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Assessing Wind Erosion: A Review of Recent Measurement Techniques

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Abstract

Wind erosion represents a formidable environmental challenge and has serious negative impacts on soil health and agricultural productivity, particularly in arid and semi-arid areas. The complex dynamics of wind erosion make its large-scale monitoring and quantification a daunting task. To facilitate the monitoring and quantification of wind erosion, various scientific approaches and methods have been employed. These include sophisticated wind erosion equations and models, wind tunnel experiments, and the application of radionuclides. Additionally, researchers have assessed soil physicochemical properties, used anemometers for wind speed measurement, and deployed dust collectors for particle capture. Remote sensing technologies, wind erosion monitoring stations, and evaluations of wind barriers have also been utilized. Recently, the adoption of machine learning methods has gained popularity. Despite their value, each of these techniques has limitations in capturing the full spectrum of the wind erosion process. This paper examines these limitations and assesses the effectiveness of each method in the context of wind erosion studies. It also outlines directions for future research and suggests pathways that could enhance the understanding and management of wind erosion.

Keywords

Wind Erosion, Wind Erosion Models, Remote Sensing, Machine Learning

1. Introduction

Throughout history, a significant portion of the Earth's land, more than one-third has been affected by wind erosion in arid and semi-arid regions [1]. Between 1980 and 2019, climate change has caused a 3.2% increase in wind erosion in arid regions [2]. This natural process mainly occurs in areas with strong winds or on land without vegetation cover [3]. Human activities like deforestation, monoculture farming, and overgrazing have accelerated soil erosion rates [4]. Wind erosion involves the detachment of both fine and coarse soil particles leading to their displacement into the atmosphere and around the Earth's surface [5] [6]. The environmental impact of these particles upon release depends on factors such as their size, and aerial trajectory [7].

Sudden changes in weather patterns can also cause wind erosion [8]. Factors such as wind velocity, soil texture and structure, rainfall, surface roughness, farming practices, vegetation coverage and field size all contribute to wind erosion [9] [10]. Wind erosion poses a considerable threat to farmland, leading to soil degradation and reduced agricultural productivity. However, due to its complex nature, accurately monitoring and quantifying soil wind erosion on a large scale remains challenging [11]. Addressing this challenge requires a comprehensive approach that integrates various research techniques. These techniques provide more understanding of the wind erosion mechanisms and measurement techniques. By utilizing and understanding these approaches, effective strategies can be developed to manage and mitigate the negative impacts of wind erosion on agricultural land.

While several review articles have addressed specific aspects of wind erosion measurement techniques in different studies, such as the wind erosion models, Wind tunnel experiments, application of radionuclides, remote sensing studies, and long-term wind erosion particle measurements in the field [3]. However, there is still a notable gap in the literature regarding methodologies across different contexts and scales in one study. The novelty and necessity of the present research lie in it is discussing of various methods used in wind erosion studies, examining both their limitations and potential avenues for future research discussed in one literature. This thorough review aims to fill this gap by providing an integrated overview of the state-of-the-art in wind erosion measurement techniques.

The main objectives of this review article are as follows: i) To delve into the current state of measurement techniques in wind erosion research, ii) To evaluate the shortcomings of existing approaches while suggesting innovative directions for progress in the field, iii) To highlight recent advances and key findings, and iv) To provide a basis for decision-making or further research in a time-critical context.

Multiple databases were used to identify relevant articles for this literature review. Initially, Google Scholar was utilized to obtain an initial sample of available articles. Regarding Google Scholar, broad search terms were initially employed to compile a list of primary source research articles that were peer-reviewed. A more focused search was then conducted using the Northwest A&F University library database to access articles that were not accessed on Google Scholar. The search terms selected for this literature analysis included: wind erosion, wind erosion measurement techniques, wind erosion models, wind tunnel, wind erosion radionuclides, wind erosion anemometers, wind erosion dust collectors, wind erosion remote sensing, wind erosion monitoring, wind barrier, and wind erosion machine learning. These terms were combined in various ways to obtain the most relevant and narrowly defined articles. The snowball method [12] was also used to locate articles.

2. Wind Erosion Processes

Wind erosion occurs in three stages: 1) the beginning of soil particle movement, 2) soil particle transportation, and 3) soil particle deposition [13]-[16]. This process begins when wind forces act on the soil surface, influenced by factors such as wind speed, aerodynamic roughness, particle size, surface condition, and soil type [16] [17]. For soil displacement to start, a minimum wind speed, known as the threshold velocity, is required. In 1951 Stallings [16] introduced this concept, defining it as the minimum wind speed necessary to initiate particle movement. For example, soil particles with diameters between 0.1 mm and 0.15 mm require a threshold velocity of 12 - 14 m/hr to begin displacement. The erosive force of the wind detaches fine soil particles, and when these particles are lifted and impact the surface, they can cause additional particles to be displaced from soil aggregates. Reference [6] has explained that lifted fine soil particles when they strike the surface, can further displace particles from soil aggregates.

The transportation of soil particles involves movement through three primary mechanisms: surface creep (rolling), saltation (jumping), and suspension (dust float), as illustrated in **Figure 1** [5] [13] [15] [18]. The energy required to detach and transport soil particles varies with size and weight, with stronger winds capable of carrying heavier particles [16]. Soil particles in saltation, which typically have diameters ranging from 0.1 to 1mm, are detached from the surface and carried horizontally by the wind, causing damage to soil surfaces, plants, and vegetation cover. The transportation of both large soil particles and fine soil dust particles is influenced by the process of saltation [15]. Particles smaller than 0.1mm in diameter, including fine silt, clay, and organic matter, are lifted into suspension by the wind and other particles. These particles can remain airborne for long periods and potentially travel long distances, affecting areas far from their origin. These finer particles, when inhaled, can cause health problems [15] [19] [20].

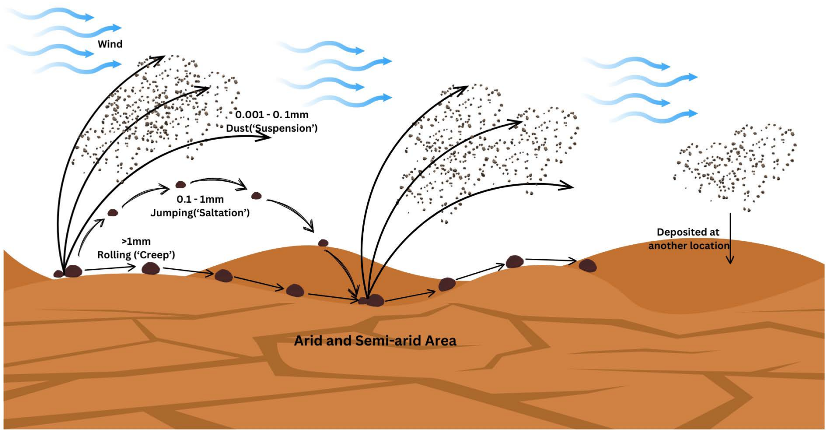

Figure 1. Different sizes of soil particles move due to wind at the transportation stage [21].

When wind velocity diminishes, soil particles eventually settle and deposit on the ground. This deposition commonly takes place in vegetated areas and furrows [22], ditches, and sheltered areas protected by windbreaks. Very fine particles will travel too far away before deposition, contributing to the formation of mounds and dunes particularly in sandy lands [23].

3. Techniques Used for Estimating, Measuring and Monitoring Wind Erosion

3.1. Wind Erosion Equations and Models

Wind erosion equations and models serve as essential tools for estimating wind erosion [24]. Wind erosion models and equations provide guidelines for efficient ways to quantify wind erosion. Researchers and other users such as soil conservation extension officers use these models for various purposes including the assessment of wind erosion rates, spatial and temporal distributions of wind erosion, soil particle transport mechanisms, changes in land surface conditions, soil properties, and the impact of soil wind erosion mitigation measures [25]. Wind erosion models are divided into three categories: Empirical models, Conceptual models and Processed-based models [26]. The commonly used wind erosion models are shown in **Table 1**.

Table 1. Wind erosion equations and models that are commonly used.

Model	Model type	Model output	Reference
Wind Erosion Equation (WEQ)	Empirical	The average soil loss in an area	[27]
Revised Wind Erosion Equation (RWEQ)	Empirical/ Process-based	The average soil loss in an area (including short-term average soil loss)	[28] [29]
Wind Erosion Prediction System (WEPS)	Process-based	Soil loss in terms of its direction and magnitude over the land surface	[30] [31]
Single-event Wind Erosion Evaluation Program (SWEEP)	Process-based	Soil loss in terms of its direction and magnitude over the land surface	[32]
Erosion Productivity Impact Calculator (EPIC)	Empirical	Soil loss over a specific period	[33]
Agricultural Policy Environmental eXtender (APEX)	Empirical	Soil loss over a specific time frame	[28]
Texas Erosion Analysis Model (TEAM)	Process-based	Total soil loss, soil movement rate over the field	[34]
Wind Erosion on European Light Soils (WEELS)	Process-based	Soil loss per unit time	[35]
Wind Erosion Assessment Model (WEAM)	Process-based	Soil loss over a specific period in tons per acre	[5]
Dynamic Model of Soil Wind Erosion (DMSWE)	Process-based	Amount of soil transport at downwind border	[36]

The WEQ, RWEQ, WEPS, and SWEEP models have achieved significant success and advancements, and as a result, they have been widely used for studying wind erosion around the world [9] [36]-[38]. Additionally, a comprehensive review of these wind erosion models has been discussed in reference [28].

Wind erosion models and equations have incorporated various parameters, including soil erodibility, weather factors (such as wind speed, wind direction, precipitation, temperature, humidity, evaporation, and solar radiation), soil surface roughness, field length, vegetation coverage, topography, surface soil moisture content, soil texture, soil aggregation, and land management practices (including tillage, fertilization, irrigation, and harvest). For future studies, it is essential to develop an advanced model that integrates all these factors into a single comprehensive framework [24] [28] [39]-[41].

The WEQ is useful in assessing land management practices for reducing soil erosion. Studies in the United States of America (USA) and China have shown that increased vegetative cover and ecological restoration measures can significantly reduce soil loss and mitigate water and wind erosion. The WEQ's adaptability and practical application in diverse environments have contributed to long-term environmental sustainability in many places where it was applied to assess wind erosion [42]-[44]. In a recent study in the Inner Mongolia Autonomous Region of China, the RWEQ was used to assess wind erosion and analyze soil loss on compacted soils. The study found significant correlations between RWEQ predictions and field measurements, providing accurate assessments of wind erosion, crucial for managing land degradation and protecting soil health [45]. Researchers in Inner Mongolia and in the Midwest region of the USA used WEPS to assess the impact of vegetation management practices on reducing soil erosion. In Inner Mongolia, sustainable grazing methods reduced soil erosion rates by up to 30% compared to traditional practices [46]. In the Midwest, no-till farming and strip cropping reduced soil loss by up to 50% compared to conventional tillage methods [47]. These case studies highlight the utility of WEPS in promoting sustainable land management across different regions.

However, wind erosion equations and models have faced limitations in accurately predicting sand fluxes [28] [48]. These models primarily rely on wind friction velocity to estimate near-surface turbulent momentum fluxes, which have proven less predictive over shorter periods and under non-ideal surface conditions [49]. The discrepancies in these models arise from the dominance of other less predictable terms in the near-surface wind momentum budget, leading to challenges in accurately forecasting sand fluxes [9].

Future studies on wind erosion should focus on estimating soil moisture, monitoring surface roughness, and evaluating erosion using Remote Sensing (RS) techniques [50]. It is also crucial to address the uncertainties and limitations present in current wind erosion models, particularly regarding their applicability to various regions and specific research questions [28]. Research gaps in post-fire wind erosion include understanding the ongoing effects of wind erosion after wildfires, the impact of fire and landscape characteristics on wind erosion, and the interaction between land management actions and post-fire ecosystem recovery

[51]. To advance wind erosion modelling, it is necessary to study a wider range of plant communities and landscapes, as well as the effects of post-fire weather, climate, and land use on site stability and vegetation recovery rates [52].

3.2. Wind Tunnel

Wind tunnel experiments have been a crucial technique for wind erosion research since the 1940s, with significant contributions from Chepil [53]. Chepil's work has involved assessing soil physicochemical properties and their relationship with wind erosion. He has found that several factors affect the severity of erosion, including the proportion of fine dust in the soil, the ratio of erodible to non-erodible fractions, soil surface roughness, the measurement location within the eroding field, and the previous erosion history. Wind tunnels have proven to be valuable instruments for simulating natural wind erosion processes in controlled environments, providing significant insights into the mechanics of wind erosion and validating wind erosion models. Wind tunnels provide controlled environments for the generation of wind erosion, including soil surface, wind direction, speed, and turbulence [54].

There are two types of wind tunnels that are used for wind erosion assessments: stationary wind tunnels, which are utilized for laboratory research, and mobile wind tunnels, which are employed for field investigations [55]. Stationary tunnels offer larger dimensions and a closer approximation to natural conditions, although they may not accurately replicate surface conditions such as soil crusting and structure [56]. On the other hand, mobile wind tunnels have been suitable for field use without disturbing natural conditions, making them well-suited for observing wind erosion on undisturbed surfaces [56]. To determine wind erosion in a selected region, mobile wind tunnels have been used [57]. For the field analysis and measurement of wind erosion processes on natural surfaces under controlled wind conditions, these mobile wind tunnels serve as invaluable resources [56].

A study using wind tunnel experiments to assess the wind erosion potential on agricultural lands found that conservation tillage and cover cropping reduced erosion compared to conventional tillage. These results showed significant differences in erosion rates associated with soil texture and moisture content [58]. Reference [59] measured the impact of Land Cover on wind erosion in arid regions. This study utilizes wind tunnel experiments to evaluate how different types of land cover influence wind erosion rates in arid environments. The findings suggest management practices that can help mitigate erosion effectively.

Wind tunnels have faced challenges in replicating wind erosion processes at the field scale due to their operation under controlled laboratory conditions, which may not fully capture the variability and complexity of natural wind erosion events. Additionally, they may encounter difficulties in simulating the influences of topography, vegetation, and land management practices on wind erosion [60] [61]. Studies have shown that wind erosion models like the RWEQ and WEPS may inadequately simulate soil and particulate matter loss under certain tillage conditions, indicating limitations in defining the complexity of erosion processes in the field [54]. Furthermore, wind tunnel experiments have highlighted the dynamic changes in shear velocity and aerodynamic roughness length over time, emphasizing the need to consider both bed deflation and erosion duration when calculating sand transport rates [62].

Current trends in wind erosion measurement using wind tunnels indicate advancements in the use of simulation techniques and equipment. Researchers are increasingly exploring the use of machine learning algorithms for interpreting soil susceptibility to wind erosion, as shown in the study in reference [63]. Additionally, the development of micro wind tunnels described in reference [61] has allowed for high-resolution simulations of wind erosion processes. Portable wind erosion tunnels, as discussed in reference [64], offer flexibility for field experiments. Innovations such as water injection units in wind tunnels, as proposed in reference [61], can enhance the simulation of erosion conditions. Furthermore, research collaborations have focused on correlating field measurements of erosion with wind tunnel test conditions, as demonstrated in reference [62]. These advancements have paved the way for more accurate and comprehensive studies on wind erosion processes.

3.3. Radionuclides in Soil Wind Erosion Investigations

The investigation of soil redistribution through the utilization of radionuclides, including ^{137}Cs, ^{7}Be, and $^{210}Pb_{ex}$, as well as $^{239+240}Pu$, is extensively documented in the scientific literature [65]-[68]. This methodology involves assessing the metabolic processes of target objects based on both radionuclide and non-radionuclide materials.

These radionuclides fall into two categories:

1) Artificial Radionuclides: ^{137}Cs and $^{239+240}Pu$.

2) Natural Radionuclides: ^{7}Be and $^{210}Pb_{ex}$.

For collecting bulk samples in the study area, a depth of 0 - 30/50 cm is recommended for ^{137}Cs, $^{210}Pb_{ex}$, and $^{230+240}Pu$, while 0 - 2/3 cm is suggested for ^{7}Be. Radionuclides are strongly adsorbent to soil particles, so studying their behavior in the landscape is a reliable way to study soil erosion caused by wind. ^{137}Cs is the most commonly used radionuclide to detect soil erosion rates [69]. A dry soil sample weighing between 100 and 1000 grams is typically placed into a Marinelli beaker in the laboratory, and a multi-channel analyzer is connected to the Germanium detector of the Gamma Spectrometry. Generally, ^{137}Cs activity is estimated using a 662 keV terminal [70]-[72].

Radionuclides offer several advantages in soil tracing technology. The wind erosion assessment approach using radionuclides is straightforward and highly accurate, making it applicable across diverse landforms, soil types, and land use patterns [73]. The approach is particularly effective for examining spatial variations in soil erosion and for estimating erosion over different time scales due to radionuclides' varying half-lives, which make it easy to illustrate the spatial variations

[74] Additionally, radionuclides provide insights into different erosion processes and sediment sources based on their distribution depths. The advantages, disadvantages, limitations, assumptions, and considerations for sample collection in radionuclide studies are well-documented in reference [65].

However, utilizing radionuclides in soil tracing has several drawbacks that can be addressed. Interpreting results can be complex due to factors like changes in land use, radionuclide redistribution, and fallout variations [65]. Moreover, their effectiveness as tracers may fluctuate based on site-specific elements such as soil type, vegetation cover, and climate [65]. Working with radioactive materials poses potential health and safety hazards, necessitating proper handling, disposal, and monitoring procedures. Contamination from external sources or interference from other radionuclides can compromise measurement accuracy [75]. Furthermore, analyzing radionuclides demands specialized equipment and can incur significant costs, while skilled personnel are essential for sample collection and analysis [76].

It's important to consider certain assumptions when using radionuclides for soil erosion tracing, including uniform radionuclide fallout deposition within the local landscape, strong and irreversible adsorption to soil particles, and movement occurring solely on soil particles [77]. Considerations for sample collection include proximity to the study area, similar elevation to the study site, negligible erosion or deposition caused by external agents such as wind, water, or tillage, a flat area with minimal undulation, and consistent low grass covering with uniform distribution [78].

Wind erosion measuring using radionuclides, such as ^{137}Cs, has limitations due to factors like the complexity of the erosion process, the need for precise measurement, and the variability in radionuclide values. Studies have shown that while ^{137}Cs have been valuable in water erosion research, their application to wind erosion has been limited until recent decades [79]-[81]. The distribution patterns of ^{137}Cs in soil profiles, variations in different particle fractions, and the influence of soil characteristics on erosion rates all impact the accuracy of estimates [82]. Additionally, the presence of radionuclides in soil is affected by factors like climate, latitude, and point sources, further complicating the use of radionuclides for wind erosion studies [83]. These limitations highlight the challenges in utilizing radionuclides for accurate estimation of wind erosion rates.

Future directions in wind erosion radionuclides research involve transitioning from ^{137}Cs to alternative tracers due to its' declining utility [84]. Plutonium and Uranium-236 are proposed as viable replacements, offering advantages such as higher initial concentrations and negligible decay losses [85]. Accelerator-based ultra-sensitive measurements of these isotopes present promising opportunities for tracing soil erosion and sediment movement [85]. Additionally, RS techniques for wind erosion studies, provide cost-effective and efficient means for mapping erosion indicators like soil erodibility, moisture, and surface roughness. The integration of radionuclide tracers with RS technologies can enhance the understanding and modelling of wind erosion processes, guiding future research towards more comprehensive assessments at regional scales [86].

3.4. Measurement of Soil Biological and Physicochemical Properties

The measurement of soil biological and physicochemical properties has been crucial in determining wind erosion potential. Studies have shown that soil strength characteristics, fine content, mean weight diameter, soil moisture content, macro-aggregate ratio, wind-erodible fraction, dry aggregate stability, calcium carbonate content, and soil organic matter content are key factors influencing soil erodibility and wind erosion rates [87] [88]. Additionally, the application of mulches, such as wood chips and organic mulch, has improved soil properties by increasing soil organic carbon percentage, mean weight diameter, geometric mean diameter, penetration resistance, shear strength, and tensile strength, while decreasing soil loss rate, fracture index, soil texture index, and crust index [89] [90]. Also, studies have shown that soil erodibility, a key factor in erosion sensitivity, can be evaluated through soil physicochemical properties and other methods [87] [90] [91].

However, the measurement of soil physicochemical properties for wind erosion assessment has faced limitations due to various factors. Limited data availability has made it difficult to compare soil erodibility across different regions and in water-wind erosion studies [89] [91]. Additionally, traditional methods for measuring soil physicochemical properties have been labour-intensive, time-consuming, and require destructive sampling that can alter soil characteristics. These methods have also faced limitations due to the spatial and temporal variability of soil properties relevant to the wind erosion process [92].

Changes in soil carbon content due to wind erosion have highlighted the importance of monitoring organic carbon, nitrogen content, and soil texture [93]. Assessing non-erodible particles, clay, organic matter, sand, silt, and calcium carbonate content has provided more details into wind erodibility and soil stability studies. Furthermore, incorporating organic amendments like vermicompost has shown promising results in improving soil properties and crop performance in calcareous soils affected by wind erosion [90]. Future directions should focus on integrating these findings to develop comprehensive strategies for sustainable soil management in wind-affected areas.

3.5. Anemometers

Anemometers have been an essential tool for measuring wind erosion. They have provided accurate wind speed data crucial for erosion evaluation and have been used in electronic wind-sand erosion and deposition measuring systems [94]. Advanced techniques that incorporate anemometer data to measure soil losses due to wind erosion have been used to analyze this important process of soil degradation properly [3]. Cover crop studies have also utilized anemometers to measure actual wind erosion rates and assess the impact of cover crops on reducing soil loss by wind [89]. Moreover, anemometer data has been integrated with other measures, such as mass loss and gloss data, in the context of wind turbine blade erosion to efficiently measure changes in coating microstructure due to soil erosion, aiding in erosion stage identification and maintenance planning [95]. In a pivotal study conducted in reference [96], the impact of wind speed measurements on the accuracy of wind erosion assessments was critically evaluated. The research highlights the significance of averaging times in capturing dynamic wind conditions, showing that shorter averaging periods more effectively represent wind fluctuations, thereby improving our understanding of soil erosion processes. These findings also demonstrate that precise wind speed data from anemometers can significantly enhance soil loss rate simulations and the prediction of erosion events.

Anemometers, particularly sonic anemometers, have become standard instruments in boundary layer meteorological experiments to measure turbulence and turbulent fluxes [97]-[101]. Sonic anemometers are widely used in wind erosion research to quantify wind speed and friction velocity, and to determine relationships between various flow properties and sediment transport. However, when employing sonic anemometers, it is critical to consider the variables influencing data processing and experimental design to ensure accurate and reliable measurements [101]. For instance, the susceptibility of soil to wind erosion, which has been determined through laboratory analysis of collected soil samples, can be better understood when combined with precise anemometer data [102].

Anemometers employed for measuring wind speed and direction have encountered challenges in accuracy and precision, particularly in complex terrain or turbulent wind conditions. They may be susceptible to errors stemming from instrument calibration, sensor drift, and exposure to environmental factors [103]. Prospective advancements in anemometer technology should prioritize enhancing the reliability and robustness of measurements in challenging wind conditions. This could involve meticulous calibration of sensors to ensure accurate data collection and integrating data from multiple sensors for comprehensive analyses of the wind field.

Combining advancements in anemometer design with RS technologies and field data collection strategies has provided more accurate and comprehensive assessments of wind erosion processes. In wind erosion studies, anemometers have involved advancements in measuring turbulent flows under sand-blasting conditions [50]. These anemometers should aim to enhance the measurement of wind velocity components using pressure techniques, allowing for real-time signal processing and compensation for complex tubing effects. The integration of RS techniques, such as those utilizing MODIS and Landsat data, has provided cost-effective and efficient approaches for mapping wind erosion indicators like soil erodibility, soil moisture, and surface roughness [3]. Furthermore, field-scale wind erosion studies should focus on improving methods for sediment sampling, meteorological measurements, and understanding temporal variations in surface conditions to enhance model validation and development [104].

3.6. Dust Collectors

In wind erosion research, dust collectors, including sediment samplers, and traps, are important in capturing wind-blown particles, and dust. These collectors facilitate the analysis of particle composition and quantity [105]. While various models are available, differing in size, shape, collection efficiency, and suitability for specific materials, the Big Spring Number Eight samplers are the most commonly utilized, as reported in reference [104]. The selection of a collector depends on the research objectives, required accuracy, and available resources. Particle size significantly influences collection efficiency, with saltation-transported particles being more readily captured than those suspended in the air [106].

Dust collectors utilized for sampling airborne particles in wind erosion studies may encounter challenges in capturing the full spectrum of particle sizes and compositions present in windblown dust. They may also be susceptible to sampling biases, losses during collection, and difficulties in accurately quantifying dust emissions.

Wind erosion dust collectors have limitations despite their utility. The collectors described in the contexts offer valuable insights but also face constraints. One limitation is the potential error in sediment discharge at certain wind speeds, affecting the accuracy of data collection. Additionally, while the near-surface soil wind erosion particle collector is effective in collecting particles of various heights, it may not capture all particles without loss, impacting data accuracy. Furthermore, the wild different gradient vertical dust-fall collector, although useful for studying wind-blown sand flow, may have limitations in providing comprehensive data on vertically fallen sand dust at different gradients. Despite these limitations, the multidirectional traps (MDt) collectors demonstrate the potential in predicting particle movement with high efficiency and precision, presenting a possible resolution to certain issues encountered with conventional collectors [107].

The limitations outlined above highlight the need for advancements in both design and efficiency of wind erosion dust collectors. Specifically, improving the accuracy of sediment discharge measurements at varying wind speeds is critical for reducing errors in data collection. Enhancing the ability of collectors to capture a wider range of particle sizes without loss would directly address the issues of sampling biases and losses, leading to more reliable data on dust emissions. For example, the development of collectors like the MDt, which can differentiate sediments by origin and detect overall particle movement, represents a significant step forward in mitigating these challenges. These innovations are necessary to overcome the current limitations and to ensure that future dust collectors can provide more precise and comprehensive data on wind-blown sand dynamics. Additionally, by incorporating advanced structural features such as sand inlets, separation nets, and large-diameter inlets, future designs can improve both the practicality and accuracy of data collection in diverse environments [108]. Utilizing materials like thermoplastic filaments for manufacturing can further enhance cost-effectiveness and ease of production. Future research should also focus on optimizing collector placement in various soil types to forecast particle movement and erosion rates better, ultimately contributing to a more comprehensive understanding of wind-blown sand dynamics in different environments.

3.7. Remote Sensing

Remote sensing methods have been beneficial for monitoring wind erosion across various scales and have proven to be faster than ground-based techniques, enabling coverage of extensive areas and the recurrent monitoring of erosion incidents or factors influencing erosion [109]-[111]. MODIS images have been highlighted for detecting dust storm events [112], and the NIMBUS 7, Total Ozone Mapping Spectrometer (TOMS) aerosol index has been used to identify major global dust sources [113]. Using indices of soil wetness and vegetation greenness, remote sensing has also been used to track wind erosion risk and sand accumulation and erosion [114]. In China, researchers have constructed a wind erosion dynamic index using RS and GIS, incorporating factors such as wind speed, soil dryness, NDVI, soil texture, and land surface slope [115]. One use of RS has been mapping the risk of wind erosion [116] and the modelling of soil erosion [117], revolutionizing field data collection methods and delivering temporal and spatially uniform data acquisition on terrestrial landscape attributes [50].

However, predicting regional wind erosion at the pixel level has proven challenging due to a lack of field data to correlate with RS data and compute sand transport flux [50]. By merging widely sampled remotely sensed data with ground-based wind erosion measurements, a recently developed technique has mapped net soil transport flux over sizable areas. High-resolution satellite images like IKONOS, QuickBird, and SPOT 5, although costly and limited in revisit time, have faced image processing challenges requiring specialized techniques and software [118]. Therefore, lower resolution options such as Landsat, MODIS, Sentinel 1 and 2, National Oceanic and Atmospheric Administration Advanced Very High-Resolution Radiometer (NOAA-AVHRR), and Advanced Space-borne Thermal Emission and Reflectance Radiometer (ASTER) have been freely accessible and employed for time series analysis [119] [120].

In recent years, the development of drone-based RS, driven by technological advancements in drones, cameras, and 3D photogrammetry, LiDAR sensors, has provided an effective, low-cost, and high-efficiency means of monitoring the impact of wind erosion on landforms [121] [122]. Drone-based RS has been employed in wind erosion experiments in drylands, offering the capability to capture data over relatively large areas [123].

Wind erosion RS has faced limitations such as high costs associated with high-resolution sensors [50], challenges in detecting dust storms causing erosion due to cloud cover interference [48], and the need for complementary fieldwork to address issues like insufficient samples and spatial displacement [123]. While RS methods have offered cost-effective and efficient ways to map erosion at different scales [124], the lack of research on chemical transport with micro-particles due to wind erosion has remained a gap in the field [125]. Additionally, the limited availability of ground data for calibration and verification has hindered the quality of erosion models, emphasizing the importance of integrating RS with meteorological data for improved predictions. These challenges have highlighted the necessity for a comprehensive approach combining remote sensing with fieldwork to enhance wind erosion monitoring and modelling.

Improved soil erodibility measurements, soil moisture content monitoring, and surface roughness assessment using affordable RS methods such as Landsat, MODIS, and Sentinel satellite imagery should be the main areas of future research in wind erosion measurements using remote sensing. Furthermore, incorporating high-resolution drone-based RS images can cover a larger area and solve difficulties encountered when gathering fieldwork data [48]. The application of fuzzy logic techniques in remote sensing-based mapping can improve the monitoring of wind erosion risk at a spatial scale of 30 m, aiding in sustainable land-use planning over large areas [126]. As demonstrated in studies on changing land use/cover in southern Iran, RS data has effectively quantified changes in wind erosion potential over time, particularly in response to alterations in land management practices [123]. Further research in RS should focus on enhancing the spatial and temporal resolution of satellite and airborne sensors for detecting wind erosion features, developing advanced algorithms for processing multi-sensor data fusion, and integrating machine learning and artificial intelligence for automated erosion mapping and monitoring.

3.8. Wind Erosion Monitoring Stations

The measurement and continuous monitoring of wind erosion have presented challenges due to its sporadic occurrence in both space and time. To address this, monitoring stations have been strategically positioned across farmland to continuously record meteorological data. These data have included variables such as wind speed, temperature, humidity, and soil moisture [127]. Quality-controlled data have been stored in a database, capturing information about the time, location, dust phenomena codes, visibility, wind speed and direction, temperature, rainfall, and other weather parameters, where available [128]. It is important that the data have been primarily retained for times with dust event codes and have not covered the complete meteorological record. Furthermore, the introduction of automatic weather stations has led to a decline in observations, particularly regarding dust phenomena codes and visibility, even though the need for such data is growing [129].

Wind erosion monitoring stations have been crucial for assessing and mitigating soil degradation caused by wind. Various innovative devices have been developed for this purpose. One such device is a wind erosion monitoring system that includes a shunt-hedging and cyclone-separation sand sampler with a weighting sensor based on Fiber Bragg Grating (FBG) [130]. Additionally, simple monitoring devices for wind erosion and deposition have been designed using aluminium and iron rods, meeting the requirements for long-term field observation in sand dune areas at a low cost [3]. Furthermore, a dynamic monitoring device for surface erosion and deposition caused by wind and sand has utilized light-sensitive devices, a Charge-Coupled Device (CCD) element, a flashlight, an instruction controller, and an Analog to Digital converter to continuously and automatically monitor changes in erosion and deposition with improved precision.

Wind erosion monitoring stations have had limitations in spatial coverage, data frequency, and network density, resulting in gaps in monitoring data and limited insights into erosion dynamics at different scales [131]. They have also been affected by maintenance issues, sensor calibration, and data transmission challenges.

Future developments in wind erosion monitoring stations could focus on expanding the spatial distribution of monitoring sites for better coverage of erosion-prone areas, implementing real-time data transmission and processing for timely erosion alerts, and integrating sensor networks for continuous monitoring of wind erosion parameters [50]. Research has emphasized the importance of utilizing RS techniques for mapping indicators like soil erodibility, moisture, and surface roughness to improve wind erosion detection and modelling [130], and the advancement of intelligent wind erosion monitoring systems discussed in reference [132].

3.9. Wind Barrier Assessments

Evaluating the effectiveness of natural wind barriers, including vegetation, terrain features, and constructed barriers like windbreaks, has been crucial in mitigating wind erosion. Studies have shown that sediment grain size distributions can serve as quantitative proxies for assessing the performance of wind barriers in reducing desertification [133]. Traditional field measurements have been used to investigate wind flow characteristics around barriers and optimize designs by assessing structural parameters, such as porosity and barrier height [134] [135]. However, these measurements have had limitations due to uncertainties in wind conditions and measurement ranges, obstructing their use for quantitatively assessing shelter effects in larger-scale engineering applications [136]. In a pivotal study, reference [137] explores the effectiveness of windbreaks in controlling wind erosion and PM pollution. The study found that well-designed windbreaks significantly reduce wind velocities near the ground surface, thereby reducing soil erosion rates. This study also highlighted the importance of windbreak orientation and density in determining their efficiency. The research suggested that windbreaks can be used as a dual-purpose tool for erosion control and air quality improvement.

The GIS models have utilized pedological information, agricultural land use data, meteorological data, and topographic maps to evaluate wind erosion risks and determine the effectiveness of wind barriers in protecting against erosive effects [138]. Field experiments have demonstrated that barriers such as rubble-stone fences, acacia and olive trees, and bamboo can significantly reduce soil loss, with optimal field lengths varying based on soil texture, ranging from 44 m to 200 m for different soil types [139].

The assessment of wind barriers for wind erosion measurements has faced limitations due to the imprecise prediction of protection length by current equations [3]. To address this, alternative equations incorporating barrier porosity have been developed, showing improved accuracy in predicting protection length and satisfying known boundary conditions [139]. Additionally, the effectiveness of sand barriers in limiting desertification has been debated, with sediment grain size distributions serving as a key indicator of their performance in reducing aeolian transport and erosion [133]. Geostatistical analysis and direct measurements have been crucial for assessing sediment transport rates over different vegetation cover types, highlighting the significant role of models and risk maps in wind erosion assessment and monitoring [9].

Future studies on wind barrier assessments could focus on integrating field measurements and modelling simulations to evaluate barrier performance under different wind conditions, optimizing barrier design for maximum erosion control benefits, and conducting long-term monitoring to assess barrier longevity and sustainability. Improvements in predicting the length of protection provided by wind barriers, considering factors like barrier porosity, are essential for effective soil erosion control. Computation of wind erosion force vectors can aid in determining the proper orientation of wind barriers for maximum protection against wind erosion forces. Furthermore, advancements in RS techniques for mapping erosion indicators like soil erodibility, soil moisture, and surface roughness will be significant [50]. Additionally, using advanced methods to assess wind erosion, quantify soil losses, and derive wind erosion risk through evaluation schemes and GIS procedures will enhance understanding and management [3].

3.10. Long-Term Monitoring

Implementing long-term monitoring programs is significant for monitoring changes in wind erosion patterns and soil loss over long-term periods. These changes, when combined with modelling approaches, can provide details into estimating erosion losses. Researchers such as in the references [140]-[142] advocate for using long-term data to assess alterations in topsoil depth, soil mass, and soil organic carbon (SOC) in the A horizon resulting from soil erosion. While direct measurements of wind erosion may be scarce, long-term monitoring of these soil parameters enables the assessment of changes spanning decades [140].

Long-term monitoring of wind erosion involves various innovative systems and devices. A wind erosion monitoring system proposed in one study utilized a shunt-hedging sand sampler and a weighting sensor for real-time, continuous, and long-distance measurements [143]. Another study introduced a simple monitoring device for wind erosion and deposition, featuring an aluminium rod with an empty groove and an iron rod connected through a connection device, designed for long-term field observation in sand dune areas at low cost [130]. Additionally, a model for simulating leading edge erosion on wind turbine blades incorporates a spatiotemporal stochastic approach and a deep learning model for monitoring erosion severity, aiding wind farm operators in efficient maintenance planning [144].

Long-term monitoring of wind erosion may encounter challenges related to data continuity, resource allocation, and the sustainability of monitoring networks, resulting in gaps in long-term erosion trend analysis. Additionally, it may be influenced by evolving environmental conditions, changes in land use practices, and issues related to data quality. Also, long-term monitoring of wind erosion faces limitations due to factors such as the lack of high-frequency data, which can lead to oversimplification in predictive models [144]. Additionally, challenges arise from the need for continuous monitoring to capture short-term erosion events that may be missed by traditional methods [145]. The use of satellite imagery, while providing long records, may underestimate average erosion rates and obscure short-term erosion processes, impacting the accuracy of erosion predictions [124]. Furthermore, field studies are constrained to limited areas, making it difficult to conduct comprehensive monitoring on actively used agricultural lands, limiting the understanding of wind erosion dynamics over larger territories [146].

Enhancing the effectiveness and accuracy of RS techniques used in wind erosion monitoring, as previously discussed in section 3.7 of this paper, could greatly enhance the accuracy of long-term wind erosion monitoring, for example, in the assessment of parameters like soil erodibility, soil moisture, and surface roughness [50]. Implementing advanced monitoring systems, such as a wind erosion monitoring system with anti-strong wind interference capabilities and real-time measurement features, can aid in continuous and long-distance monitoring [130]. Longitudinal studies on soil particle size and organic matter changes due to wind erosion in historically susceptible areas can provide insights into the effects of erosion on soil quality over time, guiding future monitoring efforts [145].

3.11. Machine Learning Models

Field measurements of soil erosion have been labor-intensive, expensive, and time-consuming, often yielding region-specific results. Consequently, researchers have increasingly relied on indirect methods to predict soil erodibility using easily measurable soil properties and pedo-transfer functions [147]. Leveraging models for soil erosion prediction has been advantageous for managing vast areas of erosion on both regional and global scales, especially when combined with remote sensing and large datasets [148]. Although Multivariate Linear Regression (MLR) models have commonly been used for this purpose, the application of machine learning (ML) techniques to analyze soil wind erosion is still relatively limited. Among the ML techniques, supervised learning algorithms such as Support Vector Regression (SVR), Decision Trees (DT), Random Forests (RF), Extreme Gradient Boosting (XGB), and Artificial Neural Networks (ANN) have been widely employed [149] [150].

Machine learning techniques have increasingly been utilized to address challenges associated with wind erosion. Various studies have explored the application of ML models for different aspects of wind erosion assessment. For example, Reference [151] developed both supervised and unsupervised ML models to quantify wind turbine blade leading-edge erosion. Reference [152] employed graph convolutional networks (GCNs) to predict land susceptibility to wind erosion, achieving high accuracy. Reference [153] presented a data-driven framework for modeling leading-edge erosion based on field data and numerical weather prediction models, enhancing the accuracy of erosion damage predictions. Moreover, Reference [63] demonstrated the feasibility of using ML algorithms, particularly random forest models, to infer soil susceptibility to wind erosion. Reference [149] further introduced deep learning algorithms for spatial mapping of the wind-erodible fraction of soil, emphasizing the importance of key factors in wind erosion assessment.

Despite the growing success of ML techniques in wind erosion research, the development and implementation of these models come with several challenges that must be carefully addressed to ensure their accuracy, reliability, and applicability [152]-[155]. These challenges include:

- Data quality and availability: Developing an ML model is complex and requires large datasets. Insufficient data quantity or poor data quality can lead to inaccurate model predictions.
- Feature relevance and complexity: Some features in the dataset may be irrelevant or too complex, potentially causing the model to overfit or underfit, which can also result in inaccurate predictions.
- Sensitivity of input data: Many factors influencing wind erosion are highly dynamic and can change rapidly. This variability can affect the model's accuracy over time, necessitating regular updates with new data.
- User interface design: Implementing the model into a user-friendly interface is challenging but crucial. Without a user-friendly interface, non-technical users may find it difficult to utilize the model effectively.

Future directions in wind erosion research using machine learning can introduce approaches like graph convolutional networks (GCNs) with Monte Carlo dropout for modelling erosion hazards [156]. Additionally, employing model-agnostic interpretation approaches, such as the Shapley additive explanations (SHAP) technique, can enhance the understanding of soil susceptibility to wind erosion [63]. The combined RS techniques offer a significant way for detecting, evaluating, and modelling wind erosion indicators, highlighting the need for further research to enhance the accuracy and effectiveness of RS in wind erosion assessments.

4. Summary

This review paper highlights that various techniques have been employed to monitor, measure, and model wind erosion. While these techniques contribute valuable insights into wind erosion assessments, they have different pros and cons, and their use is susceptible to different challenges. Table 2 highlights the major themes, significant insights, and critical observations identified in the literature.

Table 2. Summary of the key findings of different techniques used for estimating, measuring, and monitoring wind erosion rates.

Method/ Technique	Description	Advantages	Shortcomings	Potential areas for future research or enhancement of the techniques
Wind Erosion Equations and Models	Used to estimate wind erosion rates, assess soil particle transport mechanisms, and evaluate the effects of land management practices on wind erosion	Widely used, Adaptable to diverse environments	Limited accuracy struggle with diverse and complex surface conditions	Develop advanced models integrating all key parameters into a comprehensive framework
Wind Tunnel Experiments	Simulates wind conditions in a controlled environment to measure erosion rates	- Controlled conditions, - High repeatability	- May not fully replicate natural conditions. - Limited in capturing variability and complexity.	Develop micro wind tunnels for high-resolution simulations
Radionuclides (^{137}Cs, $^{239+240}$Pu, ^{7}Be and ^{210}Pb$_{ex}$)	Trace soil movement using radioactive isotopes deposited on the soil	- Applicable across diverse landforms, and soil types. - Accurate in quantifying soil redistribution	- Complex and handling radioactive materials need skilled personnel. - Expensive analysis.	- Use safer, alternative tracers. - Combine with other methods for cross-verification.
Measurement of biological and physicochemical properties	Used in assessing various soil properties to determine soil erodibility and wind erosion potential	Enhances understanding of soil stability and erosion potential	Labour-intensive, time-consuming and limited spatial coverage	Integrating with sustainable soil management strategies
Anemometers	Measure wind speed and direction at various heights above the ground, providing important data for wind erosion assessment	- Measure real-time data. - Portable and easy to deploy	- Doesn't directly measure erosion. - Limited to wind data.	Combine with dust collectors and RS technology to estimate erosion rates

Continued

Dust Collectors	Devices placed in the field to collect wind-blown dust and soil particles.	- Direct measurement of soil loss. - Easy to use in the field.	- Limited capture efficiency. - Requires regular maintenance.	Use of multiple collectors across different locations.
Remote Sensing	Monitor wind erosion across different scales using satellite and drone-based sensors	Monitoring large-scale, Faster than ground-based methods, low cost	Cloud cover, require field works for validation, difficulties in image processing	Integration of RS data with ground measurements and ML techniques
Wind Erosion Monitoring Stations	Continuous monitoring of wind erosion	Provides real-time meteorological data relevant to wind erosion	- Limited spatial coverage and network density - Maintenance issues	Expand monitoring networks and integrate real-time data transmission
Wind Barrier Assessment	Reduce near-ground wind velocities and soil erosion	Reduces wind velocity, soil erosion control and air quality improvement.	Measurement ranges can be obstructed by variable wind conditions, Existing equations often do not satisfy all boundary conditions	Integration with RS and use of advanced simulations
Long Term Monitoring	Direct measurement of soil loss using stakes, plots, or marked surfaces.	- Provides real-world and timely data. - Simple and cost-effective	- Time-consuming. - Limited spatial coverage	Incorporating RS for broader coverage.
Machine Learning Models	Predict soil erodibility and assess wind erosion based on easily measurable soil properties, integrating with RS and large datasets	- Can handle large datasets. - Improves prediction accuracy.	- Requires large amounts of training data. - Complex to implement.	Develop and train models with high-quality datasets.

5. Conclusion

Wind erosion represents a significant environmental challenge to the Earth's terrestrial landscapes, particularly in arid and semi-arid regions where climate change is exacerbating this problem. Human activities, including excessive vegetation removal, monoculture farming practices, and overgrazing, have been exacerbating the problem, leading to land degradation and an escalation in soil erosion rates. In this paper, the authors reviewed the different techniques used for estimating, measuring, and monitoring wind erosion rates. The major findings of each technique are summarized in Table 2. Among the soil erosion measurement techniques, several have gained notable success. Wind erosion models, wind tunnel experiments, radionuclide studies, and remote sensing techniques have all achieved significant successes and contributed substantially to the advancement of wind erosion research. The adoption of machine learning methods has recently gained popularity. However, challenges remain in the accurate prediction of wind erosion and fluxes. Each technique used in wind erosion studies has its own gaps and limitations. Key challenges include collecting field data over vast areas, detecting real-time identification of environmental variabilities, addressing the complexity of vegetation dynamics, ensuring data continuity, and securing long-term resource allocation. Future research in wind erosion studies should focus on improving wind erosion models, refining remote sensing technologies, improving machine learning models for more accurate erosion predictions, and implementing sophisticated monitoring systems designed for robust long-term data collection.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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