

Evaluation and modeling of fungi towards wood degradation

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ABSTRACT

Fungi play a significant role in wood fiber degradation since they possess enzymatic tools for the degradation of recalcitrant plant polymers. The study aims to demonstrate the interactive fungal traits when they grow together and its development with total dead wood fiber degradation speed. A lab experiment was designed to describe decomposition rates and fungal properties using nonlinear fitting model and logistic equation from preliminary data sets. The degradation speed of five (A, B, C, D, and E) different types of fungi with different growth rates were calculated at various relative humidity's (35, 50, 65, 80, and 95 g.kg⁻¹). Results showed that the mycelium length of fungus A, has faster ideal growth rate than that of fungus B, with ecological niche width $A < B$. Besides this the growth rate of fungus 1 was $vg_1 = 0.12$ and the environmental-holding capacity $k_1 = 3000$; $vg_2 = 0.15$ and $k_2 = 2000$ for fungus 2. Comparing the results of fiber decomposition with a single fungus, we were able to find that the overall efficiency of the two-fungal system decomposition model was higher in a defined environment. Besides this the successfully simulated the competitive relationship between different species of fungi and the effect of different environments on the decomposition rate of fungi, with a good fit and in accordance with the biological laws. Our model is well generalizable and can be extended to multiple environmental variables (light, temperature, and heat) with good accuracy.

ARTICLE HISTORY

Received 4 November 2021
Revised 14 December 2021
Accepted 31 December 2021

KEYWORDS

Fungal traits; decomposition speed; mathematical models; mycelium length; wood degradation

1. Introduction

Fungi are widespread components of nearly all ecosystems on Earth, including aquatic habitats ranging from high mountain lakes to the deep ocean and are phylogenetically and functionally complex [1]. The oldest terrestrial fungus dates back around 600 million years, making it one of the nature's oldest species [2]. Fungi are important agents in many ecological and biogeochemical cycles, including the carbon, nitrogen, and sulfur cycles, as well as the solubilization of minerals, the dissolution, and precipitation of metal ions, the degradation of silicates, and the dissolution of rock phosphates in oxygen-limited environments [3,4]. They inhabit nearly all ecosystems on the planet's surface, favoring dark and damp temperatures, and thriving in seemingly hostile settings like the tundra [5]. For the survival of other kingdoms, fungi play a crucial role in decomposition and recycling as a result of their presence in these habitats. Fungi, as saprobes, assist in the maintenance of a healthy environment for the animals and plants that occupy the same space [6]. In

addition to replenishing nutrients in the environment, fungi interact positively with other species, assisting in the succession of communities in the earth's ecosystem [7].

Fungi play a critical role in the bioindustries, enabling increased resource efficiency and the production of renewable substitutes for products derived from fossil fuels. By converting waste streams into valuable food and feed ingredients, strengthening the gut microbiota and acting as host organisms for the production of new biological drugs, we can combat lifestyle diseases and antibiotic resistance [8]. Vitamins, pigments, lipids, glycolipids, polysaccharides, and polyhydric alcohols are all produced by fungi [9]. They are antimicrobial and are used in biomineralization, as a food source due to their high protein content, and as biofertilizers. Fungi are extremely beneficial because they produce mycoproteins and act as growth promoters and disease suppressors for plants. *Penicillium* sp., *Mucor* sp., and *Rhizopus* sp. are all examples of fungi [10]. Fungi are used as food sources in the preparation of leavened bread

and fermented juices (*Saccharomyces crevisiae*) [11].

Fungi are an important part of terrestrial ecosystems because they aid in breaking down organic matter [12]. Fungi's capacity to breakdown several large and insoluble compounds is related to their nutrition mode. To digest nutrients, fungi create a range of exoenzymes. These enzymes are either released into the substrate or remain attached to the fungal cell wall's outside [13]. Large molecules are fragmented into smaller molecules, which are then carried into the cell *via* a protein carrier system anchored in the cell membrane. Because the presence of water is required for the movement of tiny molecules and enzymes, active growth necessitates a high level of moisture in the surroundings [14]. The fungal population contributes as least as much to wood degradation rates as the local climatic conditions and hence is an important driver of ecosystem function [15]. As a result, microbial activities are increasingly being included in biogeochemical models of the global carbon cycle that are used to anticipate climate change (Earth System Models). Microbial biomass was traditionally used as a proxy for decomposer activity, with the microbial community being treated as a single homogenous group or a small number of functionally different pools [12,16]. However, there is a growing recognition that fungal species range considerably in their capacity to decompose, resulting in an enormous breakdown of diversity within fungal communities [17,18]. Understanding how decay rates change with fungal community composition will be crucial for developing accurate predictions of terrestrial carbon cycles, as represented in current biogeochemical litter decomposition models. A clear, experimentally verified relationship between fungal features and their contribution to ecosystem function across landscapes is critical for improving these predictions [19–22].

Several ideas have been presented to explain why fungal-mediated wood breakdown rates are predicted by biotic degradation of wood fibers by fungi [23]. Slow-growing fungus with a high hyphal density have long been thought to degrade wood more quickly than thin fungi with a rapid outward extension rate [24]. The earliest studies that included the microbial

community in decomposition models, on the other hand, assumed that the rate of decay increased with the rate of development of the decomposers [25]. Various studies have indicated that several functional genes regulating decomposition (particularly, cellulose, and lignin breakdown) are negatively associated with genes increasing stress tolerance at the genetic level. However, it is uncertain whether these genetic patterns are related to the development of phenotypic traits [26,27].

A lack of insight into the mechanisms influencing varied wood breakdown rates across fungi limits our capacity to relate fungal community composition to ecosystem functioning [28]. Nicky et al. discovered in the previous research that associations between certain fungi traits can jointly determine their decomposition rates; in particular, slow-growing fungal strains tend to survive and grow better in the presence of environmental changes, whereas faster-growing strains are less stable to the same changes [12]. Due to the multitude of fungal traits, we focus on the effect of two traits, fungal growth rate, and fungal water tolerance, on the rate of decomposition.

To better understand how fungal quality and species diversity interact in dynamic environments, we study the relationship between the pace at which wood fibers are broken down and specific fungus traits. Due to the enormous number of fungal properties, we concentrated our efforts on the impact of two specific fungi growth rates and water tolerance on decomposition rates. The objective was to develop mathematical representations of how different fungus species impact wood fiber degradation, either between themselves or in relation to specific fungus traits. The novelty of our current work is finding the length of mycelium and wood fiber breakdown rates using a nonlinear fitting model and a logistic equation model.

The main objective of the study was to find the mycelial length and wood fiber breakdown rates using a differential equation model and construction of a logistic model of fungal growth in natural environment. Furthermore, the research predicts the effect of fungal community diversity on wood fiber decomposition rate during local environmental changes.

2. Materials and methods

2.1. Data processing and fitting

Figures and tables were constructed using $\text{Log}(w) - \text{Log}(v_g)$ which has a better correlation and a linear regression fit of $\text{Log}(w) - \text{Log}(v_g)$ was established using the least-squares method [29,30].

$$\log w = 0.32 - 0.24 \log v_g, R^2 = -0.69 \quad (1)$$

$$\log w = \log 10^{0.32} - \log v_g^{-0.24} \quad (2)$$

Finally, a nonlinear fitting model (equation 2) was developed for the relationship between the width, growth rate of the mycelium and humidity. Scatter plots were drawn based on the data set of the water niche width-ideal growth rate of various species of fungi in ideal [30]. The empirical logarithm model with independent and dependent factors is used. After that scatter plots and correlations were calculated for the fungal water niche width-ideal state growth rate and $\text{Log}(w) - \text{Log}(v_g)$ and the results were plotted in the form of heat maps.

2.2. Fitting the decomposition rate to the ideal state growth rate

The IBM SPSS version 2009 was used to draw the scattered plots against $\text{Log}(r) - \text{Log}(v_g)$, which specifies that the independent factors represent correlation with the dependent factors. Hence, the total mass applied in the testing is unidentified without constructing the model. Because the

quantity of wood fiber degradation is directly related to the extent of the disintegration rate. A linear fitting model of $\text{Log}(r) - \text{Log}(v_g)$ was developed using the same least-squares concept (Figure 1).

The prediction functions for $\text{Log}(r)$ to the $\text{Log}(v_g)$ at each temperature are given below,

$$\begin{aligned} \log v_g &= -0.53 + 1.02 \log r, 10^\circ\text{C}, R^2 \\ &= 0.483 \end{aligned} \quad (3)$$

$$\begin{aligned} \log v_g &= -0.82 + 1.10 \log r, 16^\circ\text{C}, R^2 \\ &= 0.476 \end{aligned} \quad (4)$$

$$\begin{aligned} \log v_g &= -1.07 + 1.04 \log r, 22^\circ\text{C}, R^2 \\ &= 0.367 \end{aligned} \quad (5)$$

Correlation tests were conducted, and the R^2 coefficients are presented in equations 3–5, representing that the fitting results are associated with one another. The hypothetical conditions represent that the effect of varying temperature in the ecosystem is negligible and thus the fit results with the strongest correlation.

$$r = (10^{1.07} v_g)^{\frac{1}{1.04}} \quad (6)$$

Equation 6 is developed using the referring logarithmic transformation equation. A nonlinear fitting model explaining the degradation speed and fungal growth rate was constructed from this [31].

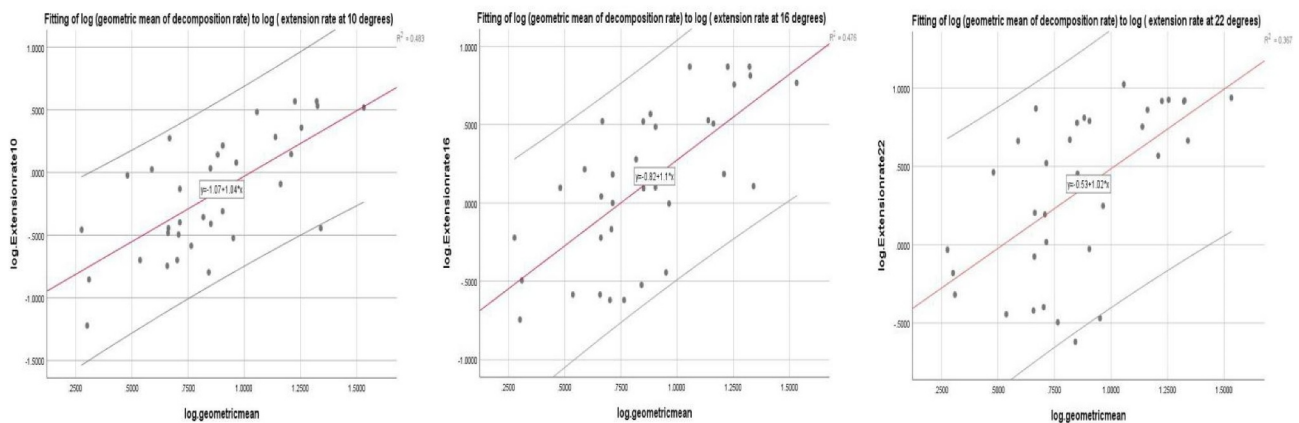


Figure 1. Fitting of the $\text{Log}(r)$ to the $\text{Log}(v_g)$ model at each temperature.

$$v_r = f(l) \quad (7)$$

$$l = v_g \cdot t \quad (8)$$

$$\int_0^{122} v_r dt = r \quad (9)$$

Equation 8 is developed by putting equation 7 in 8 and 10. The factor (t) is then integrated on both sides of equation 10 to develop equation 11.

$$v_r = f(v_g \cdot t) \quad (10)$$

$$\int_0^{122} v_r dt = \int_0^{122} f(v_g \cdot t) dt \quad (11)$$

We put equation 9 in equation 11, to obtain equation 12. Substituting the fitted equation 6 in equation 12 gives us equation 13 as a result.

$$r = \int_0^{122} f(v_g \cdot t) dt \quad (12)$$

$$v_r(t) = \frac{10^{-\frac{1.07}{1.04}}(1 + 10^{1.07})}{122^{1.04^{-1}+1}} * L^{1.04^{-1}}(t) \quad (13)$$

Equation 13 of v_r with respect to l , which defines the connection between the mycelium length and the rate of fiber degradation [32]. Under the postulation that only wood fiber degradation due to fungal action is considered, and the direct effect of the natural factors on wood fiber material were ignored, the degradation rate at the current stage can be attained even if the environmental situations change.

2.4. Modeling the decomposition speed

In equation 13 the physical meaning of v_r , following equation 14 is available under random conditions.

$$\begin{aligned} r &= \int_0^t v_r(t) dt \\ &= \int_0^t \frac{10^{-\frac{1.07}{1.04}}(1 + 10^{1.07})}{122^{1.04^{-1}+1}} * L^{1.04^{-1}}(t) dt \end{aligned} \quad (14)$$

Therefore, the variation of the degradation rate with time (t) can be obtained from this factor having an upper limit integral expression (equation 14) if the relationship between the mycelium length and time under arbitrary conditions is known [33].

2.5. Modeling fungi growth in natural ecosystem

We explore the growth of fungi under natural conditions, i.e., the relationship between fungal length and time taken [34].

2.5.1. Model for the growth of individual fungal species in natural environment

In the natural environment, the hyphae length L of the fungus satisfies the Logistic model using equation 15.

$$\frac{d}{dt}L(t) = v_g L(t) \left[1 - \frac{L(t)}{k} \right] \quad (15)$$

The growth speed (v_g) of the fungus under ideal environment is determined by the species of the fungus itself. The environmental capacity (k), which is determined by the ecological conditions [35].

The above equation does not reflect the effect of environmental humidity and the width of the fungal water niche. Therefore, we extend the relevant covariates to correct the model. When the environment contains covariates that have a more pronounced impression on the growth of organisms or populations, the Logistic model can be corrected by the following way [36].

$$\frac{d}{dt}L(t) = v_g L(t) \left[1 - \frac{L(t)}{k} - \frac{\sigma}{w} |\varphi - \varphi_0| \right] \quad (16)$$

The individual fungal growth curve under natural conditions can be obtained by a modified first-order differential equation 16, when the initial hyphae length $L(0)$ is known.

2.5.2. Model for the growth of various fungi under natural situations

The growth of multiple fungi together within an ecosystem satisfies the Lotka-Volterra model (equation 17) [34].

$$\begin{cases} \frac{d}{dt}L_1 = v_{g_1}L_1 \left[1 - \frac{L_1}{k_1}\right] - \alpha L_1 L_2 \\ \frac{d}{dt}L_2 = v_{g_2}L_2 \left[1 - \frac{L_2}{k_2}\right] - \beta L_1 L_2 \end{cases} \quad (17)$$

Analogously to the Logistic concept, we extend the humidity and the water ecological niche width of the mycelium to modify equation 17 to obtain equation 18.

$$\begin{cases} \frac{d}{dt}L_1 = v_{g_1}L_1 \left[1 - \frac{L_1}{k_1} - \frac{\sigma}{w}|\varphi - \varphi_1|\right] - \alpha L_1 L_2 \\ \frac{d}{dt}L_2 = v_{g_2}L_2 \left[1 - \frac{L_2}{k_2} - \frac{\sigma}{w}|\varphi - \varphi_2|\right] - \beta L_1 L_2 \end{cases} \quad (18)$$

The various fungal growth curves under natural environment can be obtained by the modifying first order differential equation 18. When the initial hyphae lengths $L_1(0)$ and $L_2(0)$ are known.

2.6. Modeling fungal degradation rates in natural ecosystem

The fungal degradation rates of various fungal species can be determined by combining the equations 16–18, we can obtain the fungal degradation rate equation.

2.6.1. Model of decomposition rate of single species of fungi under natural conditions

The above equations were combined to obtain an equation for the degradation rate of mono-fungi under natural conditions [36].

$$\begin{cases} \frac{d}{dt}L(t) = v_g L(t) \left[1 - \frac{L(t)}{k}\right] \\ r = \int_0^t v_r(t) dt = \int_0^t \frac{10^{-\frac{1.07}{122^{1.04-1+1}}(1+10^{1.07})}}{122^{1.04-1+1}} * L^{1.04-1}(t) dt \end{cases} \quad (19)$$

2.6.2. Model of decomposition rate of various fungi under natural environment

The above equations are combined to obtain an equation for the decomposition speed of different fungi under natural conditions.

$$\begin{cases} \frac{d}{dt}L_1 = v_{g_1}L_1 \left[1 - \frac{L_1}{k_1}\right] - \alpha L_1 L_2 \\ \frac{d}{dt}L_2 = v_{g_2}L_2 \left[1 - \frac{L_2}{k_2}\right] - \beta L_1 L_2 \\ r = \int_0^t v_r(t) dt = \int_0^t \frac{10^{-\frac{1.07}{122^{1.04-1+1}}(1+10^{1.07})}}{122^{1.04-1+1}} * L^{1.04-1}(t) dt \end{cases} \quad (20)$$

The total degradation rate of the fungal assemblage is obtained by superimposing the degradation rates of various fungi.

2.7. Procurement of fungi and chemicals and reagents

Fungi derive their sustenance by absorbing organic substances from the environment. Fungi are heterotrophic: they rely completely on carbon acquired from other species for their metabolism and nourishment [37]. Saprophytes play a vital role as decomposers of organic substances so that nutrients can be recycled. Some fungus, combined with bacteria, contribute to breaking down hard seed coverings, thereby rendering the seeds accessible to water, so that they can germinate [38]. It turns out that fungus, just like people and animals, take in oxygen and respire carbon dioxide (CO_2), a significant greenhouse gas.

2.8. General assumptions

To solve the problem, we make subsequent reasonable assumptions.

- The traits of the fungus do not change during the experiment.
- The growth speed of the fungus remains continuous for the environment achievable in the lab.
- The speed of wood fiber decomposition by fungi is to a greater amount related to the growth speed of the fungi and the moisture tolerance.
- Only wood fiber degradation due to fungal action is considered, ignoring the direct effect of natural factors on wood fiber materials.
- These include the effect of ambient temperature on the degradation of enzymes, the oxidation of oxygen content in the ecosystem, etc.

- The main environmental factor on the growth of fungi is the environmental humidity.

Each of our norms is justified and consistent with basic keys and not contrary to biological principles and laws.

3. Results

As a consequence of this study, it has been established that fungal features and species diversity have a significant role in the degradation of wood fibers. Due to the huge number of fungal attributes, this study recorded the impact of two fungal characteristics, growth rate, and water tolerance, on the decomposition rate. Fungi breakdown in natural environments is represented by mathematical models of the impact of various fungi on the decomposition of wood fibers. When the environment contains covariates that have a more pronounced impression on the growth of organisms or populations, the Logistic model can be modified and fitted well [35]. Similarly, the growth of multiple fungi together within an ecosystem satisfies the Lotka-Volterra model [36].

3.1. Modeling the degradation speed

The degradation speed of fungi with different growth rates were calculated over 122 days [37,38]. It was noted that necessary environmental conditions were provided such that the growth speed did not alter. However, the growing speed of mycelium cannot be kept constant under natural environment due to the inadequate natural resources. Therefore, further modeling is required to permit the extension of laboratory environments to natural environment. The degradation rate (V_g) is related to the mycelium length by using eq (7). The following equations 8 and 9 can be derived from the above definition

3.2. Model validation and confirmation (water niche width and fungal growth rate)

According to the literature [29,36,39], it was confirmed that there is a link between the different traits of fungi.

3.3. Description of the growth and decomposition rate of single species of fungi

At relative humidity $\varphi = 60$. Using equation 19, the length difference curves of various types of fungi were calculated by bringing the three types of fungi A, E, and B with other constraints into the differential model as considered in Figure 2 and Table 1. The curves of the model were calculated by overlaying them with the scatter plot of the v_g - w , which showed a good correlation (Figure 3).

The results presented in Figure 4 state that the time taken by the fungi to reach the environmental-holding capacity is getting smaller and smaller. This is consistent with the growth rate v_g : which states that $A > E > B$ relationship in the ideal condition (Table 1). In addition to this, the environmental-holding capacity is getting reduced, which is caused by the influence of environmental humidity.

Because of the width of the water ecological level $A < E < B$, the strength of influence by environmental humidity $A > E > B$ (Table 1). This is consistent with the figure of the environmental-holding capacity $A < E < B$. When the fungal length reaches the environmental-holding capacity, the length is stable and constant, and the degradation speed is linear with time (t).

The average incubation time for five fungal species (A, B, C, D, and E) was constant and it ranges from 200 to 300 days. This is basically the time acquired by the fungal species to degrade the required wood. Results of Figure 5(a-c) demonstrated that the degradation rate was linearly related to time and the time used was $A < B < C$. The results were consistent with the growth speed $A > B > C$ and the environmental-holding capacity $A < B < C$ in the L-t model. The equation calculation findings are reliable with environmental

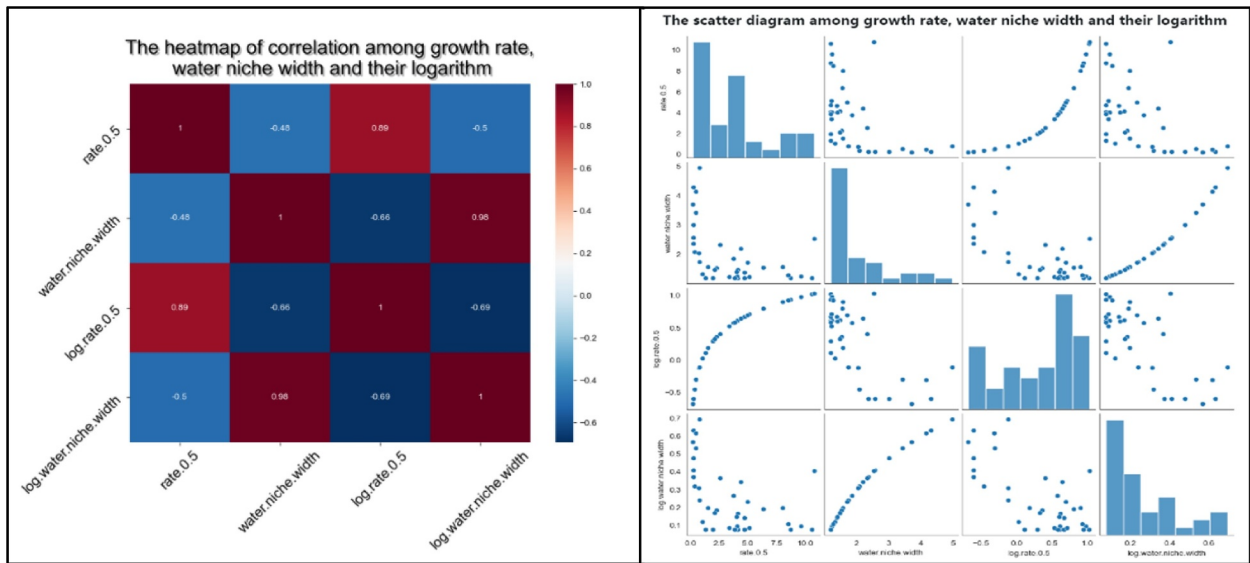


Figure 2. Scatter plot and heat map of fungal water niche width and growth rate under ideal conditions.

Table 1. Data of five different species of fungi.

Species	Growth rate vg	Water niche width $w = 100.32v - 0.24(g)$	Optimal humidity φ_0
A	Fast (1.0)	Narrow (2.09)	Wet (80)
B	Slow (0.1)	Wide (3.63)	Wet (80)
C	Fast (1.0)	Narrow (2.09)	Dry (50)
D	Slow (0.1)	Wide (3.63)	Dry (50)
E	Mid (0.5)	Mid (2.47)	Wet (80)

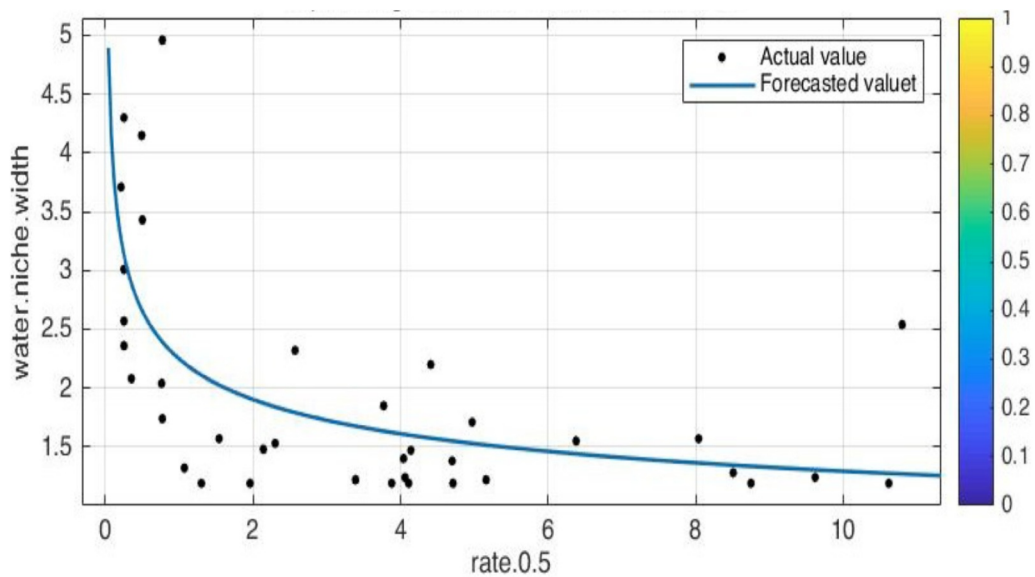


Figure 3. Nonlinear growth rate – moisture tolerance fitting model.

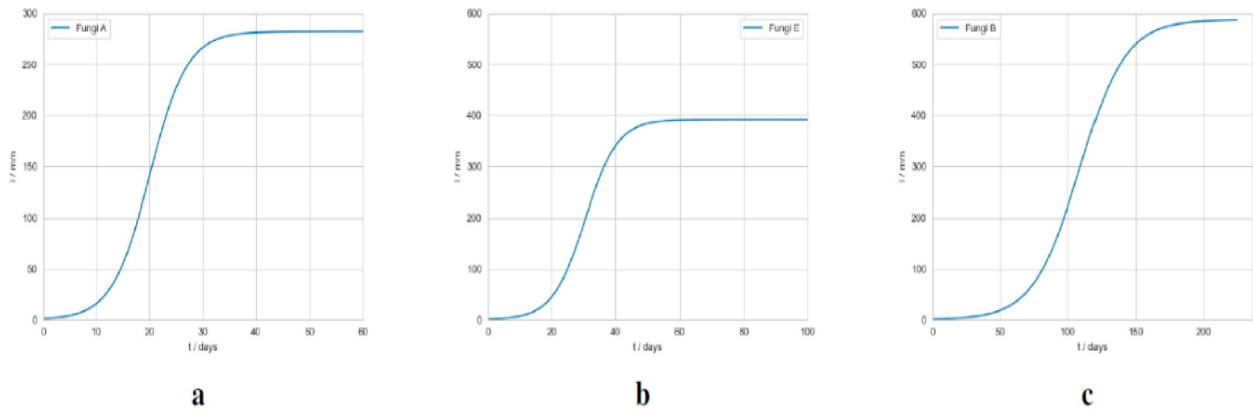


Figure 4. Length change curves of different species of fungi L-t relationship.

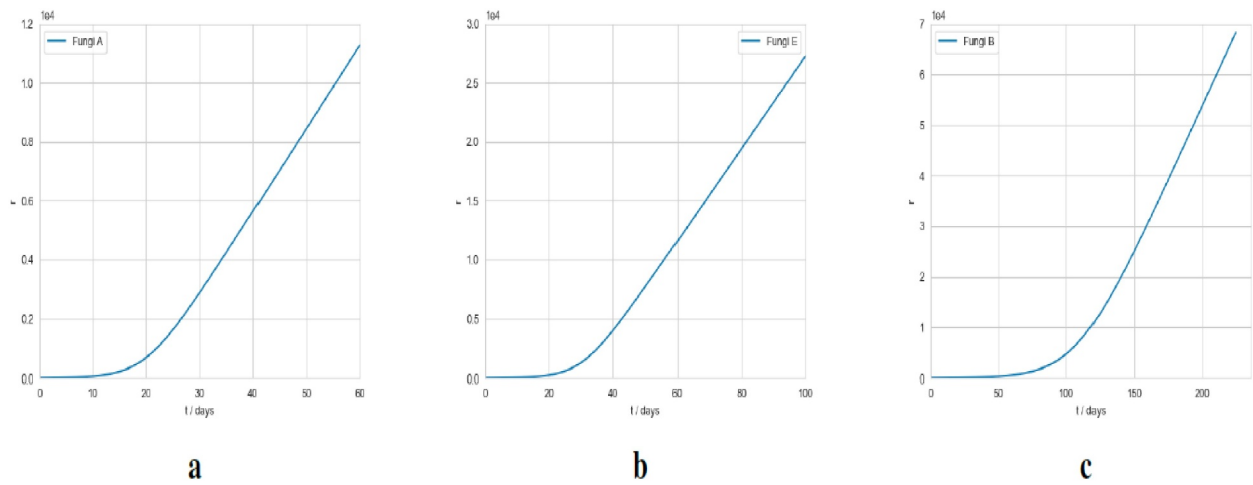


Figure 5. Variation curve of degradation speed of various species of fungi (r-t relationship).

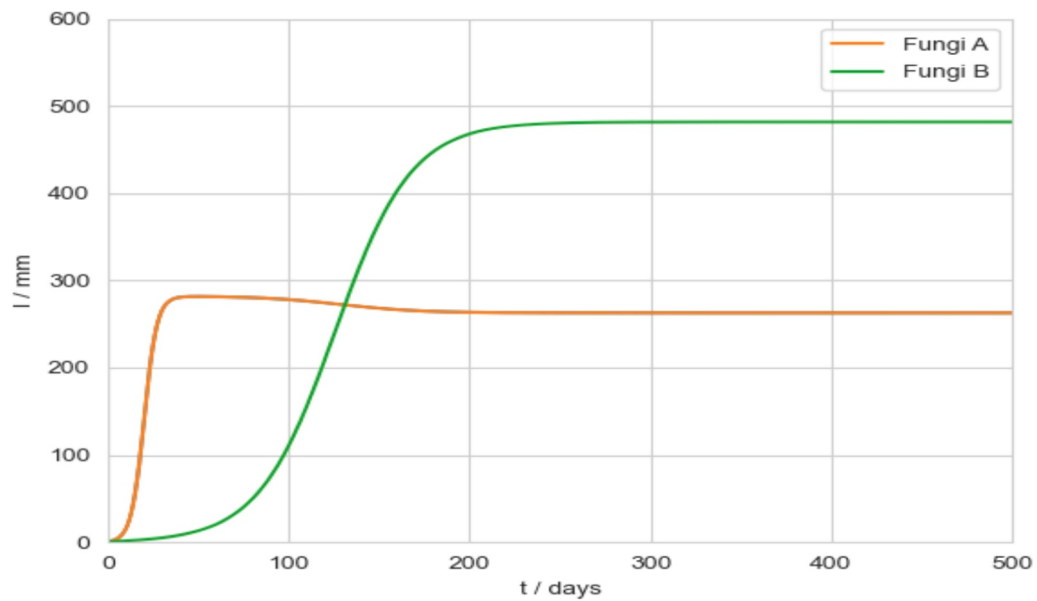


Figure 6. Mixed growth curve of fungus A and fungus B.

ecology's basic philosophies, and the model establishment can be considered a reasonable tool.

3.4. Description of multiple fungal growth interactions and degradation speed

The equation of multiple fungal growth under natural environment is presented in Figure 6. Initially, the interaction between the two fungi, the mycelium length of fungus A, which has the faster ideal growth speed exceeds that of fungus B, which has the slower growth speed. According to the equation, the water ecological niche width $A < B$, under the influence of humidity, and the environmental lodging that $A < B$. With the continuous growth of B mycelium, the environmental space of A mycelium gradually reduces. Eventually, mycelium A and B reach a common growth of stable environmental-holding capacity in the present situation.

Figure 7 demonstrates the initial growth speed of fungus B is slow, the mycelium length is small, and the degradation rate is also sluggish. While the growth rate of fungus A is fast, the mycelium length is long, and the degradation rate is fast. Initially, the degradation rate of fungus A increased rapidly, while the decomposition rate of fungus B increased slowly. The total decomposition rate of this fungal species

combination was mainly produced by fungus A. The decomposition rate of fungus B exceeded that of fungus A. Finally, the degradation rate of mycelium B exceeded that of mycelium A at about $t = 160$. The degradation rate is linear with time, when both species reach the stable environmental capacity and the mycelium length is constant. The model calculation results are consistent with the basic laws of environmental ecology, and the model can be considered realistic.

3.5. Prediction of multiple fungal assemblages under multiple environmental humidity

Based on the validated model (equation 20), the strain combinations given in Table 2 (N stands for narrow; W stands for wide; H stands for humid; D stands for dry); Figure 6 is replaced into the model, and the L-t curves were designed. The ambient relative humidity for each climate type is assumed to be as follows (Table 3).

3.5.1. Decomposition rates of multiple fungal combinations at different humidity points

The given findings elaborate that further calculations can be used to obtain the disintegration rate of multiple fungal combinations at various ambient humidity with time. By solving, it was calculated that

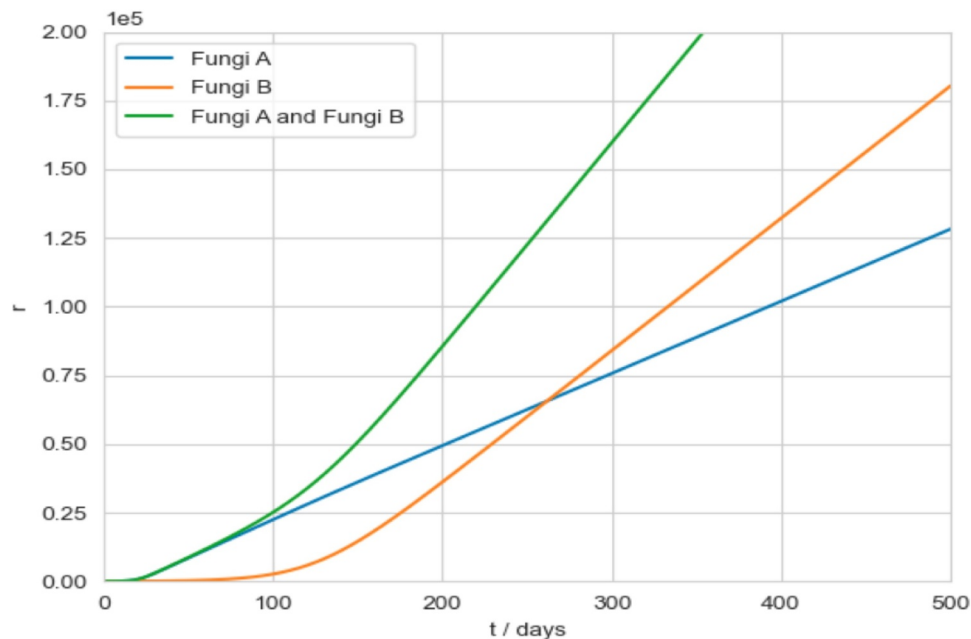


Figure 7. Fungus A and Fungus B respectively and co-decomposition rate.

Table 2. Ambient relative humidity for various climate types.

	A	B	C	D
A	NNHH	NWHH	NNHD	NWHD
B		WVHH	WNHD	WWHD
C			NNDD	NWDD
D				WWDD

Table 3. Ambient relative humidity for various climate types.

Climate Type	Ambient relative humidity (%rh)
Arid	35
Semi-arid	50
Temperate	65
Arboreal	80
Tropical rain forest	95

the growth and decomposition speed in all cases was basically stable and linear at $t = 200$. We fix $t = 200$ and vary the relative humidity φ of the environment in which each combination is located, plotting the following $r - \varphi$ diagram (Figure 8).

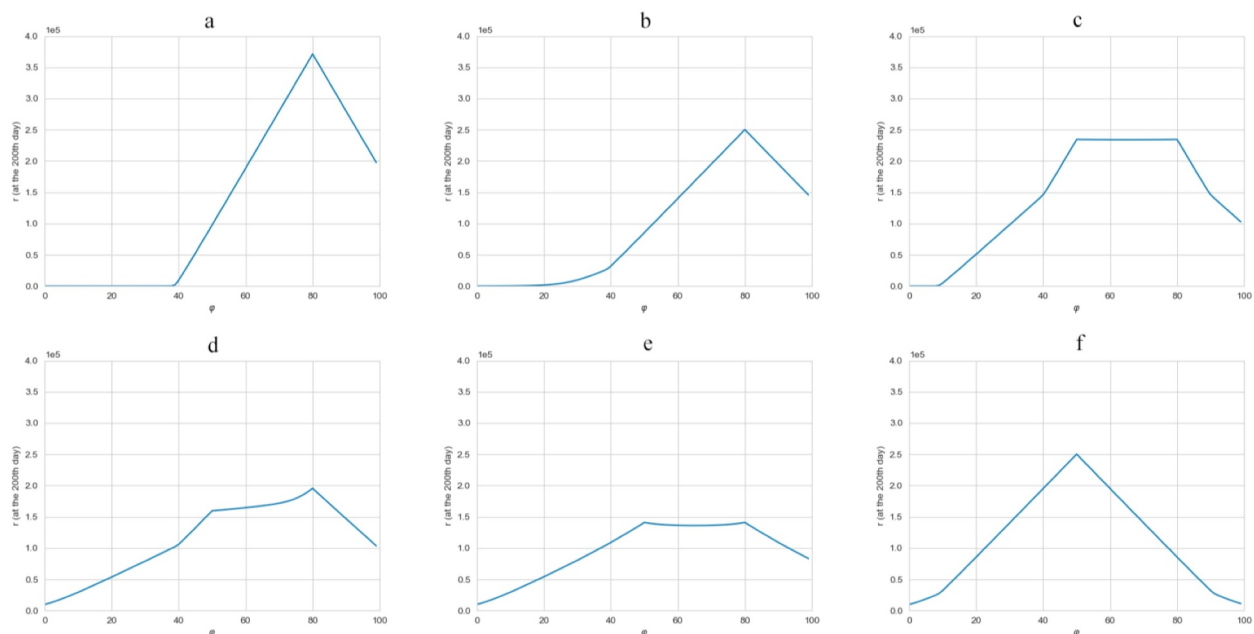
3.6. Effect of diversity on decomposition rate during local environmental changes

It has been concluded in current studies that the variability of ecosystem processes decreases as species richness increases. The interpretation of these models is complicated by the correlation between

other factors and species richness as well. In this paper, we may simplify the diverse fungal system decomposition model to a two-fungal system decomposition model and try to explain it by the existing models. We depict the growth curves of fungi 1 and fungi 2 according to the monocot growth curve equation with limited resources under ideal conditions as follows.

At this point, the growth speed of fungus 1 was $vg_1 = 0.12$ and the environmental-holding capacity $k_1 = 3000$; $vg_2 = 0.15$ and $k_2 = 2000$ for fungus 2. The mycelium length was used as a measuring standard for the fungal population size. The initial mycelium length of both fungi was 50 units. We developed a competitive model for two-fungal systems with limited resources under ideal environment (Figure 9).

It can be concluded from the results that in the case of co-competition between the two fungi, mycelium length first increases rapidly and then reaches equilibrium at a point below the

**Figure 8.** Decomposition rates of multiple fungal combinations at different humidity levels.

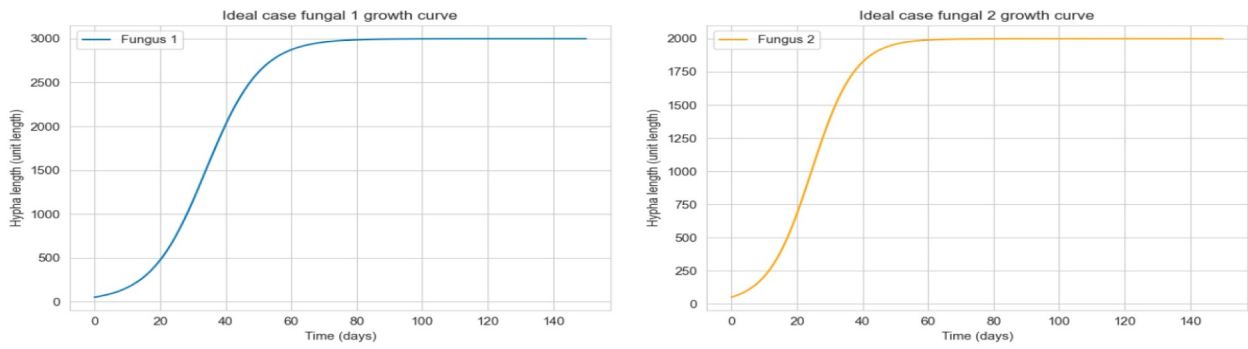


Figure 9. Fungi 1 and Fungi 2 growth curves with limited resources under ideal conditions.

environmental-holding capacity under ideal conditions (Figure 10). The rate of wood fiber decomposition by a double fungus together is greater than that of a single fungus.

The growth of mycelium is affected by environmental variables, the effect of humidity is used as an example. We introduce variables explaining the effect of humidity in the model to modify the

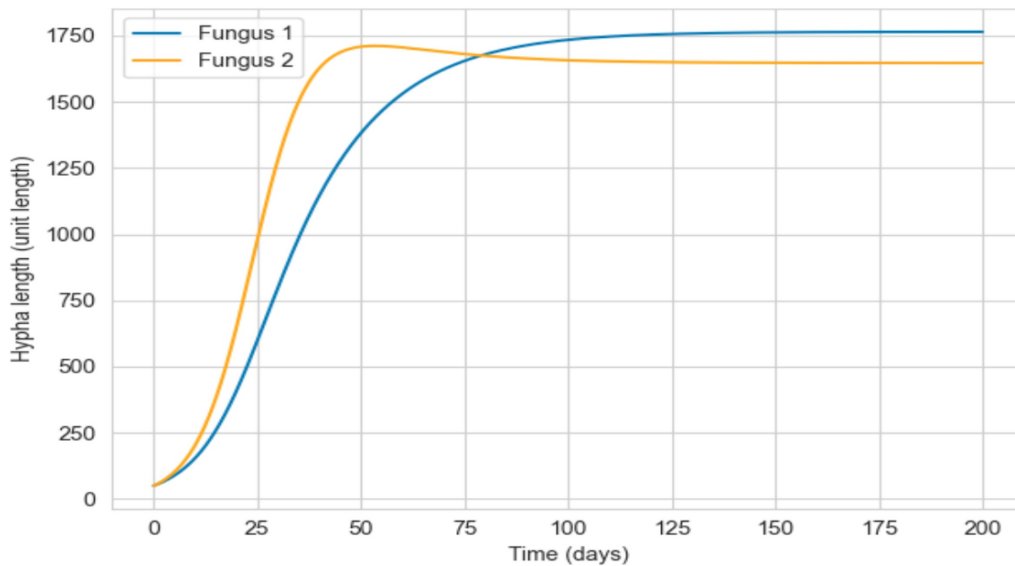


Figure 10. Ideally two fungi competing growth curves.

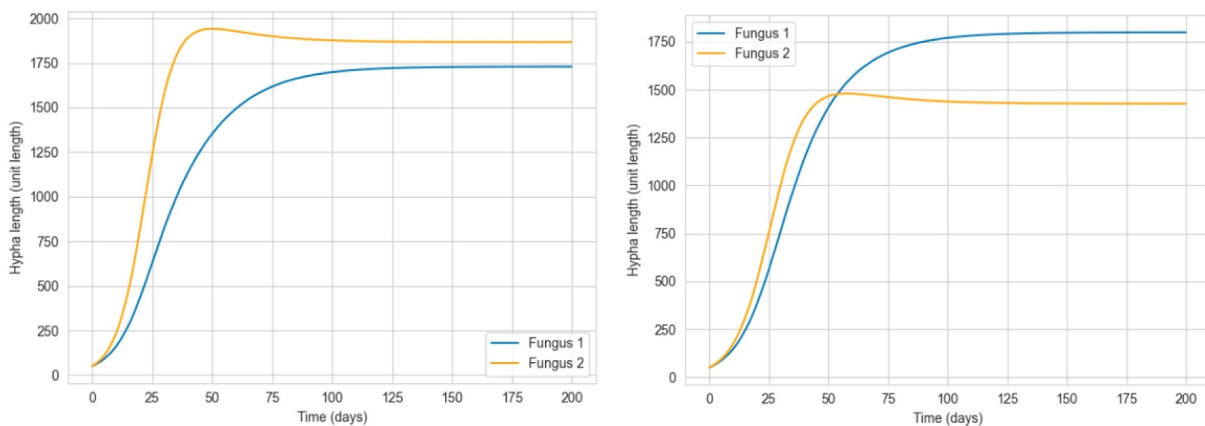


Figure 11. Competitive growth curves of two fungi at different ambient humidity.

equation and obtain the model. In this modified model, various values can be used to simulate the effect of environmental humidity on mycelium growth.

As presented in Figure 11 a clear ecological niche, environmental changes can affect the growth of organisms in the ecosystem. However, between the diverse organisms in the environment, species with certain attributes become dominant when the environment fluctuates and thus the constancy of the ecological environment is maintained by the complementarity between various species. Both fungal species eventually reach a new level of equilibrium after a period under the effect of opposite environmental humidity factors.

Further, to resolve the effect of the decomposition model of the two-fungal system in the presence of ecological perturbations, a variable (d) describing environmental agitations at time (t) was introduced. This environmental factor (d) can be used to explain rapid changes in the ecosystem, positive or negative, such as humidity, temperature, etc., in the simulated fungal growth conditions.

$$\begin{cases} \frac{d}{dt}L_1 = v_{g1}L_1 \left[1 - \frac{L_1}{k_1} - (1-d)\frac{\sigma}{w}|\varphi - \varphi_1| \right] - \alpha L_1 L_2 \\ \frac{d}{dt}L_2 = v_{g2}L_2 \left[1 - \frac{L_2}{k_2} - (1-d)\frac{\sigma}{w}|\varphi - \varphi_2| \right] - \beta L_1 L_2 \end{cases} \quad (21)$$

The perturbation variable (d) at day 200 (after the initial equilibrium of fungal growth) and withdraw the environmental influence after 100 days in order to simulate the effect of sudden and

continuous environmental changes in the natural environment on the degradation model.

In the degradation model of single fungi, the growth (mycelium length) of various fungi was declined to various degrees after the application of ecological agitations, which was generally realized as a reduction in the degradation rate of the mycelium (Figure 12).

It has been clearly observed that the effect of perturbations present in the ecological environment on the decomposition model of the two-fungal system. At an environmental disturbance intensity of $d = 1.8$ for 100 days, the mycelium length of fungus 2 decreased and that of fungus A increased and the variations in the length of both mycelia offset the effects of ecological mutations on the degradation rate of the fungus to a greater extent.

After the environmental disturbance was removed on day 300, the mycelium lengths of both fungi rapidly returned to their equilibrium values before the disturbance. Comparing the results of fiber degradation by a mono-fungus, it was able to determine the overall efficiency of the two-fungal system degradation model was higher in a defined ecological zone (Figure 13).

At the individual level, the decomposition rate was negatively correlated with moisture niche width and with the production of nutrient-mineralized extracellular enzymes. The reason behind the fast growth rate in humid areas was that fungal spores replicate faster in shady and humid places. Our results that the mycelium length of various fungi was declined to various

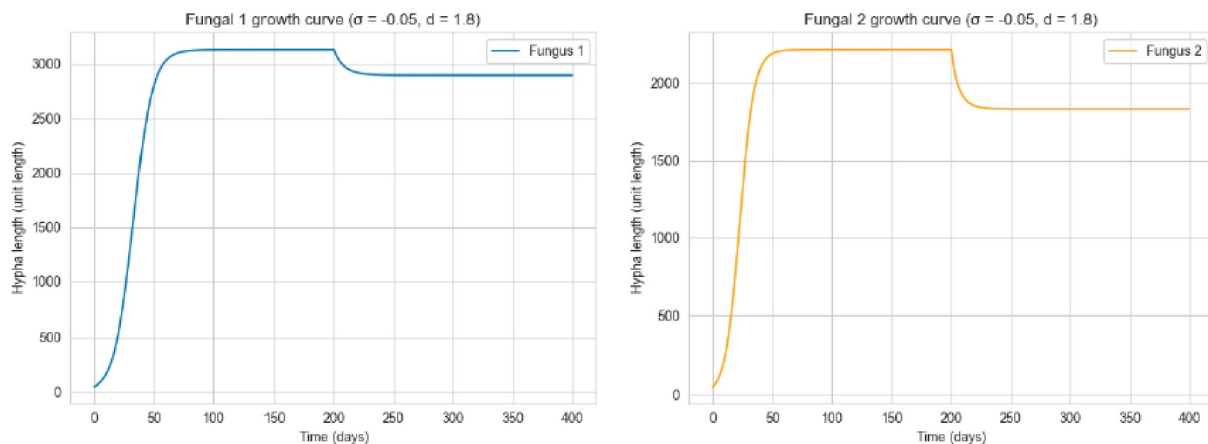


Figure 12. Growth curves of mono-fungi with environmental perturbations applied.

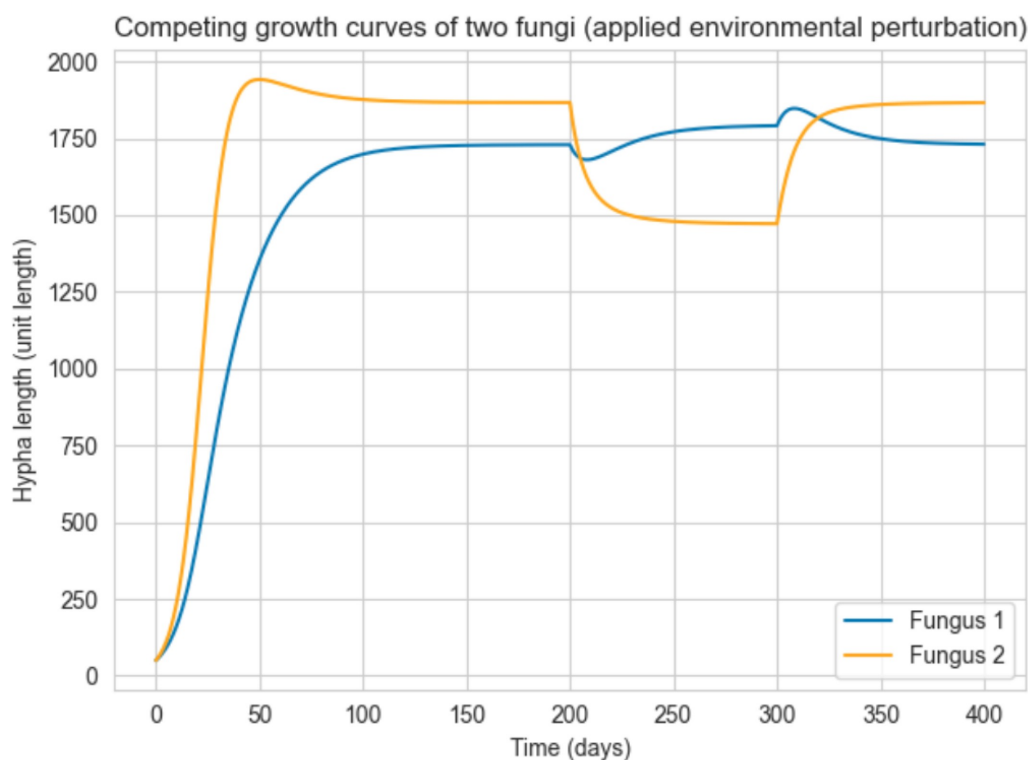


Figure 13. Growth curves of two-fungal systems in the presence of environmental disturbance.

levels after the application of ecological agitations is in line with the findings of Lustenhouwer and his colleagues [37] who also reported similar results that the decomposition rate was inversely related with the decomposition rate of fungi. He observed that the fungal growth rate (hyphal extension rate) was the strongest single predictor of fungal-mediated wood decomposition rate under laboratory conditions and accounted for up to 27% of the in-situ variation in decomposition in the field. At the phenotypic level, it has long been assumed that slow-growing fungi with a high hyphal density may decompose wood faster than thin fungi with a rapid outward extension rate [29].

In contrast, the first studies incorporating the microbial community into decomposition models assumed that the rate of decay increases with the growth rate of the decomposers [37]. These results suggest that decomposition rates strongly align with a dominance-tolerance, life-history trade-off stress-tolerant fungi, fast-growing, highly competitive decomposition rates.

We present simulations of the co-growth of various combinations of fungal species with

different characteristics in different environments. We infer that the following statements hold true for every ideal humidity environment based on data from numerous fungus combinations.

- (1) At varying humidity levels, fungal species with slower development rates and larger water ecological niche are not sensitive to competitive environments. They can live in a wide range of humidity levels.
- (2) Under optimum conditions, fungal species with higher growth rates and narrower watery niche are more sensitive to competitive environments. In a higher humidity environment, they will perish totally.
- (3) Fungi strains with optimal humidity that are more closely linked to actual environmental humidity have a competitive advantage. When the population stabilizes, the population size increases.
- (4) When the ambient humidity deviates from the optimum humidity of all the species in the assemblage is small, the fungal species with faster growth rates and narrower width

of the water ecological niche will have a competitive advantage due to their initial growth rate. They have a higher population size when they reach stability.

- (5) The slower development rate and wider width of the water ecological niche will be less influenced by the environment when the ambient humidity deviates from the optimal humidity of the strains in the combination. Furthermore, when the population number is minimal, its rivals cease increasing. When the population of this fungus becomes large enough, it becomes stable.

By studying previous research, we found that communities with more species are more likely to have higher phenotypic trait diversity and that any prejudices in community assemblies that lead to a correlation between diversity and community composition are likely to be both dominant and complementary in the previous research on biodiversity and system function in communities [37]. As a result, we used existing models to replicate and test this conclusion in our research. After the introduction of environmental influence variables, the mycelial lengths of both fungi are quickly recovered to their pre-disturbance equilibrium levels. This demonstrates the positive effect of biodiversity in the ecosystem on the ecosystem's environmental issues [40]. Furthermore, it can be determined from the previously simplified model of breakdown of the two-fungal system that the environment's species richness rises, implying that biodiversity has a positive impact on environmental homeostasis and resilience [41]. We believe that our model will aid in addressing the impact of fungus and other biodiversity, which is detailed in the section on model extensibility that accompanies it.

The models we propose in this study incorporate the majority of environmental impacts on fungus decomposition rates and can objectively measure and forecast fungi decomposition rates [42]. We can simulate the competitive interaction between different species of fungi and the influence of varying conditions on the decomposition rate of fungi using the anticipated decomposition rate of fungi. The model fits nicely and may be based

on biological rules. One of the major elements examined in our research is the model's generalizability [43]. The proposed model may be used to model the impact of a variety of environmental variables. In order to account for the influence of additional environmental variables on fungal development, we simply need to change the model in the same way that humidity covariates were included in the current model [44]. Because there are so many different environmental conditions that influence fungal development, we anticipate that future researchers can enhance the model's accuracy by adding additional data.

Moreover, our approach may be used to many species' interaction relationships. In this research, we simplified the model for consideration and developed a multi-species interaction model using two species as an example. The Lotka-Volterra model may be extended to a first-order ternary differential equation set by simply adding a third species differential equation to the first-order binary differential equation set in the Lotka-Volterra model [45]. More species combinations are still consistent with the main rules of this paradigm, according to possible experimental data.

Conclusion

Significant advances in science occur when observational, experimental, and theoretical studies coincide. Using a nonlinear fitting model and logistic equation derived from early data sets, a lab experiment was conducted to describe breakdown rates and fungal properties. The fundamental components of the equations are the ideal fungi width, water niche, and humidity. The degradation speed of five (A, B, C, D, and E) different types of fungi with different growth rates were calculated at various relative humidity's (35, 50, 65, 80, and 95 g.kg⁻¹). The results showed that with ecological niche width A B, the mycelium length of fungus A has a faster maximum growth rate than that of fungus B. Mycelium length rises rapidly initially, then reaches equilibrium at a point below the environmental-holding capacity, and hyphae growth is influenced by environmental variables like humidity. Using modified Lotka-Volterra

equations and biological laws, the model is provided to construct a relationship between changes in fungal mycelium length and time in naturalistic situations. Our model is well generalizable and can be extended to multiple environmental variables (light, temperature, and heat) with good accuracy.

Limitations

- The interaction of only two fungi considered is deficient in simulating the natural environment.
- The size of the data used for fitting is small, and the most accurate fitting results cannot be achieved.
- The sensitivity test only for the humidity parameter of the model is not sufficient and complete. There is still room for more improvement enhancements in this area.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data used to support this study are available from the corresponding author on reasonable request.

Funding

This research received no funds.

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