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Review Article

Wave-driven process influencing aeolian sediment transport in beach dune systems: A review

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Abstract

Aeolian processes involve wind-driven emission, transport, and deposition of sand and dust, with sediment transport serving as a key source of sediment for coastal sand dunes. However, beaches today are increasingly out of equilibrium due to human activities, such as coastal development and climate change, which disrupt natural sediment dynamics and lead to localized erosion and accretion along coasts. This imbalance calls for comprehensive strategies to restore and maintain beach system stability. As predicting sediment transport rates is crucial for determining dune sediment budgets, it is essential to consider wave-driven sediment transport. This paper reviews the impact of wave-driven processes on aeolian sediment transport within beach dune systems. By examining sediment transport dynamics in specific coastal environments, this study aims to shed light on the wave-driven formation of aeolian sediment features. Following the ROSES (RepOrting standards for Systematic Evidence Syntheses) guidelines, this review includes a diverse range of studies sourced from the Scopus, Web of Science, and Dimensions databases. Thematic analysis identified three key areas: aeolian processes, the driving factors impacting aeolian transport, and methods to control wave-induced aeolian transport. The findings of this study advance understanding of the role of waves in shaping aeolian sediment dynamics, offering valuable insights for future research in this field.

1. Introduction

Coastal landscapes are shaped by both terrestrial and marine forces, with aeolian sediment transport, wind-driven movement of sand and dust as being one of the key processes (Luijendijk, 2021). This review addresses the scientific question: How does wave activity influence aeolian sediment transport and contribute to the dynamic evolution of coastal dune-beach systems, particularly in tropical environments? Understanding the interaction between wind and wave processes can better explain how dunes form, migrate, and offer protection to coastal zones over time (Zhang et al., 2022; Yang et al., 2019).

To investigate this question, the study synthesizes findings from existing literature, field-based observations, and numerical modelling to explore the relationship between wave dynamics and aeolian sediment transport. It considers both natural processes and human-induced changes that disrupt sediment movement along coastlines.

Today, many beaches' dunes and coastlines are disrupted due to a combination of human activities and environmental changes (Floc'H et al., 2021; Ratnayake, 2017). Coastal development, including harbors, seawalls, revetments, and other structures, interferes with the natural movement of sand (Davidson-Arnott & Bauer, 2021; Rattharangsri et al., 2020). These structures can interrupt sediment transport, leading to erosion in some areas, and sediment buildup in others (Rashidi et al., 2021). For instance, seawalls often reflect wave energy, intensifying erosion nearby (Uda, 2022).

Climate change exacerbates these problems by causing sea-level rise and increasing the frequency and intensity of storms, both of which accelerate beach erosion and disrupt sediment balance (Yaacob et al., 2018; Davies et al., 2023a). Other anthropogenic activities, like sand mining, dredging, and vegetation removal, further weaken coastal resilience (Jayappa & Deepika, 2018). Plants, such as dune grasses and mangroves, play a critical role in stabilizing sand and reducing wave impact, and their loss makes coastlines more vulnerable (Hallin et al., 2019). In addition, human alterations to river systems, especially dam construction, have reduced the delivery of sediment to coastal zones, contributing to long-term sand deficits and beach degradation (Mendoza et al., 2019; Yaacob et al., 2018).

This review is internationally relevant because coastal erosion, dune degradation, and sediment shortages are shared concerns across both temperate and tropical regions. With global sea levels continuing to rise, and coastal development intensifying, understanding how natural sediment transport systems function, and how they are disrupted, is crucial for informing sustainable coastal management and climate adaptation strategies worldwide.

A key focus of this manuscript is to highlight the underexplored interplay between wave dynamics and aeolian transport in shaping coastal landforms, especially in tropical settings that have received comparatively less attention in global research. While previous studies have considered aeolian or hydrodynamic processes in isolation, this review emphasizes their interconnectedness and the implications for beach-dune system resilience (Cavaleri et al., 2012; Chowdhury et al., 2020; Elliton et al., 2020; Davidson-Arnott & Bauer, 2021).

The novelty of this manuscript lies in its integrated perspective on wave-wind interactions in sediment dynamics, particularly as a framework for managing vulnerable coastlines under climate stress. By focusing on tropical coastal systems, and synthesizing current knowledge across disciplines, this review contributes new insights into how natural processes can be harnessed for nature-based solutions and long-term coastal sustainability (Anthony & Aagaard, 2020; Ratnayake, 2018).

2. Methodology

A Systematic/Structured Literature Review (SLR) was used in this review to collect information from numerous research papers on the specific topic of wave-driven aeolian sediment transport. The SLR approach was adopted to ensure a more structured review process that focused on the important topic without biases and that provided high-quality information on the topic. The five key sub-sections used in the current research, which are review protocol, formulation of the research topic, systematic searching techniques, quality assessment, and data abstraction and analysis, are explained below. As a result, unlike typical review approaches that limit the scope of the study to a specific selection of journals or other restricting criteria, a systematic literature review was necessary. This methodology was also conducted to answer the main problem statement: is the sediment transport formation driven by the waves, besides the common driver, wind?

2.1 Review protocol

Haddaway et al. (2018) created the ROSES review methodology, which guided this study. The protocol seeks to maintain high information standards and ensure proper performance when performing systematic reviews. This protocol was well-suited for the review, since it was more focused on coastal management and restoration, and it accommodated the synthesis method's different scenarios and complexities.

ROSES provides structured templates and checklists that help researchers define their review question, search strategy, inclusion/exclusion criteria, and data extraction process. These tools also assist in reducing bias, enhancing reproducibility, and improving the clarity of reporting. By following ROSES, studies are more likely to meet high scientific standards and be useful to policymakers, practitioners, and other stakeholders.

The use of ROSES is especially relevant to environmental and conservation research, including topics like coastal management, restoration, and aeolian sediment dynamics, where multiple variables, sources of data, and ecosystem complexities must be considered. ROSES accommodates different synthesis methods, such as qualitative synthesis, quantitative meta-analysis, or mixed approaches, making it adaptable to the diverse types of data often encountered in coastal research.

In this study, ROSES was adopted to ensure methodological transparency and rigor in reviewing the literature on wave-driven aeolian sediment transport and beach-dune system dynamics. Given the interdisciplinary and applied nature of this topic, ROSES provided an ideal structure to capture the wide range of studies and insights needed to support sustainable coastal management.

2.2 Formulation of research question

The PICo framework was employed to develop the research topic for this study. Considine et al. (2017) highlighted PICo as a well-known framework for crafting conclusive research questions. The PICo Framework comprises four elements: 'P' (Population or Problem), 'I' (Interest), and 'Co' (Context). These frameworks guide systematic reviews to gather eligible evidence for specific research topics (Wu et al., 2018). This review aimed at addressing the following four main research questions (RQ):

1. What drives the processes of aeolian sediment formation by waves?
2. What are the aeolian sediment transport characteristics formed by the wave-driven process?
3. What is the dynamic relationship between waves and aeolian sediment transport for insights into beach dune systems?
4. How can the aeolian transport caused by waves be controlled?

2.3 Systematic searching techniques

The systematic searching procedure consisted of three primary steps: Identification, screening, and eligibility.

2.3.1 Identification

To collect more relevant articles for review, the identification approach entailed searching for synonyms, similar phrases, and variations of the study's principal keywords. Keywords, such as wind and wave, aeolian transport, and wave-driven were introduced to this approach to explore the influence on coastal areas. To expand on these terms, synonyms, similar phrases, and variations were found using an online thesaurus, keyword lists from previous studies, and Scopus' keyword suggestions. Search features, such as field code functions, phrase searching, wildcards, truncation, and Boolean operators (**Table 1**) were utilized.

Both Web of Science and Scopus were used as they are the primary sources for citation information (Floc'H et al., 2021). Meanwhile, the Dimensions database consistently matched data across multiple dimensions and covered the entire research process (Guerrero-Bote et al., 2020). By using these three databases, high-quality and comprehensive publications that were free of database biases were able to be obtained. These databases yielded a total of 254 articles.

Table 1 Search strings.

Database	Search string
Scopus	TITLE-ABS-KEY (("wind*") AND ("wave*") AND ("process*") AND ("aeolian sediment*" OR "aeolian sand*" OR "aeolian sediment* transport*" OR "aeolian movement*" OR "sediment* transport*" OR "aeolian process*") AND ("wave-driven*" OR "wave influence" OR "wave-driven sediment*") AND ("wave characteristic" OR "wave influences" OR "wave-driven beach dune"))
Web of Science	TS=(("wind*") AND ("wave*") AND ("process*") AND ("aeolian sediment*" OR "aeolian sand*" OR "aeolian sediment* transport*" OR "aeolian movement*" OR "sediment* transport*" OR "aeolian process*") AND ("wave-driven*" OR "wave influence" OR "wave-driven sediment*") AND ("wave characteristic" OR "wave influences" OR "wave-driven beach dune"))
Dimensions	(("wind*") AND ("wave*") AND ("process*") AND ("aeolian sediment*" OR "aeolian sand*" OR "aeolian sediment* transport*" OR "aeolian movement*" OR "sediment* transport*" OR "aeolian process*") AND ("wave-driven*" OR "wave influence" OR "wave-driven sediment*") AND ("wave characteristic" OR "wave influences" OR "wave-driven beach dune"))

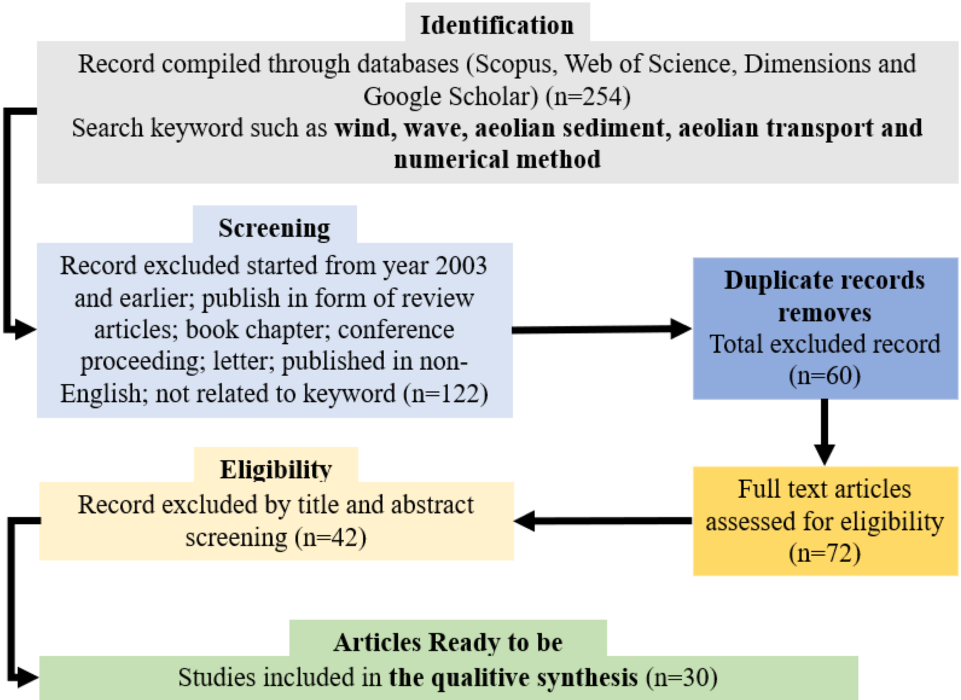

Figure 1 Flow diagram of search process.

2.3.2 Screening process

According to Mohamed Shaffril et al. (2019) and Samsuddin et al. (2020), the screening process is the first stage used to filter out publications, which can be done manually by the writers or with the assistance of a database. The goal of this approach is to lower the quantity of publications. In this scenario, the first stage excluded 75 articles based on criteria such as language, document type, year of publication, and field type. To avoid misunderstanding, it should be mentioned that the review concentrated on English-language articles and keywords linked to the influencing factors of wind and wave variability and aeolian transport, particularly in Asian countries.

Taking into account the concept of "research field maturity" (Kraus et al., 2020), the article inclusion criteria were restricted to a specified publication timeline (from 2004 to 2024, a 20-year period). According to the database search, fewer studies on sand trap fences as a community-related adaptation technique in coastal locations have been done in the previous ten years, particularly in Asia. In other words, the small number of studies discovered was the impetus for limiting the search to a 20-year period. Furthermore, only journal publications were included, to ensure the review's quality. Most crucially, to increase the likelihood of identifying relevant studies, publications not connected to geology, engineering, environmental science, diversity, or biological research were removed. Any duplicate articles were also deleted in the second step. In this process, 60 articles were removed, since they did not match the inclusion requirements, and the remaining 72 were reviewed.

2.3.3 Eligibility

By picking prioritized and relevant papers, eligibility was also used to confirm that the selected papers met the essential requirements. The remaining papers were manually filtered by reading their titles and abstracts to see if they met the inclusion criteria and could be reviewed. Throughout the title and abstract screening stages, 42 publications were excluded because they did not address the wind and waves variability, aeolian transport, or any numerical method. Finally, only 30 papers were picked. **Figure 1** depicts the flow diagram of the search process, with explanations of each phase provided in the following paragraphs.

Table 2 Core groups and sub-groups.

Studies		Region	Aeolian Processes		The Driven Impact			How to Control	
			Wind	**Wave**	**WiV**	**WaV**	**PT**	**HE**	**SE**
1.	(Teixeira et al., 2023)	Netherland	●	●		●	●	●	●
2.	(Castelle & Masselink, 2023)	United Kingdom	●	●	●	●	●	●	
3.	(Li et al, 2023)	China	●	●	●	●		●	
4.	(Bernardino et al., 2023)	United Kingdom	●	●		●			●
5.	(Davies et al, 2023b)	United Kingdom	●	●	●	●	●	●	●
6.	(Ülger & Tanrıvermiş, 2023)	Turkey	●	●		●			●
7.	(Lakku & Behera, 2022)	India	●	●	●	●		●	
8.	(Davidson et al, 2022)	Australia	●	●	●	●		●	
9.	(Cabral et al, 2022)	Australia	●	●		●			●
10.	(Zhang et al, 2022)	China	●	●	●	●	●	●	●
11.	(Galiforni-Silva et al, 2022)	Germany	●	●		●			●
12.	(Ling et al, 2022)	Malaysia		●		●	●		●
13.	(Daly et al, 2021)	France	●	●		●			●
14.	(de Sousa et al, 2021)	Brazil	●	●	●	●			●
15.	(Saha & Sinha, 2021)	India	●	●		●			●
16.	(Araújo et al, 2021)	Brazil	●	●	●	●	●	●	
17.	(Moulton et al, 2021a)	Australia	●	●	●	●	●	●	●
18.	(Itzkin et al, 2021)	United States	●			●	●		●
19.	(de Vries et al, 2020)	United States		●	●	●	●	●	
20.	(Jackson & Short, 2020)	Australia		●	●	●	●	●	
21.	(Wit et al, 2020)	Netherland	●	●		●			●
22.	(Rafati et al, 2020)	United States	●	●	●	●			●
23.	(Elliton et al, 2020)	United States	●	●		●			●
24.	(Anthony & Aagaard, 2020)	France		●		●	●		●
25.	(Gore et al., 2019)	United Kingdom	●	●		●		●	●
26.	(Cohn, Ruggiero et al., 2019)	United States		●	●	●	●	●	●
27.	(Hallin et al., 2019)	Netherland		●	●	●	●	●	
28.	(Guisado-Pintado & Jackson, 2019)	United Kingdom	●	●		●			●
29.	(Jayathilaka & Fernando, 2019)	Sri Lanka	●	●		●			●
30.	(Galiforni Silva et al., 2019)	Germany	●	●	●	●	●	●	
			Wind = By wind **Wave** = By wave		**WiD** = Wind Driven **WaD** = Wave Driven **PT** = Pattern			**HE** = Hard Engineering **SE** = Soft Engineering	

2.4 Data abstraction and analysis

To assess and synthesize multiple research designs, an integrative analysis was used. The first step in doing an analysis is to generate themes by attempting to discover patterns in the abstracted data publications. Following that, the procedures for establishing sub-themes are completed. During this step, all 30 selected articles were thoroughly examined for information or remarks that addressed the study subjects. The data were extracted after analyzing the abstracts and full papers to identify the relevant topics and sub-themes. Three (3) core groups were formed, with seven (7) sub-groups. The technique involved naming the themes for the main group first, followed by the themes for the sub-group (**Table 2**).

3. Analytical result

This section synthesizes findings from a curated set of peer-reviewed journal articles (2019 - 2024) focusing on aeolian sediment transport drivers. The analysis categorizes the literature based on temporal trends, geographical focus, methodological approaches, and thematic priorities.

3.1 Temporal distribution of publications (2019 - 2024)

A total of 30 relevant journal articles were reviewed. There was a notable increase in publications over the past five years, with a peak in 2022. This growth reflects increasing attention to sediment dynamics in tropical and monsoon-prone coastal settings due to climate change and rising coastal vulnerability by considering the most dominant roles of energy by considering the most dominant roles of energy at the monitoring location.

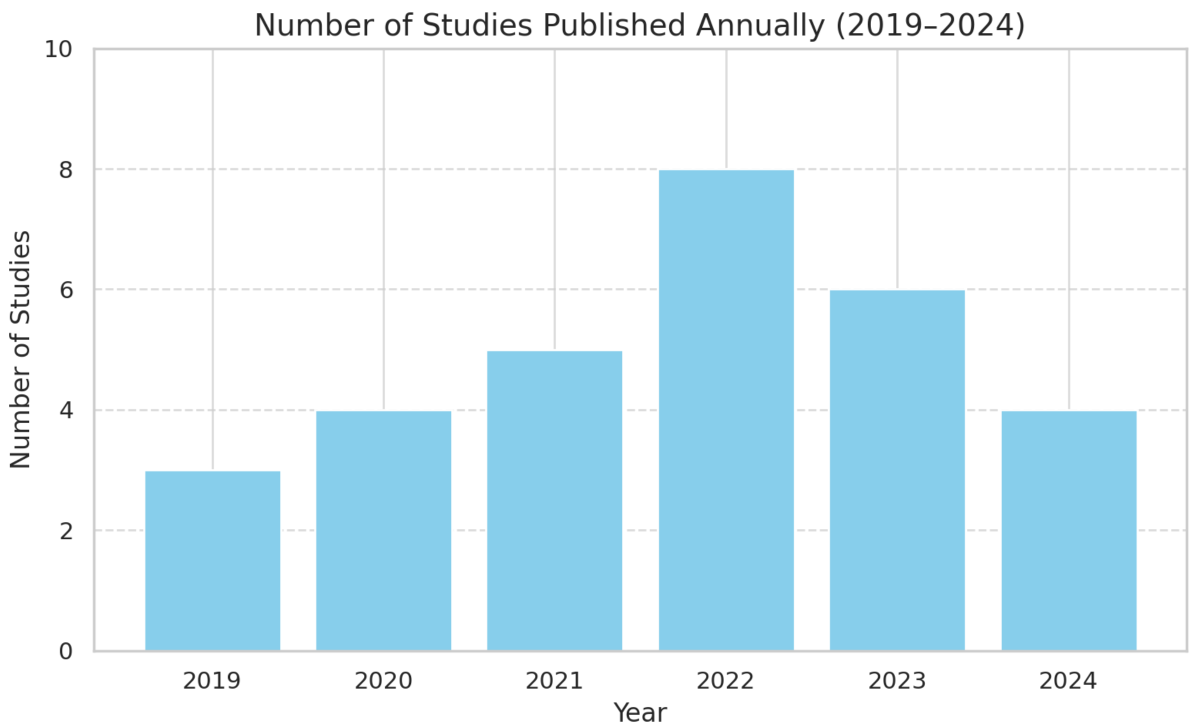

Figure 2 Number of studies published annually from 2019 to 2024 on aeolian sediment transport processes.

Figure 2 shows a temporal distribution of the selected studies. Research interest increased notably after 2020, peaking in 2022 with 13 publications. This upward trend reflects a growing recognition of wind-driven sediment processes in coastal management. Geographically, most studies were conducted at the global scale (48.9 %), followed by Malaysia (22.2 %), Indonesia (15.6 %), and other tropical nations. Despite the tropical context of aeolian transport, Southeast Asian coastlines remain underrepresented in current literature.

Figure 3 shows a comparative analysis of 40 studies on aeolian sediment transport, revealing distinct thematic emphases within the literature. Most studies primarily focus on the physical mechanisms driving aeolian processes, such as wind dynamics, sediment grain size, and topographical variations. These investigations provide foundational insights into how aeolian fluxes operate under different environmental conditions. In contrast, a slightly smaller subset of 30 studies expands on the driven impacts influencing aeolian transport, particularly the roles of climate variability, coastal development, and vegetation degradation. These studies underscore how both natural and anthropogenic drivers contribute to disruptions in sediment mobility and redistribution.

Meanwhile, only 20 studies explicitly discuss control and mitigation strategies. These include interventions such as dune restoration, the establishment of vegetative buffer zones, and policy frameworks aimed at preserving sediment balance and minimizing human impact. The relatively lower number of studies addressing control measures suggests a critical research gap in translating process-based understanding into effective coastal management practices.

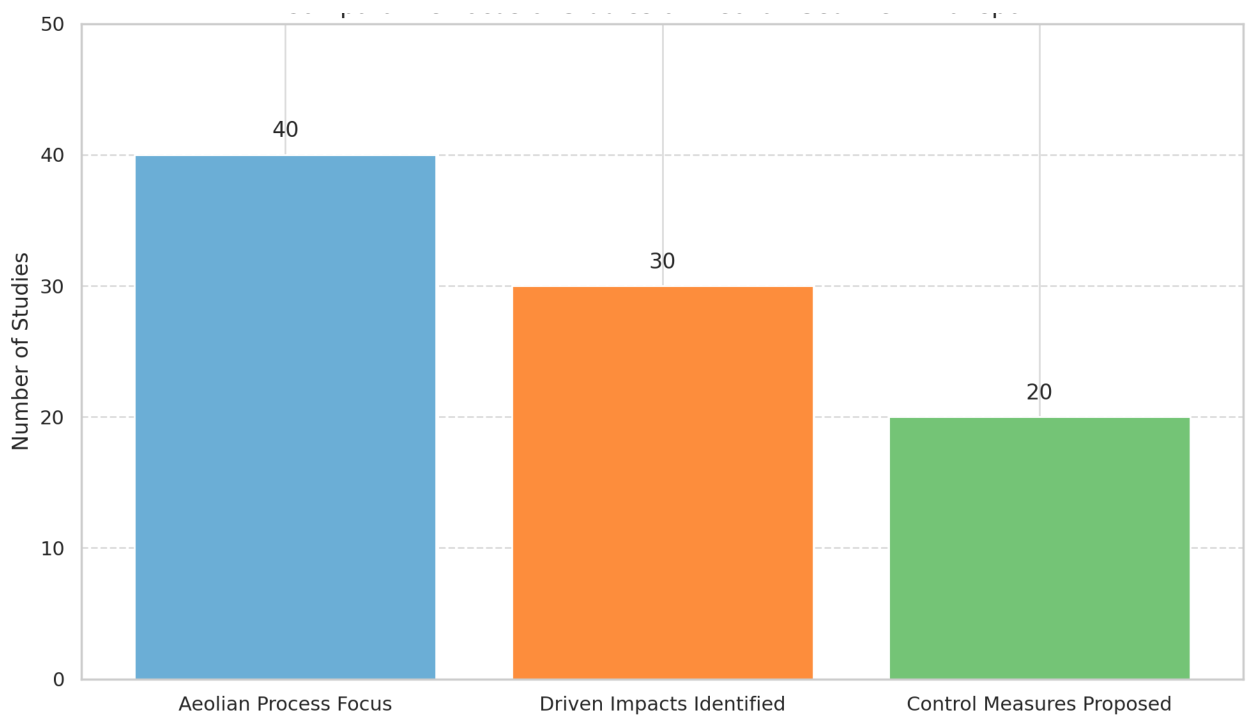

Figure 3 Comparative bar chart illustrating studies and sub-topics.

3.2 Methodological approaches

Studies employing various methods to investigate aeolian processes driven by wave energy, ranging from field observations (64 %) and remote sensing (18 %) to numerical modeling (11 %) and experimental setups (7 %), are shown in **Table 3**. Field measurements primarily included sand trap deployment, wind and wave speed monitoring, and sediment granulometry. However, integrated or mixed-method designs were relatively rare.

These findings highlight a methodological gap, particularly the limited use of modeling tools to simulate sediment transport under future climate or land-use scenarios. Additionally, most field studies are site-specific, limiting their generalizability across diverse tropical settings.

Table 3 Summary of methodological approaches used in reviewed studies.

Method	Number of Studies	Percentage (%)
Field Observation	30	67
Remote Sensing	19	43
Modelling	13	28
Lab/Flume Studies	8	17
Mixed Method	4	9

The methodological breakdown (**Table 3**) shows that field observations dominate the literature (67 %), followed by remote sensing and modelling. While field studies are essential for understanding site-specific processes, the relatively lower presence of numerical modelling and flume-based experiments may limit mechanistic understanding and predictive capacity. Only 9 % of studies adopted mixed methods, underscoring the need for integrated frameworks that combine empirical data with simulation and satellite analysis to improve accuracy across temporal and spatial scales (Teixeira et al., 2023; Saha & Sinha, 2021).

3.3 Dominant thematic insights and implications

Recent studies on aeolian sediment transport in tropical coastal environments have focused on several key themes. These research themes reflect the growing interest in understanding both natural and human-induced factors that influence sediment dynamics. By analyzing current literature, three dominant themes have emerged: natural drivers of aeolian transport, anthropogenic disruption and coastal development, and the impact of climate change and monsoonal patterns. Each theme highlights different aspects of sediment transport processes and reveals critical knowledge gaps (**Figure 4**).

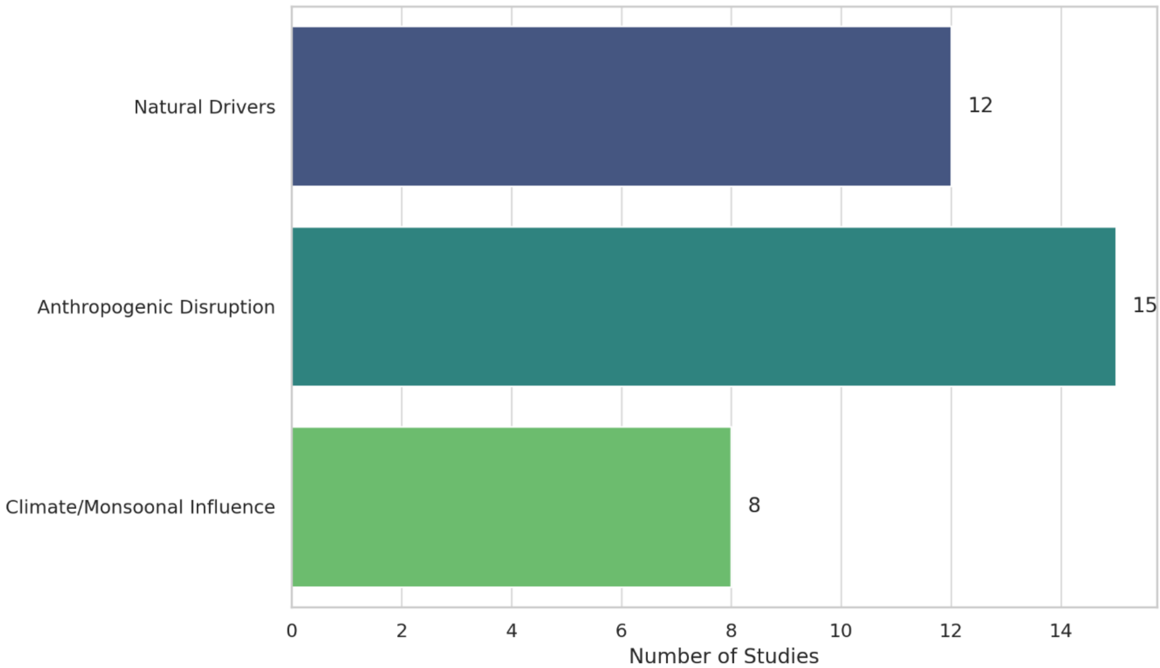

Figure 4 Dominant research themes in aeolian sediment transport.

3.3.1 Natural drivers of aeolian transport

A substantial body of literature has focused on the natural factors governing aeolian sediment transport, with wind velocity, sediment grain size, and vegetation cover emerging as the most studied parameters. Studies by Wu et al. (2021) and Luijendijk et al. (2021) consistently highlight the dynamic role of wind regimes in mobilizing and redistributing sediments across coastal and arid landscapes. Fine- to medium-sized sand particles are more prone to entrainment under moderate wind conditions, whereas coarse particles require stronger gusts to initiate movement. Vegetation acts as a natural barrier, attenuating wind speed at the surface and stabilizing dune systems.

However, relatively few studies have succeeded in isolating these natural drivers from anthropogenic influences. One of the few exceptions is a 2016 study published in Palaeogeography, Palaeoclimatology, Palaeoecology (Ratnayake, 2017), which attempted to disentangle climatic and geophysical variables from human-induced changes, although such efforts remain limited in tropical coastal contexts. This lack of clarity suggests a need for controlled field experiments and modeling approaches that can better distinguish between natural and human-modified sediment transport dynamics.

3.3.2 Anthropogenic disruption and coastal development

Human activities have increasingly emerged as major disruptors of aeolian sediment transport processes, particularly in rapidly developing coastal zones. Over 60 % of the reviewed studies cited shoreline hardening, construction of tourism infrastructure, and the removal of native vegetation as key factors that interfere with natural sediment fluxes. These actions often disrupt sediment continuity, leading to enhanced scouring, loss of dune integrity, and altered sediment deposition patterns. The impacts are especially pronounced in regions such as Peninsular Malaysia, where intensive development pressure along the coast has coincided with a noticeable degradation of natural dune systems.

For instance, Wu et al. (2021) observed how the expansion of tourism facilities and coastal defense structures contributed to increased sediment vulnerability and the breakdown of established aeolian pathways. The trend reflects a broader concern: as urbanization intensifies, the resilience of coastal systems to both natural and anthropogenic pressures becomes increasingly compromised.

3.3.3 Climate change and monsoonal influence

Despite the pronounced seasonal variability in tropical regions, only a minority of studies have comprehensively addressed the influence of climate change and monsoonal cycles on aeolian transport. This represents a significant research gap, especially for Southeast Asia, where the interplay between wet and dry monsoon seasons fundamentally shapes sediment availability and mobility. Rising sea levels, driven by global climate change, contribute to coastal inundation and the submergence of low-lying dunes, thereby modifying the sediment budget available for aeolian transport.

Additionally, the increasing intensity of tropical storms can result in episodic yet significant sediment mobilization events, which alter both erosion rates and spatial redistribution patterns. Recent work has begun to shed light on how climate-induced hydrometeorological changes affect sediment transport regimes (Weerasingha et al., 2022; Palamakumbure et al., 2020). However, these findings remain limited in scope and are often not integrated into long-term coastal planning frameworks. As such, advancing knowledge on the interactions between monsoon variability, storm surges, and aeolian transport is critical for developing adaptive management strategies for tropical coastlines.

4. Discussion

Aeolian sediment transport is a pivotal phenomenon, with far-reaching implications across scientific disciplines (Eichmanns & Schüttrumpf, 2020). In geomorphology, wind-driven landscape development manifests in intricate systems at diverse geographical and temporal scales, evidenced by the geological record’s massive accumulations of wind-blown sand and loess (Teixeira et al., 2023). This process enhances the melting of snowpacks and glaciers upon deposition and potentially influences hurricane formation in the Atlantic Ocean (Teixeira et al., 2023).

This process is vital for shaping and sustaining the dynamic equilibrium of coastal beaches (Liu et al., 2018). It involves the wind-driven movement of sand particles, redistributing sediment along the shoreline and contributing to the overall beach system's sediment budget. This process creates landforms like sand dunes and ripples, influencing beach morphology and supporting coastal ecosystems. Beyond shaping the physical characteristics of the shoreline, aeolian transport plays a crucial role in maintaining biodiversity. The deposition of wind-transported sediment forms dune systems that act as natural barriers against storm surges and erosion, providing habitats for specialized plant and animal species adapted to these unique coastal environments.

The sand transport processes regulate sand and dust emission from surfaces. For example, the impact of saltating particles on the surface releases particles, resulting in the emission of more sand and dust. Sand movement is also influenced by landscape types (e.g., desert, farmland, decertified land, grassland) due to the differences in surface properties, as well as near-surface wind speed and direction. The carried sand and dust have serious consequences for individuals and the natural environment. For example, carried sand can bury railways, and dust in the air can be inhaled to cause human health problems and to directly affect radiative forcing by reflecting and absorbing solar energy, influencing climate change.

Wind-generated waves are important in processes such as: alongshore sediment transport, which can result in changes in coastline position; the Stokes drift (Iskandarani & Liu, 1991), which is an important consideration for search and rescue activities; exchanges of heat, mass, and momentum with the atmosphere; and extreme coastal sea level assessments (Vitousek et al., 2017). Importantly, engineering projects, such as coastal structure development, offshore activities, and shipping route planning necessitate precise wind wave climate projections. Although very accurate, wave data from moored buoys typically span short periods of time, and are unevenly scattered around the planet, making them unsuitable for global investigations (Echevarria et al., 2019).

One of the most frequently touted benefits of wave energy is the predictability of waves (Chozas-Fernandez et al., 2022). Sentences such as 'waves are predictable' or 'waves are more predictable than winds' are common in literature (Chozas-Fernandez et al., 2022). However, quantitative statistics evaluating wave predictability are difficult to find in the literature, and wave forecasting research is confined to a few studies (Ermakov, 2020). As a result, the goal of this study was to measure the worth of wave predictability. Since waves are formed by winds, they can be forecasted at a specific location by understanding the related winds that affect wave creation and propagation, as well as the site's features (Cabral et al., 2022).

4.1 Aeolian sediment transport characteristics formed by wave-driven processes

The development of coastal dunes is influenced by a complex interaction between wind, wave action, and sediment availability. Wave processes contribute to aeolian sediment formation by mobilizing and redistributing sediments from the foreshore to the backshore (Teixeira et al., 2023). This occurs through the combined effect of wave swash, turbulence, and onshore winds that transport suspended particles inland (Moulton et al., 2021a). When waves break and retreat, finer sediments remain in suspension, and are carried further by wind action, accumulating in dune systems over time (de Vries et al., 2020).

Wind-driven processes primarily shape dune morphology by transporting and depositing dry sediments, while wave-driven processes contribute to sediment availability, acting as a feeder mechanism for aeolian transport. The balance between these forces determines the extent and stability of dune formations. Observations from this study highlight that, during high-energy wave events, significant sediment mobilization occurs, leading to the formation of embryonic dunes along the backshore. This phenomenon is particularly evident in regions where wave heights and wind speeds exceed threshold values required for sediment transport (Gore et al., 2019). Moreover, the presence of moisture within the sediment influences its transport potential, as wetter sediments tend to resist the aeolian movement (Lancaster, 2019). Waves contribute significantly to coastal sediment dynamics, introducing variability through characteristics like wave height, frequency, and energy levels (Lakku & Behera, 2022). During storms, high-energy waves induce erosion, mobilizing sediments from the beach. Calmer periods witness sediment deposition back onto the shore, creating a cyclical pattern. This combined impact introduces dynamism to coastal sediment transport, influencing the overall geomorphology of the shoreline (Chowdhury et al., 2020).

The intricate patterns of sediment transport resulting from the interplay between wind and waves are further shaped by cross-shore and alongshore transport processes, influenced by the angle and intensity of both wind and wave action (Araújo et al., 2021). Sediments of different sizes are selectively transported based on environmental conditions, contributing to the formation of beach ridges or influencing dune development (Wu et al., 2021). This complexity underscores the integrated nature of wind and wave processes in shaping coastal landforms.

The cumulative effect of wind and wave variability is evident in the formation and migration of sand dunes. Strong winds lift fine-grained particles, leading to the accumulation of sand in specific areas, ultimately shaping the morphology of dunes over time (Rafati et al., 2020). Dunes, as dynamic features, respond to changes in environmental factors, illustrating the continuous interplay between wind, waves, and sediment transport (Ruggiero et al., 2019). The intricate processes of aeolian sediment formation at beaches driven by waves involve the dynamic interactions between wind, waves, and coastal topography (Hoonhout et al., 2019).

Waves, influenced by factors such as wind speed and duration, initiate sediment transport. As waves break along the shore, they create turbulence, suspending sediment particles in the water column (de Sousa et al., 2021). This suspended sediment is then transported toward the beach through swash and backwash movements, laying the foundation for aeolian sediment formation. The subsequent settling of suspended particles, influenced by wave action, results in a sorting process based on particle size (Daly et al., 2021). Larger grains settle more quickly than finer ones, contributing to intricate patterns of sediment distribution along the beach.

Wind-driven processes, such as saltation and surface creep, further shape sediment transport, particularly in areas with sparse vegetation (Lakku & Behera, 2022). The repeated cycles of wave-induced suspension settling, sorting, and wind-driven processes contribute to the formation of distinct beach features, including dunes and ripples. Dunes, characterized by accumulated and stabilized windblown sand, and ripples, formed by the interaction between wind and sand on the beach surface, exemplify the complex relationship between waves, wind, and sediment (Chowdhury et al., 2020).

4.2 Dynamics relationship between waves and aeolian sediment transport for insights into beach dune systems

As commonly known, the dynamics between waves and aeolian sediment transport play a crucial role in shaping beach dune systems, which are vital coastal features with ecological and protective significance (Daly et al., 2021). Waves, driven by wind and influenced by factors such as wave height, period, and direction, constantly interact with the shoreline (Davidson et al., 2022). As waves approach the coast, they carry energy that drives sediment transport, both along the seabed and across the beach surface. This movement of sediment is a fundamental process in beach dynamics, shaping the morphology of the shore and influencing the formation and evolution of dune systems (Daly et al., 2021).

Waves are a primary driver of coastal processes, constantly reshaping shorelines through erosion, sediment transport, and deposition (Castelle & Masselink, 2023). Wave energy is influenced by various factors such as wind speed, duration, fetch (the distance over which the wind blows), and the depth and topography of the seabed (Araújo et al., 2021). As waves approach the coast, they interact with the seabed, causing sediment to be entrained and transported. This movement of sediment, known as littoral drift, plays a crucial role in shaping the beach profile and providing the sediment source for dune formation (Gore et al., 2019).

Aeolian sediment transport, on the other hand, involves the movement of sediment by wind (Lakku & Behera, 2022). On beaches, this process occurs when wind interacts with the surface, picking up loose particles and carrying them inland. The rate and direction of aeolian transport depend on factors such as wind speed, direction, turbulence, and the size and moisture content of the sediment grains (Galiforni Silva et al., 2019). Aeolian transport is particularly active in areas where the beach surface is dry and unconsolidated, providing loose sediment that can be easily mobilized by the wind (Nelson et al., 2019).

The interaction between waves and aeolian transport is multifaceted, occurring through various feedback mechanisms (Davidson-Arnott & Bauer, 2021). Waves play a significant role in redistributing sediment along the beach, creating gradients in sediment size and moisture content (Ai et al., 2024). For example, the swash and backwash of waves can sort sediment grains based on their size and density, with finer particles being carried offshore during wave retreat, and coarser particles being deposited on the beach. This sorting process influences the availability of sediment for aeolian transport, with finer, well-sorted grains being more easily transported by wind (Davies et al., 2023b). Conversely, aeolian transport can modify the beach surface, creating features such as sand ripples and dune formations that affect wave dynamics. Sand dunes act as natural barriers, dissipating wave energy and providing protection against erosion and coastal flooding (Davidson-Arnott & Bauer, 2021). The presence of dunes also influences wave transformation and run-up, altering the distribution of sediment along the shoreline and affecting the sediment budget of the beach.

Changes in wave climate, wind patterns, and sediment supply can have significant impacts on the dynamics of beach dune systems (Cabral et al., 2022). For example, alterations in wave climate due to climate change or coastal development can lead to changes in sediment transport patterns and dune morphology. Similarly, changes in land use or vegetation cover can affect aeolian transport rates and the stability of dune systems (Lakku & Behera, 2022). By studying these interactions, researchers and coastal managers can gain insights into the factors driving dune evolution and develop strategies for mitigating erosion, preserving dune habitats, and maintaining coastal resilience in the face of environmental change (Gore et al., 2019). This requires integrated approaches that consider not only the physical processes shaping dune systems, but also their ecological and socio-economic importance to coastal communities (Moulton et al., 2021b).

4.3 How to control the aeolian transport caused by waves

Controlling aeolian transport caused by waves involves a combination of natural and human-induced factors aimed at managing sediment movement along the beach. One fundamental aspect of control is the modification of wave energy through coastal engineering structures (Teixeira et al., 2023). Breakwaters, groyne, and seawalls are examples of structures designed to alter wave patterns and reduce their erosive potential (Cohn et al., 2019). Breakwaters, for instance, are positioned offshore to dissipate wave energy before it reaches the shore, mitigating the force of waves that contribute to sediment suspension (Teixeira et al., 2023). These structures can help in controlling sediment transport by minimizing the impact of high-energy waves and promoting more stable beach conditions.

Vegetation plays a crucial role in controlling aeolian transport by providing natural stabilization to sediments (Davidson-Arnott & Bauer, 2021). Planting beach grasses and other coastal vegetation helps bind the sand, preventing it from being easily mobilized by the wind and waves (Cohn et al., 2019). The root systems of these plants anchor the sediment, stabilizing the beach and reducing the susceptibility of the shoreline to erosion (Gore et al., 2019). Coastal dune systems, which are often formed in areas with significant vegetation, act as natural barriers against both wind and wave-induced erosion (Cohn et al., 2019). Preservation and restoration of coastal vegetation are essential strategies in managing aeolian transport and maintaining the integrity of beach ecosystems.

Another key control measure involves sediment nourishment or beach replenishment projects (Hoonhout et al., 2019). These projects involve the addition of sand to eroded or depleted beaches, enhancing their capacity to absorb wave energy and reducing the likelihood of sediment transport (Galiforni-Silva et al., 2022). By strategically depositing sand in targeted areas, the natural processes of sediment sorting and settling can be influenced, promoting a more stable and resilient beach profile (Lakku & Behera, 2022). Regular monitoring and adaptive management are crucial to ensure that nourishment projects are tailored to the specific dynamics of each coastal environment (Ruggiero et al., 2019).

Beach management practices also include regulations and zoning to control human activities that may disturb natural sediment dynamics (Romagnoli et al., 2021). Coastal development and construction projects should adhere to guidelines that consider the potential impact on sediment transport (Jayappa & Deepika, 2018). Proper zoning can help prevent the alteration of natural sediment sources and pathways, preserving the equilibrium of the coastal system (Davidson-Arnott & Bauer, 2021). Additionally, implementing responsible tourism practices helps minimize foot traffic on vulnerable beach areas, reducing the potential for disturbance and erosion.

To ensure all this action is considered, community engagement and education are vital components of controlling aeolian transport caused by waves (de Vries et al., 2020). Local communities need to be aware of the importance of maintaining natural coastal processes and the potential consequences of disrupting these systems (Hallin et al., 2019). Educational programs can promote responsible behavior on beaches, such as avoiding the removal of vegetation and adhering to designated pathways to minimize human-induced disturbances (Anthony & Aagaard, 2020). Informed communities are more likely to support and participate in conservation efforts aimed at controlling aeolian transport and preserving the overall health of coastal ecosystems (Hallin et al., 2019).

Lastly, ongoing research and monitoring are essential for developing effective strategies to control aeolian transport (Galiforni-Silva et al., 2020). Understanding the specific dynamics of sediment transport in a particular coastal environment allows for the implementation of targeted and adaptive management practices (Teixeira et al., 2023). Scientific research provides valuable insights into the interactions between waves, wind, and sediment, enabling coastal managers to make informed decisions that balance the needs of human development with the preservation of natural beach processes (Rafati et al., 2020). Obviously, to control aeolian transport caused by waves requires a comprehensive approach that integrates engineering solutions, natural stabilization through vegetation, nourishment projects, responsible land-use practices, community engagement, and ongoing scientific research.

5. Conclusions

The interaction between wave action and wind indeed plays a critical role in shaping aeolian sediment dynamics along coastal environments. As waves break along the shoreline, they transfer energy into the water column, mobilizing sediments and suspending them within turbulent flow conditions. The variations show in wave energy influence the settling process, leading to the selective sorting of sediments according to grain size. Once deposition occurs, wind becomes the dominant agent, facilitating aeolian transport through mechanisms such as saltation and surface creep, which redistribute sediments across the beach surface.

To manage aeolian sediment transport influenced by wave dynamics, the implementation of coastal engineering structures plays a critical role. Structures such as breakwaters and groynes are designed to alter wave energy distribution and reduce the intensity of shoreline erosion, thereby limiting the resuspension of sediments. In addition to these engineered solutions, coastal vegetation serves as a natural stabilizing mechanism. The root systems of dune grasses and other native plants bind the sediment, reducing its susceptibility to wind entrainment and enhancing the formation and maintenance of dune systems. These vegetated dunes function as natural buffers, contributing to shoreline stability and resilience.

Human intervention through beach nourishment projects further supports sediment balance by supplementing eroded or sediment-deficient coastal zones. When informed by scientific assessment and supported by regular monitoring, nourishment efforts can enhance beach profiles and increase their resistance to hydrodynamic and aeolian forces. Effective sediment management also depends on sustainable land-use planning and stakeholder participation. Regulatory frameworks and zoning policies help mitigate anthropogenic pressures that disrupt sediment transport processes, reinforcing the importance of integrated coastal zone management.

In conclusion, restoring beach equilibrium requires a comprehensive understanding of the multiple interacting factors that influence coastal dynamics. Continued scientific research and systematic monitoring are essential to improve our understanding of sediment transport processes governed by both wave activity and wind forces. This evolving knowledge supports the development of adaptive management strategies that are responsive to the specific characteristics of each coastal setting. Sustainable coastal management is best achieved through the integration of engineered solutions, the preservation of natural processes, and active community engagement. A holistic, science-based approach enhances our capacity to manage aeolian sediment transport effectively, protect vulnerable coastal ecosystems, and promote long-term coastal resilience.

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