# PM10 dust emission in the Erenhot-Huailai zone of northern China based on model simulation Postprint

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## Abstract

The Erenhot-Huailai zone, as an important dust emission source area in northern China, affects the air quality of Beijing City, Tianjin City, and Hebei Province and human activities in this zone have a profound impact on surface dust emission. In order to explore the main source areas of surface dust emission and quantify the impacts of human activities on surface dust emission, we investigated the surface dust emission of different land types on the Erenhot-Huailai zone by model simulation, field observation, and comparative analysis. The results showed that the average annual inhalable atmospheric particles (PM10) dust emission fluxes in arid grassland, Hunshandake Sandy Land, semi-arid grassland, semi-arid agro-pastoral area, dry sub-humid agro-pastoral area, and semi-humid agro-pastoral area were 4.41, 0.71, 3.64, 1.94, 0.24, and 0.14 t/hm2, respectively, and dust emission in these lands occurred mainly from April to May. Due to the influence of human activities on surface dust emission, dust emission fluxes from different land types were 1.66–4.41 times greater than those of their background areas, and dust emission fluxes from the main dust source areas were 1.66–3.89 times greater than those of their background areas. According to calculation, the amount of PM10 dust emission influenced by human disturbance accounted for up to 58.00% of the total dust emission in the study area. In addition, the comparative analysis of model simulation and field observation results showed that the simulated and observed dust emission fluxes were relatively close to each other, with differences ranging from 0.01 to 0.21 t/hm2 in different months, which indicated that the community land model version 4.5 (CLM4.5) had a high accuracy. In conclusion, model simulation results have important reference significance for identifying dust source areas and quantifying the contribution of human activities to surface dust emission.

# Full Text

## Preamble

### PM10 Dust Emission in the Erenhot-Huailai Zone of Northern China Based on Model Simulation

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**Abstract:** The Erenhot-Huailai zone serves as a critical dust emission source area in northern China, significantly affecting air quality in Beijing, Tianjin, and Hebei Province. Human activities in this region profoundly impact surface dust emissions. To identify the primary source areas of surface dust emission and quantify the effects of human activities, we investigated surface dust emissions across different land types in the Erenhot-Huailai zone using model simulation, field observation, and comparative analysis. Results showed that average annual PM10 dust emission fluxes for arid grassland, Hunshandake Sandy Land, semi-arid grassland, semi-arid agro-pastoral area, dry sub-humid agro-pastoral area, and semi-humid agro-pastoral area were 4.41, 0.71, 3.64, 1.94, 0.24, and 0.14 $t/hm^2$, respectively, with emissions occurring primarily from April to May. Due to human activity impacts, dust emission fluxes from different land types were 1.66–4.41 times greater than those from their background areas, while fluxes from major dust source areas were 1.66–3.89 times greater. Calculations indicated that PM10 dust emissions influenced by human disturbance accounted for up to 58.00% of total emissions in the study area. Comparative analysis revealed that simulated and observed dust emission fluxes were relatively consistent, with differences ranging from 0.01 to 0.21 $t/hm^2$ across different months, demonstrating high accuracy of the Community Land Model version 4.5 (CLM4.5). These findings provide important reference value for identifying dust source areas and quantifying human contributions to surface dust emission.

**Keywords:** northern China; land type classification; model simulation; dust emission; human disturbance

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## 1 Introduction

Surface dust emission is the process by which wind erosion lifts dust particles from the surface into the atmosphere. As a major source of atmospheric aerosols, dust can alter atmospheric radiation balance, influence global water, carbon, and nitrogen cycles, and affect global climate and geochemical processes. Additionally, surface dust emission removes substantial soil nutrients, causing land degradation, and reduces air quality, threatening human health. Consequently, research on surface dust emission is essential.

Current studies have comprehensively examined dust emission mechanisms, patterns, intensities, and influencing factors through field observations and laboratory experiments, while numerous dust models have been developed to estimate emission quantities. Model simulations are valuable for exploring spatiotemporal characteristics of dust emission and play crucial roles in identifying dust source areas, transport pathways, and deposition zones. However, despite the ability of dust models to investigate emissions across different regions, research gaps persist across various scales. In recent years, increasing attention has focused on human disturbance impacts on surface dust emission, yet most studies operate at the plot scale under similar climatic conditions, with regional-scale research across different climates remaining relatively limited. The primary challenge lies in extracting human disturbance factors and assessing disturbance intensity at regional scales, leading to inconsistencies in quantifying human contributions to surface dust emission. Therefore, regional-scale dust emission studies across varying climate conditions, particularly regarding human disturbance effects, are urgently needed.

Surface dust emission predominantly occurs in arid and semi-arid regions of northern China, causing severe air pollution across vast areas. The Erenhot-Huailai zone, an important dust source area in northern China, has experienced significant topsoil nutrient loss and ecological fragility due to human activities and wind erosion, subsequently affecting air quality in Beijing, Tianjin, and Hebei Province. The zone encompasses arid, semi-arid, and semi-humid climates, with land types transitioning from north to south as desert steppe, typical steppe, agro-pastoral areas, and urban-rural fringe zones, accompanied by gradually increasing precipitation, vegetation cover, and human activity intensity. Thus, the Erenhot-Huailai zone was selected to investigate spatial and temporal dust emission distribution characteristics and human activity contributions.

Dust emission research primarily employs field observation, laboratory experiments, and model simulation, with the latter being particularly important for regional-scale studies. In recent years, the Community Land Model version 4.5 (CLM4.5) has been widely applied in surface dust emission research. Therefore, this study utilized CLM4.5 to simulate PM10 dust emission in the Erenhot-Huailai zone. The objectives were to characterize dust emission patterns, quantify human activity contributions, and provide scientific guidance for developing rational land use and management strategies, controlling and improving air quality in Beijing, Tianjin, and Hebei Province, and strengthening ecological environmental protection.

## 2.1 Study Area

The Erenhot-Huailai zone (39°30 -45°10 N, 111°10 -116°50 E; 1187 m a.s.l.) extends from Erenhot in the Inner Mongolia Autonomous Region to the Huailai Basin in Hebei Province, northern China. The study area measures approximately 600 km in length and 180 km in width, featuring a mid-temperate continental monsoon climate. Spring winds are particularly strong, especially in April and May. July experiences the highest temperatures, while January has the lowest, with minimum temperatures dropping below -25°C. Precipitation is unevenly distributed, gradually decreasing from 500 mm in the south to 200 mm in the north. The terrain consists primarily of undulating hills and high plains, with dominant soil types including brown calcic soil, brown desert soil, chestnut soil, saline soil, and cinnamon soil.

The northern region has an arid climate with grassland (desert steppe) and sandy land as primary land use types. Scarce precipitation and strong wind erosion remove substantial soil nutrients, resulting in infertile soils and fragile ecological environments. The central region features a semi-arid climate with grassland (typical steppe), cultivated land, and forest land. Despite dry conditions, wind erosion remains severe. The southern region has a semi-humid climate dominated by cultivated land, followed by forest land and grassland. Low-lying terrain makes this area susceptible to dust deposition, leading to relatively poor air quality. Severe wind erosion poses serious challenges to local agricultural and pastoral development, while the zone serves as a dust transport corridor from north to south, affecting air quality and public health in Beijing, Tianjin, and Hebei Province.

## 2.2 Methods

Based on influencing factors including wind speed, soil texture, soil water content, vegetation coverage, surface roughness, and soil freezing ratio, we employed the CLM4.5 model to estimate PM10 emissions from the study area. Recent implementation of grazing prohibition policies and farmland-to-grassland conversion has improved vegetation conditions. Therefore, areas with high grassland coverage were considered background areas with better protection and minimal human disturbance. By comparing emissions between the study area and background areas, we analyzed human activity impacts. Additionally, to explore differences between model simulation and field observation results, we established two dust observation instruments in the grassland of Sonid Right Banner (43°51 21 N, 113°42 29 E) in the Inner Mongolia Autonomous Region.

### 2.2.1 Model Structure and Data Sources

Dust emission flux (Fj; $\text{kg}/(\text{m}^2 \cdot \text{s})$) in the CLM4.5 model is calculated by Equation 1 (Wu et al., 2016).

where T is the adjustment factor of time and space resolution in the DEAD (Dust Entrainment and Deposition) model ($1.32\times10^{-2}$); S is the soil erosion factor (0.02); fm and $\alpha$ are the soil exposure ratio (%) and sand initiation mass power, respectively; Qs and Mi,j are the horizontal flux of saltation particles ($\text{kg}/(\text{m}^2 \cdot \text{s})$) and mass fraction of different dust source modes (%), respectively; and i is the dust source mode.

The soil exposure ratio (fm) in Equation 1 is calculated as follows:

where flake is the area percentage of rivers, lakes, and reservoirs (%); fwelt is the area percentage of wetlands (%); fsnow and fv are snow coverage percentage (%) and vegetation coverage percentage (%), respectively; wice and wliq are ice thickness and water thickness in the soil layer (m), respectively; and ice,1 ice,1 liq,1 is the soil freezing ratio.

The sand initiation mass power ($\alpha$) in Equation 1 is calculated as follows:

where e is the natural logarithm and Mclay is the mass fraction of clay in the soil (%).

The horizontal flux of saltation particles (Qs) in Equation 1 is calculated as follows:

where Cs is a constant (2.61); and atm, *t,* s, and g are atmospheric density ($\text{kg}/\text{m}^3$), threshold friction wind speed for dust emission (m/s), friction wind speed (m/s), and gravitational acceleration ($\text{m}/\text{s}^2$), respectively.

The mass fraction of different dust source modes (Mi,j) in Equation 1 is calculated as follows:

where mi, Dv,i, and $\sigma$g,i are the mass fraction (%), mass median particle size (m), and geometric standard deviation of dust source mode i, respectively (Table 1 ); and Dj,min and Dj,max are the minimum and maximum particle sizes of transport mode j (m), respectively (Table 2 ).

**Table 1** Mass fraction (mi), mass median particle size (Dv,i), and geometric standard deviation ($\sigma$g,i) of dust source model i

| Model i | Dv,i (m) | $\sigma$g,i |
|---|---|---|
| $0.832\times10^{-6}$ | $4.820\times10^{-6}$ | $19.380\times10^{-6}$ |

**Table 2** Minimum and maximum particle sizes of particle size group j

| Model j | Dj,min | Dj,max (m) |
|---|---|---|
| 0.1$×10^{-6}$ | 1.0$×10^{-6}$ | 1.0$×10^{-6}$ |
| 2.5$×10^{-6}$ | 5.0$×10^{-6}$ | 5.0$×10^{-6}$ |
| 10.0$×10^{-6}$ | | |

### 2.2.2 Data Collection

Wind speed, soil moisture (0–5 cm), and surface temperature data were obtained from the China Meteorological Science Data Center. Wind speed and soil moisture data were collected at hourly intervals, while surface temperature data were recorded at four time points (02:00, 08:00, 14:00, and 20:00 LST). Daily average surface temperature was calculated from these four measurements. Leaf Area Index (LAI) data were acquired from the Atmosphere Archive and Distribution System Distributed Active Archive Center (LAADS DAAC) using MODIS MOD15A2H data, collected every 8 days at 1 km spatial resolution. Snow cover data were obtained from the National Snow and Ice Data Center using MOD10A2 data, collected every 8 days at 500 m spatial resolution. Land use, soil texture, and land cover classification data were sourced from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences, the Cold and Arid Area Science Data Center, and LAADS DAAC, all at 1 km spatial resolution. All data underwent projection transformation, mosaicking, and clipping, with a final unified spatial resolution of 1 km. The data collection period spanned January 2017 to December 2020.

### 2.2.3 Regional Division and Background Area Selection

The Erenhot-Huailai zone comprises four climate types: arid, semi-arid, dry sub-humid, and semi-humid areas (Fig. 1a [Figure 1: see original paper]). Based on climate classification, we divided the study area into six sub-regions according to land use types: arid grassland (I1), Hunshandake Sandy Land (I2), semi-arid grassland (I3), semi-arid agro-pastoral area (I4), dry sub-humid agro-pastoral area (I5), and semi-humid agro-pastoral area (I6) (Fig. 1b [Figure 1: see original paper]). For each land type, we designated grassland areas with high LAI values as background areas with better protection and minimal human disturbance, selecting two background areas per land type, each with a 10 km diameter (Fig. 1c [Figure 1: see original paper]). Human disturbance effects on surface dust emission were quantified by comparing emissions between land type areas and background areas using Equation 6:

where FIn is the average dust emission flux from different land types ($t/hm^2$); F' In is the average dust emission flux from background areas ($t/hm^2$); SIn is the area of different land types ($km^2$); and n represents land use types.

**Fig. 1** Regional climate (a) and land type (b) classification and distribution of background areas (c) in the Erenhot-Huailai zone, northern China

### 2.2.4 Field Dust Observation

To verify model simulation accuracy, we conducted field dust emission observations in the grassland of Sonid Right Banner (Fig. 2a [Figure 2: see original paper]). Two DustTrak 8540 devices (TSI Incorporated, Shoreview, USA) (Fig. 2b [Figure 2: see original paper]) were installed at 1.0 m and 2.0 m heights to measure dust concentrations, while two DS-2 two-dimensional ultrasonic wind speed sensors (ATMOS 22, Meter Group Inc., Pullman, USA) (Fig. 2c [Figure 2: see original paper]) were installed at the same heights to measure wind speed. Observation intervals for both dust and wind speed were 1 minute, with the observation period extending from April 2018 to October 2019. Surface dust emission fluxes at the observation site were calculated using Equation 7:

where FV is the vertical flux of dust emission ($mg/(m^2 \cdot s)$); K is the Von Karman constant (0.4); * is the friction wind speed (m/s); Z1 and Z2 are heights of 1.0 m and 2.0 m, respectively; and C(Z1) and C(Z2) are PM10 concentrations at 1.0 m and 2.0 m heights ($mg/m^3$), respectively.

**Fig. 2** Field dust observation. (a) Instruments; (b) DustTrak 8540; (c) DS-2 two-dimensional ultrasonic wind speed sensor

## 3.1.1 Spatial Distribution

Spatial distribution analysis revealed that PM10 dust emission fluxes were relatively high in the northern part of the study area and lower in the southern part. Specifically, average PM10 dust emission fluxes were highest in arid grassland (4.41 $t/hm^2$) and semi-arid grassland (3.64 $t/hm^2$), followed by semi-arid agro-pastoral area (1.94 $t/hm^2$). Fluxes in Hunshandake Sandy Land, dry sub-humid agro-pastoral area, and semi-humid agro-pastoral area were relatively low, all below 0.80 $t/hm^2$ (Table 3 ). These findings indicate that grassland and cultivated land in arid and semi-arid regions represent important dust sources. Spatial distribution patterns were primarily influenced by wind speed and vegetation cover. However, the relatively low dust emission flux from Hunshandake Sandy Land in the northern region, compared to higher fluxes from surrounding grasslands, suggests that soil texture also significantly influences surface dust emission.

**Table 3** Average PM10 dust emission fluxes of different land types based on model simulation during 2017-2020

| Land type | Average PM10 dust emission flux ($t/hm^2$) |
|---|---|
| Arid grassland | 4.41 |
| Hunshandake Sandy Land | 0.71 |
| Semi-arid grassland | 3.64 |
| Semi-arid agro-pastoral area | 1.94 |
| Dry sub-humid agro-pastoral area | 0.24 |
| Semi-humid agro-pastoral area | 0.14 |

**Fig. 3** Annual PM10 dust emission flux based on model simulation during 2017-2020. (a) 2017; (b) 2018; (c) 2019; (d) 2020

### 3.1.2 Temporal Distribution

Model simulation results indicated substantial interannual variation in dust emission fluxes, with the highest emissions occurring in 2018. The average surface dust emission flux reached 4.08 t/hm$^2$ in 2018, compared to less than 2.16 t/hm$^2$ in other years. High emissions in 2018 were primarily associated with strong spring winds. Seasonally, average PM10 dust emission flux peaked in spring and reached its minimum in summer, with autumn and winter values being relatively similar (Fig. 4 [Figure 4: see original paper]). These seasonal differences were mainly related to vegetation coverage, wind speed, and topsoil freezing ratio. In spring, exposed surfaces combined with high wind speeds (Fig. 5 [Figure 5: see original paper]) resulted in high PM10 emissions, averaging 1.24 t/hm$^2$ during 2017-2020. In winter, although surfaces were bare and wind speeds were high, frozen topsoil prevented dust release, resulting in relatively low winter emissions of only 0.55 t/hm$^2$.

Monthly analysis from January to December during 2017-2020 (Fig. 6 [Figure 6: see original paper]) revealed clear temporal patterns. Average PM10 dust emission flux remained at lower-middle levels during January-March, increased rapidly to monthly maximums during April-May, decreased sharply to minimums during June-September, then rose again to lower-middle levels during October-December. Monthly average fluxes were 0.51 and 0.47 t/hm$^2$ in April and May, respectively, compared to 0.13, 0.04, 0.02, and 0.07 t/hm$^2$ in June, July, August, and September. These results demonstrate that April-May represents the most active dust emission period, while June-September is the most subdued.

**Fig. 4** Average PM10 dust emission flux in different seasons based on model simulation during 2017-2020. (a) Spring; (b) Summer; (c) Autumn; (d) Winter

**Fig. 5** Average wind speed in different seasons during 2017-2020. (a) Spring; (b) Summer; (c) Autumn; (d) Winter

**Fig. 6** Average monthly PM10 dust emission flux based on model simulation during 2017-2020. (a) January; (b) February; (c) March; (d) April; (e) May; (f) June; (g) July; (h) August; (i) September; (j) October; (k) November; (l) December

## 3.2 Effects of Human Activities on Surface Dust Emission

Comparative analysis of PM10 dust emission fluxes between land types and background areas during 2017-2020 (Fig. 7 [Figure 7: see original paper]) revealed that emissions from arid grassland, Hunshandake Sandy Land, semi-arid grassland, semi-arid agro-pastoral area, dry sub-humid agro-pastoral area, and semi-humid agro-pastoral area were 3.89, 3.62, 1.66, 3.18, 2.05, and 4.41 times higher than their respective background areas. The northern region, comprising the main dust source areas (arid grassland, Hunshandake Sandy Land, semi-arid grassland, and semi-arid agro-pastoral area), showed emission fluxes 1.66-3.89 times greater than background areas. High emissions in grasslands were primarily attributed to grazing, while elevated emissions in agro-pastoral areas resulted mainly from plowing and grazing. Using Equation 7 and considering the area occupied by each land type, we calculated that PM10 dust emissions influenced by human disturbance accounted for 58.00% of total emissions in the study area. Since selected background areas represent regions with maximum grassland coverage, this 58.00% can be considered the maximum contribution of human disturbance.

**Fig. 7** Comparison of PM10 dust emission fluxes between land types and their background areas based on model simulation during 2017-2020. (a) 2017; (b) 2018; (c) 2019; (d) 2020. I1, arid grassland; I2, Hunshandake Sandy Land; I3, semi-arid grassland; I4, semi-arid agro-pastoral area; I5, dry sub-humid agro-pastoral area; I6, semi-humid agro-pastoral area

## 3.3 Model Simulation Verification

PM10 dust observation data from May and November 2018 and February and August 2019 in the Sonid Right Banner grassland were selected to represent different seasons. Comparison between model simulation and field observation (Fig. 8 [Figure 8: see original paper]) showed that PM10 dust concentrations from field observation (at 0.2 m and 2.0 m heights) exhibited similar trends to simulated dust emission fluxes. Observed and simulated fluxes were relatively close, with differences ranging from 0.01 to 0.21 t/hm$^2$, indicating that model simulation results accurately reflect actual dust emission conditions in the study area.

**Fig. 8** Comparison of dust emission flux between field observation and model simulation

## 4.1 PM10 Dust Emission Source

The primary PM10 dust emission source was located north of the dry sub-humid agro-pastoral area, with maximum emissions occurring during April-May. Low vegetation coverage and high wind speeds during this period resulted in high PM10 emissions, consistent with research identifying wind and vegetation as the main controlling factors in northern China. Although emission intensity was relatively high north of the dry sub-humid agro-pastoral area, PM10 dust emission flux from Hunshandake Sandy Land within the main dust source area was relatively low, primarily due to soil texture. Hunshandake Sandy Land has low dust content (1.66% clay and 1.92% silt), resulting in relatively low PM10 emissions—a finding supported by field observations showing low emission intensity from sand dunes. Nevertheless, emissions from Hunshandake Sandy Land were significantly higher than those from dry sub-humid and semi-humid agro-pastoral areas, indicating that it represents an important potential dust source. Previous studies have demonstrated that activated dunes can release substantial dust and constitute significant dust sources.

## 4.2 Influence of Human Disturbance on Dust Emission

Multiple factors affect surface dust emission, including wind speed, soil moisture, vegetation coverage, soil dust content, topsoil freezing ratio, and human disturbance, with human activities having profound impacts. In this study, human disturbances consisted of grazing and farming. In pastoral areas, livestock grazing reduces vegetation cover and destroys topsoil structure through gnawing, root digging, and trampling. In agricultural land, tillage completely breaks up topsoil structure, resulting in higher disturbance intensity. The northern region, located in dry sub-humid and semi-arid agro-pastoral areas, is dominated by grazing, while the southern region is dominated by farming. Although human disturbance intensity is lower in the north, dust emission intensity shows the opposite trend. This phenomenon occurs because the northern arid and semi-arid areas have fragile surface environments highly susceptible to wind erosion, and grazing activities significantly intensify dust emission. In contrast, the southern dry sub-humid to semi-humid region has more robust ecosystems, and soil physical crust formation mitigates dust emission despite severe soil structure degradation from farming. Additionally, farming practices such as crop residue retention further reduce surface dust emission.

Further analysis revealed that under similar climatic conditions, dust emission fluxes from different land types were 1.66–4.41 times higher than those from background areas. Due to relatively high emissions in the northern region, total dust emission variations increased correspondingly, indicating that human interference had more significant effects on northern dust emissions. This regional-scale study showed single-digit increases in surface dust emission under human disturbance, whereas plot-scale studies have reported increases of several, dozens, or even hundreds of times. This difference arises because plot-scale results represent uniformly disturbed surfaces reflecting specific interference types, while regional-scale results represent various disturbed surfaces reflecting overall conditions. This discrepancy also demonstrates that human disturbance effects on surface dust emission vary considerably across research scales.

## 4.3 Implications

Rational land use, ecological restoration and protection projects, and timely dust storm warnings are crucial for limiting dust emission and mitigating its impacts. As shown in Figure 6, peak dust emission occurs during April–May, necessitating enhanced early warning and preventive measures during these months. Furthermore, monthly average dust emission fluxes from January–March and October–December range from 0.32 to 0.56 times those in April–May, requiring timely dust warnings during severe wind events in these months as well. Spatial distribution characteristics indicate relatively high dust emission intensity in the northern dry sub-humid agro-pastoral area, emphasizing the need for strengthened land use management and crop residue retention. For Hunshandake Sandy Land, priority should be given to cultivating surface biological crusts to prevent dune activation. In grasslands, rational grazing practices should be adopted to minimize soil structure damage, enhance vegetation cover, and reduce wind erosion. In areas experiencing severe wind erosion and significant dust emission, ecological restoration projects are essential, as research has shown that forest land effectively reduces surface dust emission.

## 4.4 Limitations

This study simulated surface dust emission along dust transport pathways in northern China using the CLM4.5 model, with accuracy verified through field observation. Results indicated that CLM4.5 can simulate surface dust emission with reasonable accuracy, though several limitations remain. First, due to field observation constraints, validation used a limited dataset spanning only a few months, rendering the validation insufficient. Second, winter topsoil freezing should theoretically prevent dust emission, yet model results showed some dust release in December and January, suggesting potential overestimation under frozen soil conditions. These limitations highlight the need for additional field observations and correction of model parameters related to topsoil freezing ratio.

## 5 Conclusions

This study simulated PM10 dust emission in the Erenhot-Huailai zone using the CLM4.5 model. Results showed that dust emission was concentrated primarily in spring, with the northern dry sub-humid agro-pastoral area representing the most important dust source. Due to soil texture effects, sandy land emissions were relatively low. Dust emission in the study area was mainly controlled by wind speed, vegetation coverage, soil freezing ratio, soil texture, and human disturbance, with human disturbance having profound effects. Under human disturbance, PM10 dust emission fluxes from source areas were 1.66-3.89 times higher than background areas. Additionally, human disturbance effects on surface dust emission differed significantly between regional and plot scales. Therefore, further comprehensive studies on human disturbance effects across different scales are needed.

**Conflict of Interest:** The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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