in Indonesia. Generally, this trend is consistent with national-level ES research trends (Firdaus et al. 2022) and global-scale trends (Gangahagedara et al. 2000; Costanza et al. 2014), as well as the increasing trend in peatland research globally (Van Bellen and Larivière 2020). The analysis also showed that the number of articles related to peatland ES grew impressively after the extensive disaster of land and forest fires in 2015, and this trend has been directly and indirectly influenced by policy interventions and global initiatives to address the fire issue. One such intervention is the provision of research funding to individuals or organizations, such as (Sumarga and Hein 2016; Sumarga et al. 2016), who received funding from The European Research Council to conduct a holistic study on peatland ES in Central Kalimantan. Similarly, the establishment of the Peatland Restoration Agency (PRA) in 2016 has played a significant role in bridging peatland science and national policy discourse, which has influenced research on peatland ES in Indonesia. For instance, Gunawan (2018) and Gunawan et al. (2021) studied the relationship between peatland restoration and ES in the PRA's intervention areas. Thus, the temporal trend of articles on peatland ES is closely related to land and forest fires.

The study revealed that the spatial distribution of research studies was clustered around certain areas. Specifically, the findings indicate a significant emphasis on ES studies in the Kalimantan and Sumatra islands, with most studies concentrated in the Central Kalimantan and Riau provinces. There are likely sev-

eral reasons for this pattern, including the fact that these provinces are home to the largest areas of peatland in Indonesia (Anda et al. 2021). Furthermore, it is reasonable to assume that these provinces have been most impacted by peatland degradation and loss, particularly due to land and forest fires (Kiely et al. 2021; Hein et al. 2022). Additionally, the increasing concern of the Indonesian government and global organizations regarding peatland management after the extensive land and forest fires in 2015 has led to an increase in research funding provided by various organizations such as foreign country grants, research council funds, NGOs, ministries, private companies, and UN sub-units. These factors have attracted the interest of many researchers to conduct studies in these areas.

Provisioning services, such as raw materials and food, are extensively researched, followed by regulating services like climate control and recreation opportunities. Cultural services and supporting services receive less attention. ES indicators such as erosion prevention, spiritual experience, and nutrient cycling are underrepresented in studies. This is likely because these cultural and supporting services are challenging to identify and value, making it difficult to measure, map, model, and manage peatland ecosystem services effectively (Satz et al. 2013; Small et al. 2017). Therefore, there's a need for the scientific community to develop improved methods for measuring, valuing, mapping, modeling, and managing these services.

4.1. Current status of knowledge gaps and challenges

1. While peatland ES research in Indonesia is a relatively new field, it has witnessed progressive development over the past two decades. However, several knowledge gaps and challenges persist, including limitations in data and methodologies, incomplete understanding of ES provision, inherent uncertainties in valuation, insufficient consideration of cultural values, and a lack of integration between research, management, and policy. Our research reveals an uneven distribution of focus areas. We have noticed an impressive concentration of research in specific regions, overlooking many large peatland areas nationwide. This skewed concentration could distort perceptions of peatland ecosystem services and affect decision-making. This gap hampers effective conservation and management efforts, making it challenging to make informed decisions on land use practices and conservation strategies crucial for preserving and enhancing these valuable services.
2. Peatland ES are often influenced by different scales because peatland ecosystems and human needs for ES vary across space. However, most studies on peatland ES focus on small local areas, and there's a lack of research looking at how ES interacts across different scales. This limited multi-scale research can result in a narrow understanding of ES interactions.
3. Limited understanding of supporting and cultural ES. While some studies exist on supporting and cultural ES. Implicit ES indicators might not capture the full complexity of supporting and cultural ES. This may lead to the undervaluation and underutilization of these services.

4. Lack of integrated assessments that consider interactions between peatland ES and global peatland issues such as biodiversity, drainage and conversion, fire, climate change, overexploitation, and other stressors affecting peatland sustainability.
5. Insufficient consideration of social and economic factors, our review showed the studies tends to focus on biophysical aspects, neglecting social and economic factors that can affect the value of these services to local communities. Neglecting social and economic factors can lead to an incomplete understanding of the value of peatland ES and may limit the effectiveness of management and policy decisions.
6. The absence of standardized methodologies for assessing peatland ES results in inconsistencies and difficulties in comparing findings across studies and locations, inhibits the development of effective management strategies for peatland ecosystems, and complicates the evaluation of management practices' long-term impact on ES.
7. Temporal patterns and the limited consideration of long-term sustainability. Many studies emphasize short-term benefits without adequately addressing the potential consequences of continued exploitation or degradation of these ecosystems. This lack of long-term sustainability consideration can result in unintended consequences and negative impacts on ES.

4.2. Research needs for the future

1. Research on peatland ES is strategically important as it directly concerns humanity's reliance on nature for prosperity. It plays a crucial role in peatland management and sustainable utilization. Therefore, we recommend several future research needs, including conducting representative studies, integrating approaches, addressing global peatland issues, valuing complete ES, and facilitating policy integration. Future research needs to prioritize a broader geographic scope. Expanding studies into understudied peatland areas is essential to capture the full spectrum of peatland ecosystems and the range of services they offer. Nationwide peatland inventories would be a valuable tool for identifying and prioritizing areas that require further investigation and conservation efforts.
2. Research across different spatial scales is necessary to comprehend the interactions among various peatland ES. Modeling, participatory mapping, and citizen science represent promising approaches for achieving this understanding. Involving local communities in data collection and analysis could yield more detailed and context-specific insights into these interactions.
3. There is a need to create clear indicators to measure supporting and cultural ES of peatlands. These indicators are essential for capturing the complete range of supporting and cultural ES offered by peatlands. Additionally, it's important to explore new methods for assessing these types of ES. Furthermore, integrating traditional ecological knowledge and cultural practices into the assessment process can improve our understanding of the benefits provided by these services.

4. The integrated assessments are required to gain a comprehensive understanding of the interactions between various peatland ES and their sustainability in the face of global challenges. Researchers should employ approaches that integrate biophysical, social, and economic dimensions of peatland ecosystems. Additionally, it's vital to consider temporal scales in assessments to ensure they address the long-term sustainability of peatland ES.
5. Future studies should give more attention to the social and economic factors that influence the value of peatland ES to local communities. These approaches can provide insights into the values, beliefs, and preferences of local communities regarding peatland ES. Furthermore, researchers should consider the historical and cultural contexts of the local communities to better understand how social and economic factors have shaped their relationship with peatland ecosystems.
6. There is a need for standardization of methods used to assess peatland ES. Researchers should develop standardized protocols and guidelines for data collection and analysis to ensure consistency and comparability across studies and locations. Standardization of methods used to assess peatland ES is essential to ensure that the results are reliable, robust and comparable across different studies and locations.
7. Future studies should consider the long-term sustainability of peatland ES, including their potential trade-offs and unintended consequences. Researchers should use scenario-based approaches to explore the long-term impacts of different management strategies on the sustainability of peatland ecosystems.

5. Conclusion

This paper provides a critical review of the research on peatland ES in Indonesia. The publications on the topic have slowly increased annually. The findings showed that a significant emphasis of ES studies is on the Kalimantan and Sumatra Island, and most of the study is concentrated in a specific province of the Island, Central Kalimantan and Riau. Secondary data, look-up tables, and economic valuation are the most applied data type, method, and mode of assessment. The majority of ES category found is provisioning services, studied by half of the selected articles, followed by regulating services, supporting services, and cultural services. At the same time, we have pointed to some gaps and challenges—specifically those on lack of data and methods, understanding, uncertainties, lack of integrated assessment, and insufficient long-term sustainability consideration. Future research should address peatland ecosystems that lack representative studies, integrating various research approaches, incorporating the global peatland issues, valuing complete ES, and should consider the long-term sustainability of peatland ES.

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Additional information

Conflict of interest

No conflict of interest was declared.

Ethical statement

No ethical statement was reported.

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Author contributions

The author solely contributed to the conception, design, and execution of the entire research study. The author conducted the literature review, collected and analyzed the data, and interpreted the results. The author drafted the manuscript and critically revised it for intellectual content. The author also approved the final version of the manuscript and is accountable for the accuracy and integrity of the work.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

Supplementary material 1

List of selected articles

Authors: Mohammad Yunus

Data type: docx

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Link: <https://doi.org/10.3897/jbgs.e117635.suppl1>

Supplementary material 2

The criteria used for the extraction of information from the selected articles

Authors: Mohammad Yunus

Data type: docx

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