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Assessing Dandelion Seed Dispersal and Environmental Impact: A Comprehensive Study

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Abstract:

The study investigates the dispersal range of dandelion seeds influenced by wind, considering fruit ripening and invasive species' impact. CFD fluid dynamics simulation using Ansys Fluent software, integrating Navier-Stokes equations and turbulence theory, analyzes seed motion characteristics and dispersion dynamics in an ideal fluid domain. Parameters like air density and viscosity, representing various seasons, were adjusted in diffusion range across different time scales. We obtained the approximate distribution of dandelion seeds across different seasons and climates, finding larger dispersal areas in arid climates due to stronger winds. In comparison, temperate climates exhibit smaller areas due to gentler winds. To assess the impact of an alien plant on the local environment, we constructed judgment criteria using the Analytical Hierarchy Process (AHP). Through pair-wise comparisons, we calculated weightings for criteria encompassing environmental interference, economic influence, and effects on human health. By assigning ratings to each criterion based on logical reasoning and scientific evidence, we quantified the plant's impact, yielding a score of 5.74 out of 10 for dandelion, indicating an overall positive effect in the community. Sensitivity testing confirmed the robustness of our model.

Keywords: Dandelions; hydrodynamics; diffusion range; Analytic Hierarchy Process

1. Introduction

1.1 Background

The dandelion (Taraxacum officinale), a common flowering plant, is known for its flower of chromatic yellow color and unique system of seed dispersal [1]. Typically, a mature dandelion would produce a white and fluffy structure. This structure that each of the numerous tiny seeds in the puffball comes attached to a bundle of fine bristles contributes to the dandelion's ingenious seed dispersal method: Instead of merely dropping its seeds, dandelion utilizes wind dispersal, which is also known as anemochory [2].

In the life cycle of plants, seed dispersal is especially vital as it enables the survival of dandelions and contributes to plant biodiversity, colonization of habitats, and escape from predators and diseases [3]. By considering factors of seed dispersal, such as wind patterns and intensities, which are affected by climate change, studying the dynamics of dandelion seed dispersal could offer insights into future climate scenarios [4]. Therefore, we must build an understanding and research the dandelion's seed dispersal mechanism.

1.2 Problem Restatement

l We are tasked with creating a mathematical model for predicting dandelion distribution over 1, 2, 3, 6, and 12 months. Seed dispersal is affected by various factors, including climate. Consideration must be given to climate elements such as wind speed, direction, and air density.

l We should utilize the turbulence model and hydrodynamic equations to build Model 1, estimating seed dispersal across diverse climate scenarios.

l To explore the dandelion-community correlation, we must develop a new mathematical model (Model 2). Initially, we'll delineate key aspects for assessing plant impact, such as dandelion species' pros and cons.

l After listing the points, we conclude the sensitivity analysis and evaluation model in Model 2 for assessing relationships. To evaluate the impact of a non-native plant on the local ecosystem, consider various variables related to the qualities or impacts of the alien plant. Use the Analytical Hierarchy Process (AHP) method to compare criteria and obtain judgment matrices.
l We can extend our analysis to other invasive plants based on the previous model, applying the model to observe its effectiveness.

2. Assumption and Justification

2.1 Assumption and Reason

2.1.1 Ideal Wind Field

Assumptions

- Air density, wind direction, and wind speed remain unchanged. In addition, there is no updraft of air; we also don't consider heat conduction. In addition, the height limit is 20m.

Explanations

- The heat from dandelion friction can lead to instantaneous changes in air density and viscosity coefficients. Simulating this situation is difficult due to the rapid changes; therefore, we neglect updraft and heat conduction considerations.
- The air movement above 20m high causes little impact on the distribution of dandelion seeds. Thus, we don't consider the air situation above the height of 20m.

2.1.2 Ideal Model of Dandelion Seed

Assumptions

- The geometric model of a dandelion seed is a sphere
- The force caused by seeds leaving the seed core is not considered

Explanations

- The complexity of dandelion seed shapes and uneven density distribution can lead to unexpected simulation changes. Idealizing parameters allows us to find a representative geometry for accurate simulation.
- The biological composition of a dandelion seed is complicated and frustrating. It will increase the tasks significantly. Hence, the fore created such a way doesn't be concerned in our model.

2.2 Symbols and Justifications

Table 1: Index needed

Symbol	Justification
v	fluid velocity
ρ	fluid density
p	pressure
μ	dynamic viscosity
g	gravitational acceleration
F D	resistance
k	turbulent kinetic energy
Pκ	The term that generates turbulent kinetic energy
v t	viscosity coefficient of turbulent flow
σκ	Prandtl number of k
ϵ	Turbulent dissipation rate
C1ϵ, C2ϵ	model constant
σϵ	Prandtl number of ϵ
Cμ	model constant
m	seed mass
v s	seed seed
Fb	resistance
Fd	buoyancy

3. Model development

3.1 Model 1

3.1.1 Mathematical Modeling

In Model 1, we use hydrodynamic equations and the k-ε model to predict dandelion seed dispersal accurately. The Navier-Stokes equation, accounting for pressure, viscosity, and airflow velocity, governs seed motion in the wind. It can be written as below:

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+\left(\vec{v}\cdot\nabla\right)\vec{v}\right)=-\nabla p+\mu\nabla^2\vec{v}+\rho\vec{g}+\overrightarrow{F_D} \qquad (1)$$

Additionally, the continuity equation ensures mass conservation, asserting that air, the studied fluid, neither spontaneously materializes nor diminishes within the system. It's crucial to uphold this principle, especially with significant air density changes.

$$\nabla\cdot\vec{v}=0 \qquad (2)$$

Finally, the $k-\in$ turbulence model addresses real-world turbulent airflow around dandelion seeds, considering factors like turbulent kinetic energy.

$$\frac{\partial k}{\partial t}+\vec{v}\cdot\nabla k=P_k-\in+\nabla\cdot\left[\left(v+\frac{v_t}{\sigma_k}\right)\nabla k\right] \qquad (3)$$

Combined with turbulent kinetic energy, we also consider the separation rate.

$$\frac{\partial ?}{\partial t}+\vec{v}\cdot\nabla\in=\frac{\in}{k}\left(C_{1\in}P_k-C_{2\in}\right)+\nabla\cdot\left[\left(v+\frac{v_t}{\sigma_\in}\right)\nabla\in\right] \quad (4)$$

Furthermore, we propose an assumption about turbulent viscosity through the use of the equation:

$$v_t=C_\mu\frac{k^2}{\in} \quad (5)$$

Later, we utilized the kinematic equation to derive motion influenced by gravity and wind when examining seed movement. The equation is expressed as follows:

$$m\frac{d\vec{v}}{dt}=m\vec{g}+\overrightarrow{F_b}+\overrightarrow{F_d} \quad (6)$$

In this equation, m stands for the seed mass, v refers to the seed speed, and Fd is the resistance, which Stokes Law usually calculates; also, Fb represents the buoyancy, and it can be obtained through the equation below:

$$\overrightarrow{F_b}=\rho Vg\hat{k} \quad (7)$$

Factors affecting seed dispersal vary by climate and season: air density, wind direction, speed, and viscosity. Wind direction is unpredictable in temperate zones, modeled with a random distribution. Arid areas feature consistent wind direction, while tropical regions see seasonal changes due to monsoons.

Table 2: Wind speed, air density, and air viscosity for different seasons

Season	Wind speed (m/s)	Air density (kg/m^3)	Air viscosity (10^{-5}P a · s)
Spring	5	1.225	1.78
Summer	3	1.184	1.85
Autumn	7	1.125	1.78
Winter	6	1.292	1.72

Despite different climates, wind speed, air density, and air viscosity change from season, as shown in Table 2.

3.1.2 CFD Estimation

We use Computational Fluid Dynamics (CFD) simulation to predict dandelion seed distribution. We create a 3D seed core (5mm diameter) by stretching a 2D circle. Filaments, representing the crown hair, extend 20mm from the surface. This geometric model facilitates analysis.

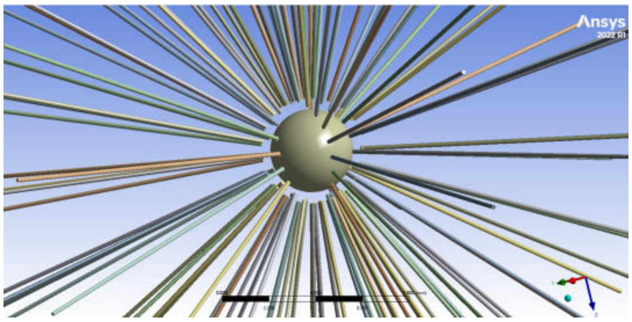

Figure 1: Geometry model

In the next step, we set boundaries and initial conditions. Wind speed and direction vary based on climatic conditions, simulated with detailed data (Table 3). The fluid domain, 1 hectare in the base area and 20 meters in height allows airflow.

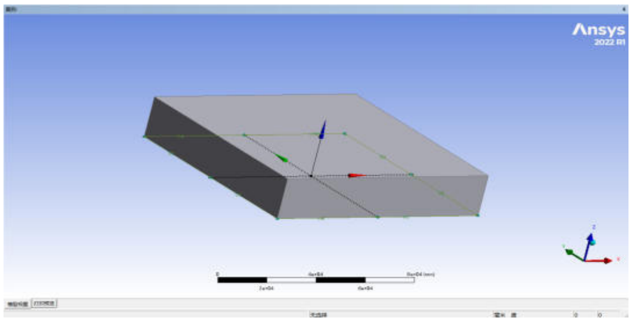

Figure 2: Fluid domain

Table 3: Wind speed and air density for different climate

Climate	Wind speed (m/s)	Air density (kg/m^3)
Temperate climate	3-5	1.225
Arid climate	2-3	1.2
Tropical climate	2-4	1.184

Having prepared the combined seed geometry and fluid domain, we proceed to grid division by fluid dynamics analysis requirements, ensuring computational accuracy. A detailed grid around the seed is maintained for precise flow data, while accuracy is reduced away from the seed to minimize computations.

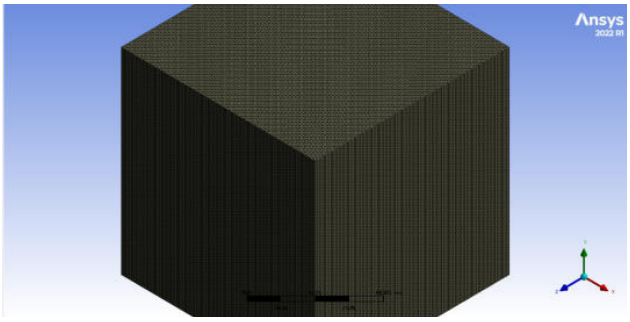

Figure 3: Meshing

In the final stages, the k-ϵ turbulence model is configured for CFD simulation, which is crucial for estimating complex air movement around the dandelion seed. Relevant constants are set, and in the last stage, the simulation is initiated, initializing the flow field and monitoring convergence to ensure the reliability of results.

3.1.3 Result

After grid division, calculations are conducted for airflow, pressure distribution, and heat distribution. Twenty iterations are set to determine the dandelion seed location while representing pressure, airflow direction, and temperature through image animation, as detailed in the accompanying figure. The animation illustrates a consistent, fixed-direction airflow at a constant speed within the fluid domain.

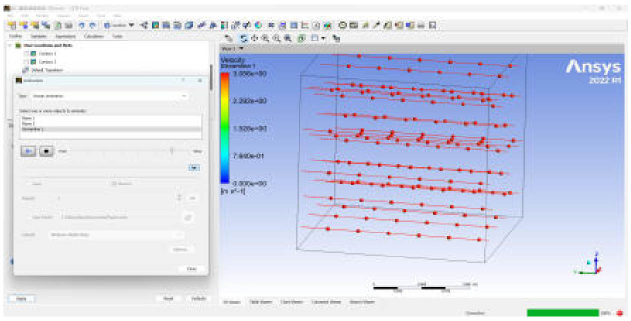

Figure 4: Airflow

This figure shows the air pressure distribution in the zone.

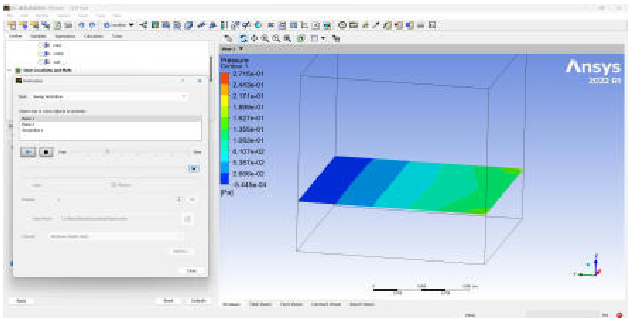

Figure 5: Pressure distribution

This figure shows that the air temperature in the zone remains the same at any height.

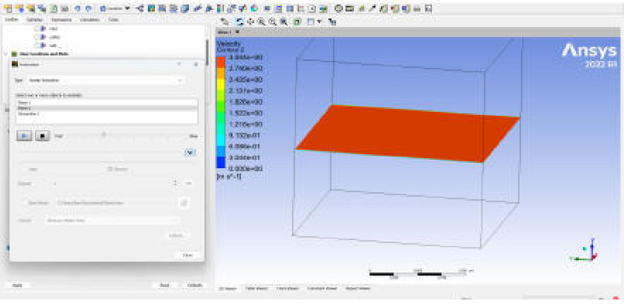

Figure 6: Temperature distribution

In conclusion, we measured the average distance between dandelion seeds and their initial positions. Adjusting parameters like air density for different temperatures in various climates, we compiled the results into Table 4.

Table 4: Weighting Primary

Mouth	Temperate climate	arid climate	tropical climate
number	diffusion (m^2)	diffusion (m^2)	diffusion (m^2)
January	172.91	233.64	231.10
February	340.55	511.22	445.90
March	520.37	770.60	650.45
June	1088.22	1544.11	1354.22
December	2170.55	3020.50	2596.45

3.2 Model 2

In Model 2, AHP, a flexible decision-making technique, structures complex problems hierarchically into simpler elements. Judgment matrices are created through pairwise comparisons to weight criteria.

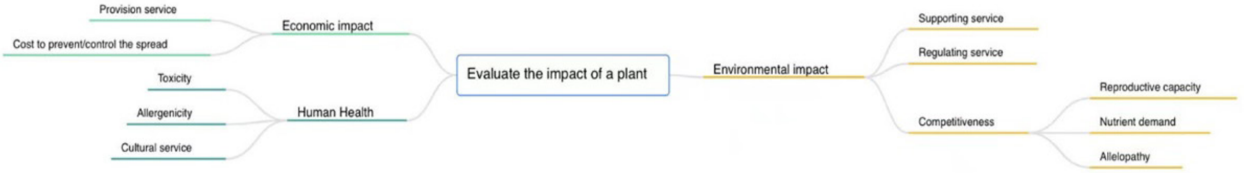

Figure 7: Decision model map

3.2.1 Constructing Criteria

The initial step in applying AHP at the workplace involves establishing criteria to grade an item's performance. For assessing the impact of an alien plant on the local ecology and people, criteria (see Fig. 7) are created by categorizing traits and effects into economic impact, influence on human health, and environmental impact – forming the first-level criterion.

Several sub-criteria make up the environmental effect criterion. According to the National Wildlife Federation, there are four types of ecosystem services, and two are considered to be environment-related [7]. Sub-criteria at the third level evaluate the plant's influence on these services, considering factors like nutritional needs, allelopathic ability, and reproductive capacity.

The plant's effects on human health are assessed in terms of toxicity, allergenicity, and cultural services, considering its impact on recreational, spiritual, and aesthetic experiences, acknowledging the growing importance of mental health alongside physical health.

The economic impact of an alien plant is assessed in terms of its influence on the area's provision of services, considering benefits like food and raw materials, as well as potential drawbacks such as reduced agricultural productivity. Additionally, the management cost involves expenses incurred by local authorities in controlling the plant's spread, addressing damages, and conducting monitoring and research.

3.2.2 Weighting Criteria

We need to compare the criteria in pairs to calculate the weightings of criteria by AHP.

Weighting the primary criteria: The environment is deemed more important than the economy, human health is prioritized over economic impact, and environmental impact is considered more significant than impact on human health due to long-term effects on ecosystems and biodiversity, in recent decades, is argued to be a new trend, advocating for sustainable development [6]. A decent environment, in other words, natural capital in economics, is inextricable from economic development [5].

Table 5: Weighting Primary

	Economic impact	Environmental impact	Human health	Eigenvector	Weighting (%)
Economic impact	1	0.167	0.333	0.382	10
Environmental impact	6	1	2	2.289	60
Human health	3	0.5	1	1.145	30

Weighting the secondary criteria: Pair-wise comparisons of second-level criteria indicate that the plant's competitiveness is considered more important than its impact on supporting and regulating services, given the potentially severe damage caused by high competitiveness, particularly in biodiversity reduction.

Table 6: Weighting Secondary

Supporting Regulating Competitiveness Eigenvector Weighting (%)				
Supporting 1	1	0.5	0.794	24.021
Regulating 1	1	0.333	0.693	20.894
Competitiveness 2	3	1	1.187	54.995

In assessing the impact on human health, toxicity is considered more critical than allergenicity due to its universal nature and potential for imminent threats to lives. Furthermore, toxicity is deemed more vital than the influence on cultural services, given its direct impact on physical health as opposed to the longer-term and less immediate impact on mental well-being associated with cultural services.

Both criteria are deemed equally significant in comparing allergenicity and cultural impact, as allergenicity affects a specific group more rapidly with varying severity. In contrast, although universal, cultural impact takes longer to manifest with moderate severity.

Table 7: Weighting Secondary

	Toxicity	Allergenicity	Cultural	Eigenvector	Weighting (%)
Toxicity	1	2	3	1.817	54.995
Allergenicity	0.5	1	1	0.794	24.021
Cultural	0.333	1	1	0.693	20.984

Provisioning services are considered more important than management costs in the economic section due to their direct contribution to fulfilling fundamental human needs and sustenance and their significant impact on local economies, such as agriculture and forestry.

Table 8: Weighting Secondary

	Reproduction impact	Nutrient demand	Allelopathy health	Eigenvector	Weighting (%)
Reproduction	1	3	6	2.621	66.667
Nutrient demand	0.333	1	2	0.874	22.222
Allelopathy	0.167	0.5	1	0.437	11.111

Weighting the tertiary criteria: Reproductive capacity is considered more critical than nutrient demand and moderately more significant than allelopathic ability in contributing to the environmental impact of plant competitiveness. In assessing nutrient demand versus allelopathy in invasive plants, greater attention should be given to nutrient demand, as high nutrient demand intensifies competition for soil nutrients, leading to soil depletion, direct impact on neighboring vegetation, and worsening of local flora disruption. This competitive advantage, surpassing allelopathy, is crucial for adaptability and colonization success.

Table 9: Weighting Tertiary

	Reproduction impact	Nutrient demand	Allelopathy health	Eigenvector	Weighting (%)
Reproduction	1	3	6	2.621	66.667
Nutrient demand	0.333	1	2	0.874	22.222
Allelopathy	0.167	0.5	1	0.437	11.111

3.2.3 Regulation of Our Rating System

Our unified rating system assigns scores from 0 to 10, with 5 as neutral. Scores above 5 indicate a positive impact, while scores below 5 suggest a negative impact. The overall score is calculated by summing the weighted scores of individual criteria.

$$R = \sum_{i=1}^{n} r_i w_i$$

3.2.4 Applying Model to the Dandelion

We start by assessing dandelion using tertiary criteria. As shown in the previous part of this essay, dandelion owns a rather robust reproductive system that can disperse its seed bundle over a certain area, which is carried by wind[9]. Dandelion scores 3 out of 10 for reproductive capacity, indicating a negative impact. Its nutrient demand is moderate, earning a score of 5 out of 10, suggesting a neutral influence on territorial competition. Dandelion's allelopathic ability, not well-documented, receives a score of 5 out of 10. Dandelion scores 3.00 out of 10 for competitiveness, 9 out of 10 for positive impact on regulating service, and 7 out of 10 for supporting service. The overall environmental impact is 5.22 out of 10, calculated by summing the products of sub-criteria ratings and corresponding weightings. Dandelion scores 5 out of 10 for toxicity, 3 out of 10 for allergenicity, and 7 out of 10 for cultural service impact on human health. For an experienced gardener, dandelions can be a worry because they can be a hindrance for them to pursue an aesthetic masterpiece out of their garden because they are quick to flower and produce many windborne seeds, while their long taproots enable them to quickly regrow in case of an unthorough removal[10]. Dandelion receives a rating of 9 out of 10 for its positive impact on the local ecosystem's provision of service and 4 out of 10 for the cost of managing its spread. The overall economic impact is 5.95, indicating that dandelion generally benefits the ecosystem with minimal harm.

3.2.5 Applying Model upon Other Species(Phragmites australis)

Figure 8: Phragmites australis

Phragmites australis (common reed) is an invasive species in North America originating from Europe that thrives in aquatic environments. It scores 5 out of 10 for toxicity and allergenicity, 2 out of 10 for reproductive capacity due to rapid spread, and 3 out of 10 for high nutrient demand. Phragmites australis exhibits allelopathy, scoring 3 out of 10, impacting competing vegetation through height, density, and chemical inhibition. Regarding cultural service, it negatively affects native plants, wildlife, recreational activities, and shoreline views and poses a fire hazard, receiving a rating of 2. Phragmites australis earns 7 out of 10 for its supporting service, providing food and shelter for wildlife, 8 out of 10 for its provision service in phytoremediation water treatment, but receives a low score of 1 out of 10 for its negative impact on regulating services due to the reduction of local biodiversity in North American wetlands. Phragmites australis receives a low score of 1 for management efficiency due to the challenges and costs associated with its eradication. Based on the three primary criteria, the rating is 3.91, indicating it is an overall negative plant in North American ecosystems, particularly in the eastern United States wetlands, causing significant harm with limited benefits.

3.2.6 Applying Model upon Other Species(Phragmites australis)

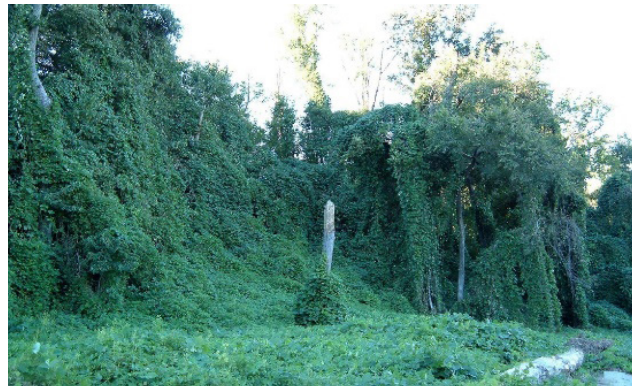

Figure 9: Kudzu

Kudzu, an invasive species introduced to the United States from Asia, scores 5 out of 10 for toxicity and allergenicity due to limited evidence of harm to humans. With a high reproductive capacity and nutrient demand, it rates 2 and 3 out of 10, respectively.

Kudzu scores 3 out of 10 for allelopathy, 2 out of 10 for cultural services, 4 out of 10 for supporting services, 8 out of 10 for provision services, 3 out of 10 for regulating services, and 1 out of 10 for management cost due to its challenging control and high management expenses.

With a total score of 3.73 for primary criteria, Kudzu is classified as predominantly detrimental to ecosystems, notably in the southeastern United States, where its invasion has significantly impacted local ecology and human activities.

4. Strength and Weakness

4.1 Strength

• When cooperating on the Model 1 construction, applying the CFD simulation model largely saves time in calculating and modeling as it is a professional software for crafting geometric models and observing the distribution of seeds.

• While developing the model, we consider variety, multi-faceted, and abundant impact factors that influence the dispersal of seeds. Therefore, our model is quite comprehensive and inclusive.

• Since we adopted the CFD simulation model when constructing the Model

1, we can consider all dandelion seeds simultaneously instead of just observing one single dandelion seed, which would offer extensive tasks.

4.2 Weakness

•There may be differences between the real-world situation and the environment. Therefore, the result of the dispersal of seeds we made may not be identical to the real distribution.

•In addition, during our modeling process, we only applied the turbulent model to the dandelion, not both the turbulent model and heal conduction. Hence, lack of consideration of heat conduction around dandelion seed may cause certain levels of inaccuracy in our results.
•Besides, the geometric model of the seed is not the same as the real dandelion seed. The geometric model is processed through simplification.
•Moreover, regarding the construction of model 2 via AHP, the number of criteria that assess the species is limited. Hence, the set of criteria is not ultra-comprehensive, so it may reflect a biased image of the species' impact.

5. Conclusion

In conclusion, this paper has presented a comprehensive analysis of dandelion seed dispersal using mathematical modeling. We were able to generate a model that depicts a highly accurate picture of real-world seed dispersion patterns by manipulating variables such as wind speed, release height, and seed terminal velocity. The model developed sheds light on the dispersal process and the potential establishment of dandelions in new habitats.
Furthermore, our findings demonstrate the power of mathematical modeling in predicting ecological phenomena and suggest that it could be widely used in assessing the invasive tendencies of other species. The ability of our model to accurately predict the distribution pattern of dandelion seeds can be used to investigate other potentially invasive species. This could be a significant step forward in managing invasive species, assisting in prevention and mitigation efforts.
However, it is important to note that while our model produces promising results, it is still a simplification of nature's complex realities. Future research could improve these models by incorporating more environmental variables, biological factors, and stochastic events. Given the growing global problem of invasive species and the resulting ecosystem disruptions, innovative tools like the one highlighted in this study will become increasingly important in our quest to conserve biodiversity and maintain ecological balance.

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