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Carrying Capacity for Sustainable Mariculture Development in The Dampier Strait Conservation Area, West Papua Province

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Abstract

The Dampier Strait Marine Conservation Area has the potential to be a location for the development of seaweed and pearl oyster cultivation. Despite the potential, there is no information on the limitations of space utilization capacity in implementing mariculture activities for both commodities. Therefore, this study aims to determine the carrying capacity of mariculture activities in the Dampier Strait Conservation Area using the Ecosystem Approach to Aquaculture (EAA) concept. The study procedures included ecological and production carrying capacity, which were analyzed using the physical capacity approach. The results revealed that the area with the potential to be developed for mariculture activities was 904.36 ha. In addition, the number of seaweed and pearl oyster units that could be developed was 1,282 units and 805 units, respectively, with annual production volumes of 8,076.60 tons of dry seaweed and 2,817,500 individual pearl oyster spats ready for operation. All stages of the analysis provided comprehensive results to achieve an optimal and sustainable utilization area from the development of mariculture activities. The analysis also considered the continuity between environmental potential and human demands in the use of ecosystem services in an integrated manner.

Keywords: carrying capacity, dampier strait, ecosystem approach to aquaculture, pearl oyster, seaweed

1. Introduction

Carrying capacity assessment is the basis for developing strategies that are needed to support the development of sustainable mariculture utilization activities (Costa-Pierce, 2003). It also provides the foundation for management practices that require examination to regulate technical limitations in the implementation of space utilization. Consequently, mariculture activities can be implemented carefully in line with nature conservation principles and applicable regulations (Radiarta et al., 2018).

The Ecosystem Approach to Aquaculture (EAA) is a concept designed to encourage the implementation of ecosystem-oriented aquaculture (Soto et al., 2008). The concept was developed to anticipate threats that affect the balance of socio-ecological systems in coastal and marine areas due to various activities (FAO, 2010, 2021). This shows that studies within the scope of the EAA and based on spatial scales are needed to determine the capacity of the water environment to sustainably support the process of mariculture and business expansion (Aguilar-Manjarrez et al., 2010). To determine the potential space that can be used, several stages of carrying capacity assessment are carried out, including physical, ecological, and production (Byron and Costa-Pierce, 2013a; Costa-Pierce, 2021). These stages affect the total area, number of aquaculture units, and production volume (Weitzman and Filgueira, 2019; Kluger and Filgueira, 2020).

In the Ecosystem Approach to Aquaculture (EAA), carrying capacity assessment is an integral step in developing mariculture activities, as explained explicitly (Ross et al., 2013a). This approach is applied as a limitation or control mechanism to prevent negative impacts that can be detrimental to both the sustainability of nature and the activities carried out (Sanchez-Jerez et al., 2016). The application can create harmony between ecological functions and the social and economic demands of the use of space (Aguilar-Manjarrez et al., 2017; Brugère et al., 2018; Johnson et al., 2019; Weitzman et al., 2021). Although these stages have been widely applied in studies on expansion planning in coastal and marine areas, the current study still needs an approach that emphasizes the principle of caution in the use of space in marine conservation areas (Dreizis et al.,2020).

Several studies have shown that the Dampier Strait Marine Conservation Area has the potential to be a location for the development of seaweed and pearl oyster cultivation. The development of mariculture activities in the Dampier Strait needs to be carried out with a precautionary approach that refers to its status and characteristics as a marine conservation area. This is intended to prevent the degradation of resources and ecosystems that impact the sustainability of conservation area functions and avoid conflicts in the use of space with other activities. This condition highlights the need for a comprehensive and integrated utilization process that prioritizes the nature conservation function (ecosystem-based management). Increased turbidity excess nutrients, dominance of coral-related algae, coral susceptibility to disease, and enhanced resilience of reef ecosystems in areas with high biodiversity values, such as the Dampier Strait. From a biological and social perspective, aquaculture waters have the potential to increase the risk of disease spread to local populations, alter genetic structure through the introduction of non-local species, and lead to conflicts in land use with capture fisheries and marine tourism. Increasing number of tourists have become a threat if the behavior of tourist are not concerned on the environment sustainability and damage the attractions for diving. Assessment of the carrying capacity of the area becomes an important factor to know for sure the maximum number of visitors that can be accommodated by the region at any given time without causing disturbance to the environment at the Dampier Strait area.

Based on previous studies (Wibowo et al., 2023), the Dampier Strait has the potential for developing mariculture in a restricted use zone with commodities, including seaweed and pearl oysters. Despite its potential, there have been no studies on the optimal production capacity for developing aquaculture for both commodities. Therefore, this study aims to determine the carrying capacity for the development of mariculture activities in the Dampier Strait Conservation Area. The study aims to determine the carrying capacity for the development of mariculture activities in the Dampier Strait Conservation Area Materials and Methods

2. Material and Methods

2.1. Study Area

This study was conducted in the Dampier Strait Conservation Area, Raja Ampat Regency, West Papua Province, which is in a restricted use zone **Figure 1**. The location has a total area of 232,588.59 ha, with potential areas of water that are used for seaweed and pearl oyster aquaculture of 576.96 ha and 553.49 ha, respectively (Wibowo et al., 2023).

Dampier Strait is part of the Raja Ampat Regency marine conservation area. The research site is located in a restricted-use zone, which means that economic activities can proceed in certain ways while prioritizing the conservation and sustainability of marine resources. This is one of the strategic conservation areas with exceptional marine biodiversity. Previous studies (Wibowo et al., 2023) have shown that parts of the waters in this region can be used for mariculture, particularly seaweed and pearl oyster farming. The results indicate that there is a marine area of 576.96 ha available for seaweed cultivation and 553.49 ha for pearl oyster cultivation. These figures demonstrate that, although the area is designated for conservation, there is still space that can be utilized productively without compromising environmental carrying capacity.

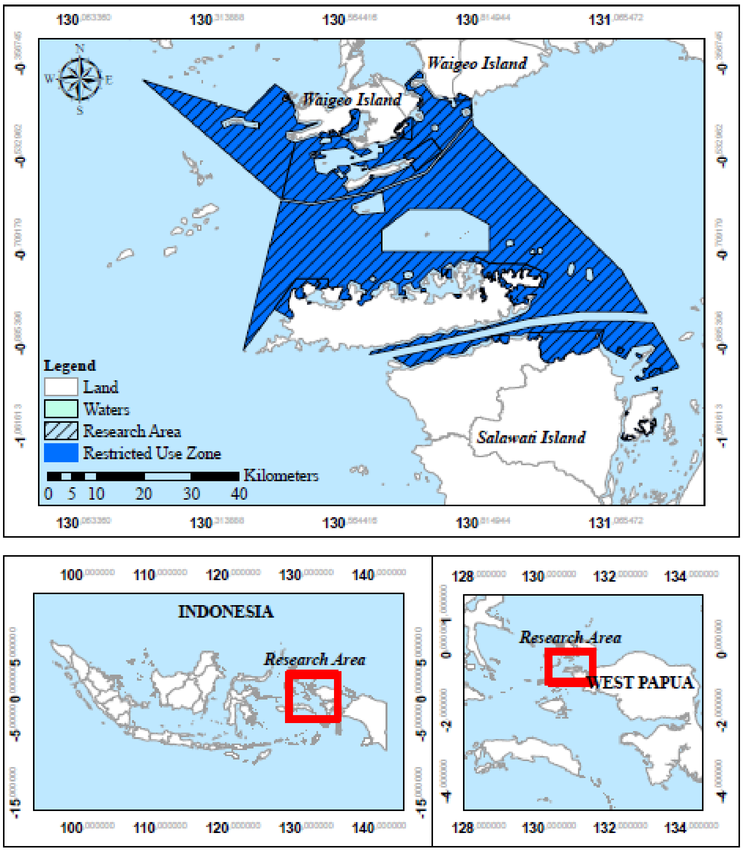

Figure 1. Research Location for carrying capacity of mariculture in the Dampier Strait Conservation Area.

2.2. Materials

The materials used in this study included primary and secondary data on the characteristics of seaweed and pearl oyster aquaculture production. The primary data included the percentage of the optimal area and production capacity of cultivated commodities, which were obtained from unstructured interviews with expert respondents. In addition, secondary data in the form of ideal area standards for aquaculture units were collected from the literature.

2.3. Method

The ecological and production carrying capacity assessment was conducted using the physical capacity approach (Erlania and Radiarta, 2014; Radiarta et al., 2018). This approach was limited by the ability of space to support aquaculture activities, as reviewed from the aspect of physical suitability. This study employs a methodological framework based on an integrated socio-ecological approach to capture the complexity of interactions between aquaculture activities and marine ecosystem dynamics in the Dampier Strait. The framework was chosen because it allows for the interconnection between biophysical components like water quality, benthic community structure and coral reef conditions, for social components is aquaculture practices, spatial use, and stakeholder perceptions, and also governance dimensions that influence ecosystem pressures and responses.

The carrying capacity model refers to the type of cultivated species classified as non-feed aquaculture commodities. In this study, there were 5 stages of carrying capacity analysis that produced 3 analysis results, namely, (1) the optimal area, (2) the number of units, and (3) the production level. This was described as follows.

1. Determination of the optimal area. The optimal water area for aquaculture was 80% of the potential (the potential for seaweed and pearl oyster aquaculture was 576.96 ha and

553.49 ha, respectively). Moreover, the remaining 20% was allocated as a buffer area. This aimed to limit the use of space to maintain the ecological function of the waters and prevent conflicts of use. These limitations reflect the process of determining an area's carrying capacity, which involves implementing environmentally friendly aquaculture activities and is based on the precautionary approach.

2. Determination of the ideal area of the aquaculture unit. The seaweed aquaculture unit used was a long line with a frame of 50 m x 50 m with a distance between units of 10 m on each side. Therefore, the ideal area of one seaweed unit was 60 m x 60 m = 3,600 m^2 = 0.36 ha. The pearl oyster unit used was a 110 m long line with a distance between units of 50 m; hence, the ideal area of one pearl oyster aquaculture unit was 110 m x 50 m = 5,500 m^2 = 0.55 ha.
3. Estimation of the number of aquaculture units. Number of aquaculture units (units) = optimal area (ha): ideal area of aquaculture units (ha).
4. Determination of production capacity. The production capacity was based on the harvest frequency in 1 year, which was assumed to be optimal production. The frequency of seaweed harvest was assumed to be 6 cycles a year, whereas that of pearl oysters was 1 cycle a year. A seaweed aquaculture unit with 1,225 kg of seeds produced 7,350 kg of wet seaweed or 1,050 kg of dry seaweed in one harvest cycle. In addition, 1 pearl oyster aquaculture unit with 10,000 individual spats and a percentage of spat survival of 35% produced 3,500 individual spats ready for operation.
5. Estimation of production level. The estimation was assessed on the basis of maximum physical and ecological capacity and via a noncontinuous calculation approach or during the same initial planting period (seaweed seeds and pearl oyster spat were planted at the same time). Production level = number of aquaculture units x production capacity x number of cycles per year.

The number of aquaculture units and production level obtained reflected the ecological and production carrying capacity of seaweed and pearl oyster aquaculture activities. These results are recommended as the maximum threshold of space utilization capacity to regulate the technical limitations of implementing sustainable mariculture activities.

3. Results and Discussion

3.1 Results

The optimal area for mariculture development was 904.36 ha (80% of its potential area is 1,130.45 ha). This allocation demonstrates that land use is managed carefully, with some areas set aside as ecological buffer zones to maintain the balance of the aquatic environment. Of this optimal area, 461.57 ha are allocated for seaweed cultivation and 442.79 ha for pearl oyster cultivation, ensuring a balanced distribution of these two commodities.

The cultivation process, which is highly dependent on water quality, currents, and the availability of natural nutrients around the Dampier Strait, is estimated to allow for the development of 1,282 cultivation units for seaweed and 805 units for pearl oysters, adjusted for spatial capacity and environmental carrying capacity. **Table 1** shows the estimated annual production potential of 8,076.6 tons of dried seaweed and 2,817,500 market-ready pearl oysters under this scenario. These figures not only indicate significant economic potential but also highlight the importance of carrying capacity-based management to ensure that mariculture activities remain sustainable and do not disrupt the aquatic ecosystem.

Table 1. Carrying capacity for mariculture development in the Dampier Strait Conservation Area.

Parameter	Unit	Commodity	
		Seaweed	Pearl Oyster
Potential area	Ha	576.96	553.49
Optimal area	Ha	461.57	442.79
Ideal area of aquaculture unit	Ha	0.36	0.55
Number of aquaculture units	Unit	1,282.00	805.00
Production level	dry tons;ind spat	8,076.60	2,817,500.00

3.2 Discussion

The results revealed that the Dampier Strait Conservation Area had an ecological and production carrying capacity, which supported environmentally friendly marine aquaculture activities. This was observed from the determination process, which considered aspects of the sustainable use of coastal and marine areas without fully exploiting the entire potential of the available space. In addition, these limitations are major considerations in the development of mariculture activities to maintain the ecological function of water. This was preserved and could not cause pressure on the environment, which has implications for the sustainability of conservation area function and community survival.

As a conservation area, its diverse resources and ecosystems must be properly preserved, as they contribute to improving environmental quality. This is achieved by limiting the physical capacity of water available for aquaculture activities (spatial characteristics classified as highly suitable for aquaculture are not fully utilized). With these restrictions in place, the functions of protecting and preserving nature can continue to operate optimally while aquaculture activities take place.

In open-ocean aquaculture, assessing carrying capacity requires consideration of the stability and resilience of natural ecosystems to ensure the maintenance of ecosystem functions and services (Byron and Costa-Pierce, 2013). This is because “carrying capacity” is defined as the maximum biomass that a system can support without negatively impacting the environment (Chapman and Byron, 2018). In aquaculture research, the assessment of carrying capacity has shifted from an individual-level focus to an ecosystem-level perspective, integrating social, economic, and ecological dimensions, and serving as a vital tool to guide sustainable management (Weitzman and Filgueira, 2020; Jiang et al., 2026).

The mariculture activities reflected environmentally friendly principles. However, the implementation of marine aquaculture activities in such conservation areas must also consider the spatial integration aspect. This referred to the characteristics of zoning that accommodated several types of utilization activities with social, economic, and cultural values in the same spatial structure. This allowed for overlapping activities that could lead to conflicts over space use. To avoid these problems, the total utilization area needs to be limited; therefore, the community can sustainably obtain socio-economic benefits. The study by Brugère et al. (2018) also reinforces this argument by stating that aquaculture development in conservation areas must consider spatial capacity and interactions between users. The study shows that explicit restrictions on cultivation areas can reduce social conflict and increase community acceptance of conservation policies.

The ecological aspects of sustainability constitute the major foundation that determines the success of aquaculture activities. In line with Folke and Kautsky (1992), ecological indicators in marine aquaculture carrying capacity analysis include water quality (temperature, salinity, pH, dissolved oxygen, turbidity, and nutrients) as determinants of habitat suitability and eutrophication risk, the condition and vulnerability of supporting ecosystems such as coral reefs, seagrass beds, and mangroves as buffers of ecological functions, as well as the assimilation capacity of the environment, which is influenced by current dynamics, depth, and water flushing rates. In addition, these indicators also consider the cumulative impact and long-term ecological interactions on community structure and ecosystem productivity. The sustainability of ecological aspects was the primary priority that needed to be achieved in conducted aquaculture activities because the fulfillment of human needs must be consistent with nature conservation principles.

The feasibility of aquaculture development can have both positive and negative impacts from a utilization perspective if carrying capacity is not considered, particularly when assessed through social and economic dimensions. Several previous studies have highlighted that aquaculture systems interact closely with local communities and resource users, often creating benefits such as increased income and employment opportunities, but also the potential for conflicts related to land use and resource utilization (Jansen et al., 2016; Krause and Mikkelsen, 2017). Furthermore, inadequate consideration of socio-economic factors can lead to unfair outcomes and reduced acceptance of aquaculture development (Diedrich et al., 2019).

The ecological and production carrying capacity could be used to estimate the threshold of water space use and become a tool for controlling utilization to support sustainable mariculture activities. Through this approach, the relationship between space availability and the success of marine aquaculture activities was observed. When the aquaculture process's implementation in the future moved toward a condition that exceeded the current carrying capacity. In this study, early mitigation steps were taken to prevent over exploitation, which could negatively affect the socio-economic system balance in the Dampier Strait.

Water carrying capacity assessment has many definitions because it consists of several approaches and analysis methods; hence, the results are uncertain (Radiarta et al., 2018; Weitzman et al., 2021). The limitations of this concept are adaptive. In this study, the calculation of carrying capacity was conducted based on a certain period, the characteristics and potential of natural resources, and the need for specific policies in an area. This description revealed that the carrying capacity was dynamic. Consequently, the carrying capacity estimation must be conducted periodically (Byron and Costa-Pierce, 2013a). This approach also helps identify risks that arise from aquaculture activities. Carrying capacity values is an important basis for supporting the implementation of aquaculture based on the ecosystem approach (ecosystem approach to aquaculture - EAA). Through the EAA, the integration of aquaculture into the wider ecosystem promoted sustainable development, equity, and resilience in socio-ecological systems.

The analysis of water carrying capacity takes into account temporal factors, biophysical characteristics, natural resource potential, and specific regional policy needs. Carrying capacity is considered a dynamic and adaptive value. Calculations are performed over a specific period, taking into account water quality, environmental absorption capacity, and the presence of supporting ecosystems. However, these calculations are constrained by zoning and conservation functions. Carrying capacity has become a comprehensive approach capable of reflecting various components of the SES. Four main "types" of carrying capacity are frequently cited (McKindsey et al., 2006), including: physical (limits set by the physical space required for aquaculture), production (stocking density to achieve maximum production levels), ecological (the level of aquaculture beyond which unacceptable environmental impacts become apparent), and social (the level of aquaculture development beyond which unacceptable social impacts emerge). Other authors have proposed additional types, such as regulatory carrying capacity (Byron and Costa-Pierce, 2013; Ferreira et al., 2013) or economic carrying capacity (Gibbs, 2009) to acknowledge the role of other factors in marine aquaculture SES.

The regular monitoring of carrying capacity is a recommended strategy to maximize the use of space to support sustainable mariculture activities and control activities. Therefore, the environmental capacity threshold for the expansion of the seaweed and pearl oyster aquaculture industry has not been exceeded. This strategy included a monitoring scheme for the sustainability of the mariculture business and its ecological characteristics, as well as community education activities to support environmentally friendly marine aquaculture activities in **Table 2**. This approach must be implemented; hence, the mariculture activities of both commodities were conducted optimally and sustainably.

According to **Table 2**, business data collection was an important basis for making strategic decisions in the business expansion process. Data collection has several important functions that can describe the utilization conditions from ecological and economic aspects. In terms of ecology, the data obtained provided an overview of water space use, both those that have and those that have not been used (Gibbs, 2009; Ferreira et al., 2013; Kluger and Filgueira, 2020). Moreover, from an economic perspective, the information obtained could help in understanding the structure of the implementation of economic activities, understanding industry sustainability trends, and identifying opportunities.

The conditions of the water environment and water quality need to be monitored because they reflect the ecological quality and potential availability of space that is used to sustainably provide natural resources in the process of using ecosystem services (Douvere and Ehler, 2009). This was monitored periodically (time series) to assess the level of feasibility of the sustainability of marine aquaculture activities, as seen from the carrying capacity perspective. The monitoring results were used as a reference for determining the location of seaweed thallus plants and pearl oyster spat nurseries in line with the ecological characteristics that coincided with the dynamics of weather and landscape transformation in the area.

Table 2. Carrying capacity monitoring strategy

Strategy	Steps	Achievements
Business monitoring	• Identifying area of utilization • Identifying mariculture business actors • Identifying the level of business unit ownership • Identifying the level of production	• Data on area of utilization • Data on business actors • Data on the number of business units • Data on the amount of production
Monitoring of water environment conditions and water quality	• Identifying trends in landscape characteristics over time (time series) • Identifying trends in hydro-oceanographic parameter characteristics over time (time series)	• Data on water quality that is following the dynamics of seasonal changes
Physical carrying capacity monitoring	• Identifying potential locations for the utilization of mariculture activities • Identifying the total area for the utilization of mariculture activities	• The potential location plans for the utilization of mariculture activities • Data on the potential area for the utilization of mariculture activities
Monitoring of ecological and production carrying capacity	• Identifying the number of aquaculture units • Identifying the volume of aquaculture production	• Standard data threshold for the number of aquaculture units • Standard data threshold for the volume of aquaculture production
Human resource capacity building	• Conducting socialization of good aquaculture techniques (best aquaculture practice) • Conducting education and training on good aquaculture techniques (best aquaculture practice) • Conducting mentoring on the implementation of good aquaculture techniques (best aquaculture practice)	• Document of socialization of good aquaculture techniques (best aquaculture practice) • Document of education and training in good aquaculture techniques (best aquaculture practice) • Document of results of mentoring the implementation of good aquaculture techniques (best aquaculture practice)

Physical carrying capacity was monitored; hence, carrying activities were conducted in an environment that followed the survival characteristics of the cultivated species on the basis of physical potential. This was related to attributes or limiting variables that affected the level of accessibility of production and conservation functions suggested that this process must be performed to ensure that aquaculture activities do not exceed the limits of environmental capabilities (Divu et al., 2020). The results of monitoring in the form of potential locations and total utilization areas were the basis for regulating the design of the layout of aquaculture construction (in the EAA, referred to as the Aquaculture Management Area - AMA).

The ecological and production capacities need to be monitored, and the implementation of marine aquaculture activities should follow the potential area of water that accommodates the maximum number of business units and the density level of cultivated species (Costa-Pierce, 2003; McKindsey et al., 2006; Byron and Costa-Pierce, 2013; Ross et al., 2013b; Divu et al., 2020). This process was conducted to maintain ecological functions as the aquaculture process progressed (Ahmad et al., 2021; Weitzman et al., 2021). The monitoring results in the form of the number of aquaculture units and production volume, which constitute the threshold and control mechanism for the use of water space for carrying activities. This was performed, and the implementation of seaweed and pearl oyster aquaculture businesses was consistent with the requirements for the use of economic activities in conservation areas that reflected the principles of natural sustainability and ecosystem insight. Moreover, it was also performed according to the principles of using ecosystem services to provide sustainable benefits to the community.

In this study, increasing human resource capacity through active community involvement was one of the keys to the success of sustainability in aquaculture activities. Based on the results of the carrying capacity analysis, the development of seaweed and pearl oyster cultivation in the Dampier Strait is recommended to remain within the established ecological and production carrying capacity limits, with the strengthening of environmental monitoring systems and sustainable efforts.

The success of implementing these recommendations is largely determined by the capacity of local human resources, who currently have practical experience but are still limited in the application of best aquaculture practices (BAP) and environmentally-based management. Therefore, increasing human resource capacity through active community involvement in outreach, training, education, and mentoring programs is key to improving compliance with sustainable aquaculture practices and maintaining ecological and production sustainability in conservation areas (McKindsey et al., 2006; Troell et al., 2009; Sivaraman et al., 2018). This was implemented through various programs, such as socialization, education, training, and assistance related to the implementation of good aquaculture techniques (best aquaculture practices - BAP). In BAP, it is necessary to improve the knowledge, skills, and abilities of individuals in the process of utilization, management, and supervision (Weitzman and Filgueira, 2019). This supported the effectiveness and efficiency of decision-making related to business development and increased community involvement in the planning process (Giri, 2017) This strengthened the implementation of spatial governance and ensured a better understanding of environmentally friendly aquaculture concepts and practices.

4. Conclusions

In conclusion, the ecological and production carrying capacity of the Dampier Strait Marine Conservation Area, West Papua, for seaweed and pearl oyster aquaculture was 1,282 units and 805 units, respectively. The production volume of dried seaweed was 8,076.60 tons per year, and the pearl oyster spat ready for operation included 2,817,500 individuals per year. This statement implies that the potential for ecological restoration and production in the Dampier Strait Marine Conservation Area depends on the land area and the maximum environmental carrying capacity that can be utilized to support community activities without compromising the area's ecological functions. The management strategies that needed to be taken were (1) business monitoring, (2) monitoring the condition of the water environment and water quality, (3) monitoring the physical carrying capacity, (4) monitoring the ecological and production carrying capacity, and (5) increasing the human resource capacity.

Conflicts of Interest

There are no conflicts to declare.

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AI Writing Statement

During the preparation of this work, the author(s) used Chat GPT to help paraphrase paragraph and translate English. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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