Paradigm
reference-global.com
DOI: 10.2478/agriceng-2026-0006

ISSN 2083-1587; e-ISSN 2449-5999
2026,Vol. 30,No.1, pp. 91-110
Agricultural Engineering
https://agriceng.org

MATHEMATICAL MODELING OF THE GERMINATION AND GROWTH OF *LEUCAENA LEUCOCEPHALA* UNDER DIFFERENT SUBSTRATES AND NURSERY CONDITIONS

José Américo Saucedo-Uriarte[a,*], Manuel Emilio Milla Pino[b], Hurley Abel Quispe-Ccasa[c], Gleni Tatiana Segura Portocarrero[a], Héctor Vladimir Vásquez Pérez[a], Deiner Jhonel Gongora-Bardales[d], Jorge Luis Maicelo Quintana[a]

[a] Facultad de Ingeniería Zootecnista, Biotecnología, Agronegocios y Ciencia de Datos, Universidad Nacional Toribio Rodríguez de Mendoza de Amazonas, Chachapoyas – 01001, Perú, e-mail: jose.saucedo@untrm.edu.pe, ORCID 0000-0003-2756-6402 (J.A.S.U.); e-mail: tatiana.segura@untrm.edu.pe, ORCID 0000-0001-5404-0321 (G.T.S.P.); e-mail: hvasquez@untrm.edu.pe, ORCID 0000-0003-4657-1397 (H.V.V.P.); e-mail: jmaicelo@untrm.edu.pe, ORCID 0000-0001-9109-0504 (J.L.M.Q.)
[b] Facultad de Ingeniería, Universidad Nacional de Jaen, 06801, Perú, e-mail: manuel.milla@unj.edu.pe, ORCID 0000-0003-3931-9804
[c] Estación Experimental Agraria San Bernardo, Instituto Nacional de Innovación Agraria, Tambopata 17000, Perú, e-mail: hurleyabelqc@gmail.com, ORCID 0000-0003-3146-5372
[d] Instituto de Investigación en Ganadería y Biotecnología, Universidad Nacional Toribio Rodríguez de Mendoza de Amazonas, Chachapoyas 01001, Perú, e-mail: gongorabardalesd@gmail.com, ORCID 0009-0006-1140-0343

Corresponding author: e-mail: jose.saucedo@untrm.edu.pe

ARTICLE INFO

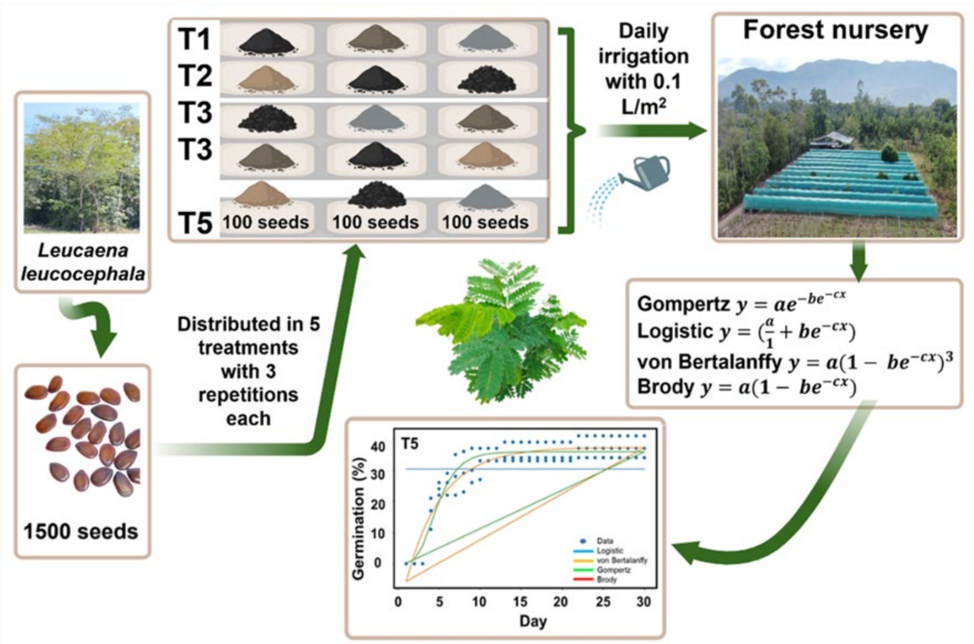
Article history:
Received: September 2025
Received in the revised form: January 2026
Accepted: March 2026

ABSTRACT

Livestock production in tropical regions is predominantly extensive and relies heavily on native or monoculture pastures, which often prove insufficient for ruminant nutrition. The incorporation of *Leucaena leucocephala* into silvopastoral systems represents a promising strategy due

ARTICLE INFO	ABSTRACT
Keywords: *Leucaena leucocephala,* *sigmoidal models,* *germination,* *plant height,* *productive system,* *sustainability*	to its high forage quality; however, information on its early establishment under nursery conditions remains limited. This study aimed to model the germination dynamics and early seedling growth of *L. leucocephala* under different substrate compositions during the nursery phase. Germination percentage and daily plant height were recorded over a 30-day period. Treatment effects were evaluated using analysis of variance (ANOVA) and growth dynamics were described using non-linear sigmoidal models (Gompertz, Logistic, von Bertalanffy, and Brody). Significant differences in germination rate among substrates were detected ($p<0.05$), whereas no significant effect of substrate on plant height was observed during the evaluation period ($p>0.05$). Among the evaluated models, von Bertalanffy, Gompertz, and Logistic functions provided the best fit for plant height based on R^2 and AIC criteria. Although some models showed high R^2 values for germination, elevated AIC values suggest limited biological adequacy. These findings highlight the usefulness of predictive modeling to support nursery management decisions, optimize substrate selection, and facilitate the establishment of *L. leucocephala* in sustainable silvopastoral systems.

Introduction



Graphical Abstract

Introduction

Leucaena leucocephala is a shrub species belonging to the family Fabaceae, subfamily Mimosoideae, distinguished by the absence of thorns. It is one of 32 species of the genus reported worldwide (Jayanthy et al. 2014; Nehdi et al., 2014; Pramod et al., 2019). The most widely recognized species within the genus include *L. leucocephala* (Lam.) from Wit. Syn. *Acacia leucocephala* (Lam.), *Mimosa leucocephala* (Lam.), and *Leucaena glabrata* (Rose) (Pandey and Kumar 2013).

The species presents bipinnate leaves up to 25 cm long and white to yellowish-white flowers. Its fruits are linear, thin, and flat pods measuring approximately 13 cm in length and 1.5 cm width, containing 15-30 seeds; pods are green when immature and turn brown when mature (Lim 2012). *L. leucocephala* thrives in tropical climates and shows high drought tolerance, withstanding dry periods of up to seven months, even during establishment (Nehdi et al., 2014).

L. leucocephala is notable for its wide range of uses, including bioenergy production (Alemán-Ramírez et al., 2022), soil phytoremediation (Jayanthy et al., 2014), control of soil erosion and slope stabilization (Normaniza et al., 2008), oil extraction for cosmetic and pharmaceutical applications (Nehdi et al., 2014), pulp and paper production (Pandey and Kumar 2013), timber production (Prasad et al., 2011), green manure and edible mushroom production (Sharma and Behera 2010; Andrew 2023), livestock feeding through its leaves (Rivera-Herrera et al., 2017; Durand-Chávez et al., 2022), and seeds as a source of human food (Guterres et al., 2022). In livestock systems, the incorporation of *L. leucocephala* into silvopastoral arrangements improves soil conditions due to its capacity for atmospheric nitrogen fixation (Bacab et al., 2013) and, when associated with tropical grasses, enhances milk production while reducing the need for nitrogen fertilizers in pastures (Sarabia-Salgado et al., 2020). These benefits are particularly relevant given that conventional livestock production remains largely based on open-field systems and monocultures, which cause economic losses, soil degradation, biodiversity decline, and low meat and milk productivity, thereby emphasizing the need for sustainable alternatives such as silvopastoral systems (Saucedo-Uriarte et al., 2023). In this context, the success of silvopastoral systems strongly depends on appropriate forage species selection, as systems integrating *L. leucocephala* with tropical grasses have demonstrated significant improvements in forage productivity and nutritional quality, as well as increased milk and meat yields under optimized harvest intervals (Dzib-Castillo et al., 2025). Furthermore, intensive silvopastoral systems based on high-density fodder shrubs, particularly *L. leucocephala*, increase edible dry matter production, reduce reliance on chemical fertilizers and concentrate feeds, mitigate greenhouse gas emissions, enhance animal welfare and biodiversity, and strengthen resilience to climate change, positioning these systems as a key strategy for sustainable livestock production in Latin America (Chara et al., 2024). Within the framework of sustainable silvopastoral systems based on *L.*

leucocephala, the successful establishment and long-term productivity of these systems depend directly on early plant performance. Plant growth and development begin with seed germination (Chauhan et al., 2018), a process regulated by key environmental factors such as temperature, substrate moisture, pH, light intensity, and photoperiod. It is these factors that ultimately determine seedling emergence, establishment success, and subsequent biomass production (Tan et al., 2013; Benincasa et al., 2019). Germination dynamics are commonly represented by sigmoidal curves comprising an initial lag phase, followed by an exponential emergence phase and a final plateau (Hadi et al., 2009).

Seed germination and early growth can be effectively predicted using nonlinear regression models, including Weibull, Gompertz, and logistic functions, which have been successfully applied across numerous plant species (Ritz et al., 2013; Blanco et al., 2014; Archontoulis and Miguez 2015; Dagogo et al., 2020; Kamar and Msallam 2020). These models have also demonstrated strong performance in describing biological growth patterns and dry matter accumulation in crops such as Yeniçeri oats (Coşkun 2018).

Modeling germination processes enables a better understanding of plant biological dynamics and supports decision-making in agricultural production systems (Smithers et al., 2019). Due to the limited availability of reports on predicting the initial development of *L. leucocephala* under the Peruvian agricultural system, and taking into account the benefits and strategic nature of this species, to contribute to the mitigation of climate change (Marques et al., 2020) and nutritional benefits for cattle. Therefore, this research aimed to model the germination rate and initial growth of *L. leucocephala* under different substrates, providing insights into early development dynamics through nonlinear sigmoidal models.

Materials and methods

Experiment *location*

The experiment was carried out in the forest nursery of the El Porvenir Agrarian Experimental Station (EEA El Porvenir) of the National Institute of Agrarian Innovation (INIA), road Fernando Belaunde Sur Km 14, Juan Guerra District, San Martín Province, Peru (6°35′11″ S, 76°19′12″ W; 228 m.a.s.l.) (Figure 1).

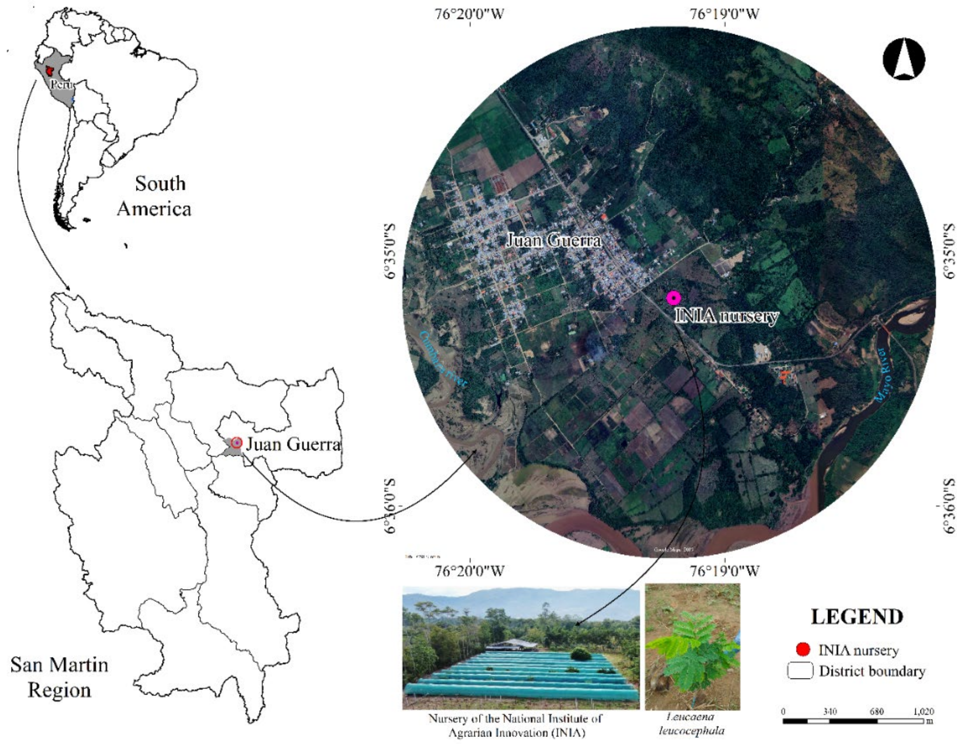


Figure 1. Geographic location of the experiment

Experimental *design*

This research was developed under a Completely Randomized Design (CRD) with five treatments or substrates: T1 = 100% virgin forest land, T2 = 50% compost and 50% sand, T3 = 50% compost and 50% virgin forest land, T4 = 50% compost, 25% sand and 25% sawdust, T5 = 50% compost, 25% sand and 25% rice straw; with three repetitions each. The seeds were collected from a plot already established in the pastures of the EEA El Porvenir. One kg of mature pods was collected, left to dry under shade for 10 days, and then morphologically homogeneous seeds were selected. 100 seeds, homogeneous in size and phytosanitary condition, were sown in each replicate, making a total of 1500 seeds (Figure 2).

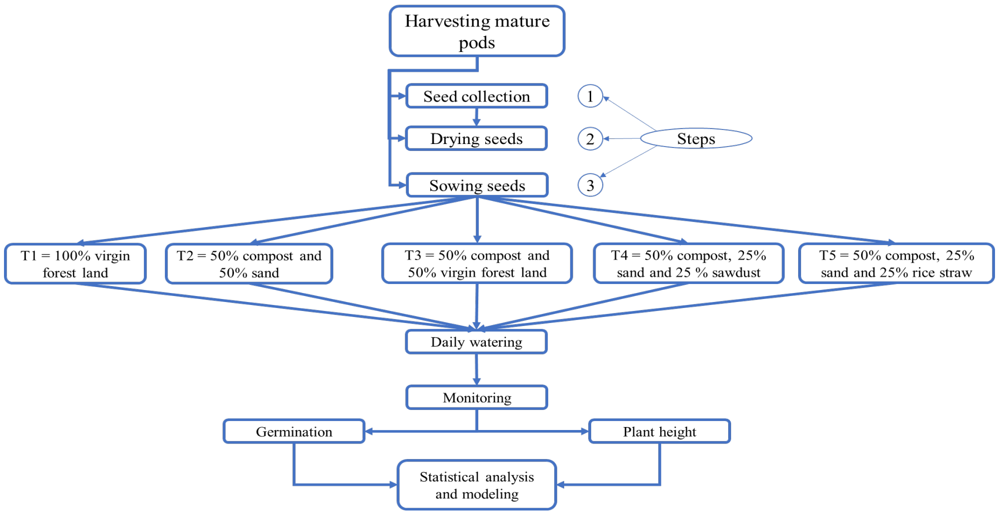


Figure 2. Graphic contextualization of the methodology

Germination *and measurement*

In each replica or germinating bed, the substrate was moistened to field capacity, and the seeds were sown. Subsequently, irrigation was supplied daily at a rate of 0.1 $L{\cdot}m^{-2}$ at the same time each day in order to maintain constant moisture conditions. Monitoring was carried out for 30 days, during which the number of germinated seeds was recorded daily. This monitoring period was deliberately defined to encompass the nursery phase of *L. leucocephala*, corresponding to the early seedling establishment stage prior to transplanting under field conditions.

The presence of the epicotyl, hypocotyl and radicle was considered the primary indicator of germination, and the germination rate was calculated as the percentage of germinated seeds relative to the total number of seeds sown (Quiñones-Huatangari et al., 2023).

Plant height of *L. leucocephala* seedlings was measured daily in the morning using a millimeter ruler, and the data were recorded in Microsoft Excel. Three measurements were taken for each treatment repetition.

Statistical *analysis and modeling*

The assumptions of normal distribution and homogeneity of variances for germination rate and plant height were verified, and ANOVA and Duncan's test ($p<0.05$) were used to compare means, according to substrate.

To adjust the behavior of both variables, the following sigmoidal mathematical models were used, depending on the substrate:

Gompertz $y = ae^{-be^{-cx}}$
Logistic $y = (\frac{a}{1} + be^{-cx})$
von Bertalanffy $y = a(1 - \ be^{-cx})^3$
Brody $y = a(1 - \ be^{-cx})$,

The statistical criteria produced by the model, for each treatment and derived from the means, were used for the comparison of time series (Kaps and Lamberson 2017). These statistics provide unbiased indicators of the performance of each model, which are: Akaike information criterion (AIC), coefficient of determination (R^2), and adjusted coefficient of determination (adjusted R^2). The AIC criterion indicates the most complex and pragmatic model, which has greater detail in the prediction within the data itself, penalizing complex models in favor of simpler ones to avoid overfitting. The higher the AIC value, the lower the quality of the model. The analysis was performed using Python software (v. 3.5.13).

Results

In the present investigation, different treatments or substrates were compared to evaluate the germination rate and plant height of *L. leucocephala*. Significant differences were found in the germination rate depending on substrates ($p<0.01$) (Figure 3A). Treatments T1 (100% virgin forest land), T4 (50% compost + 25% sand + 25% sawdust) and T5 (50% compost + 25% sand + 25% rice straw) showed the highest germination percentages (40.33±0.58%, 31.23±11.89% and 30.32±11.60%, respectively). The lowest germination rate was obtained in the substrate with 50% compost + 50% sand (T2), which reached 28.33% germination.

No significant effect of the substrate on plant height was found until 30 days of growth ($p>0.05$) (Figure 3B). On average, the plant height after 30 days was 7.65±1.24 cm.

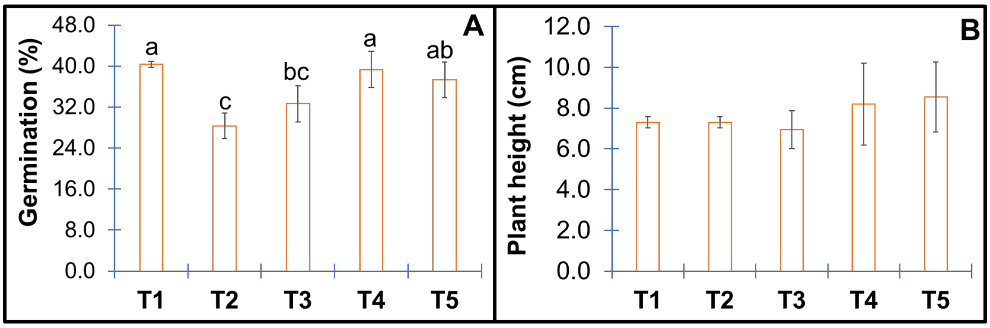


Figure 3. Germination rate (A) and plant height (B) of L. leucocephala after 30 days of growth, in different substrates. T1 = 100% virgin forest land, T2 = 50% compost and 50% sand, T3 = 50% compost and 50% virgin forest land, T4 = 50% compost, 25% sand and 25% sawdust, T5 = 50% compost, 25% sand and 25% rice straw. (a, b, c) Different letters in columns represent significant statistical differences at the p<0.01 level

The germination rate and plant height data presented a distribution with negative asymmetry with respect to the mean (Ghasami et al., 2020). The germination rate distribution (Figure 4A) was mesokurtic and plant height (Figure 4B) was leptokurtic (Boris and Chan, 2008). The general average values of germination and plant height are shown in Figure 4C.

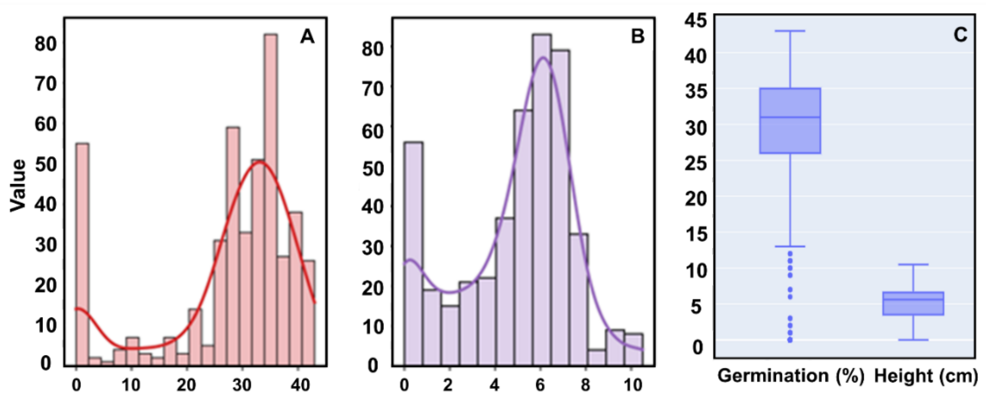


Figure 4. Normal distribution of data and descriptive statistics. A: Germination, B: Plant height, C: Descriptive statistics of germination and height of L. leucocephala

Figure 5 shows the dispersion of data for the correlation analysis. A high and positive correlation was observed in T2 (r=0.95), with 50% compost + 50% sand. In T3 (50% compost + 50% forest land) a correlation value of 0.87 ($p<0.005$) was observed. In T1, based on 100% forest land, a similar correlation of 0.88 ($p<0.005$) to T3 was found. In T5, which was the combination of three substrates (50% compost + 25% sand + 25% rice husk), the lowest correlation was observed (r=0.70) compared to the other treatments. A positive and high correlation was observed in T4 (50% compost + 25% sand + 25% wood sawdust), with the correlation value being 0.89 ($p<0.005$).

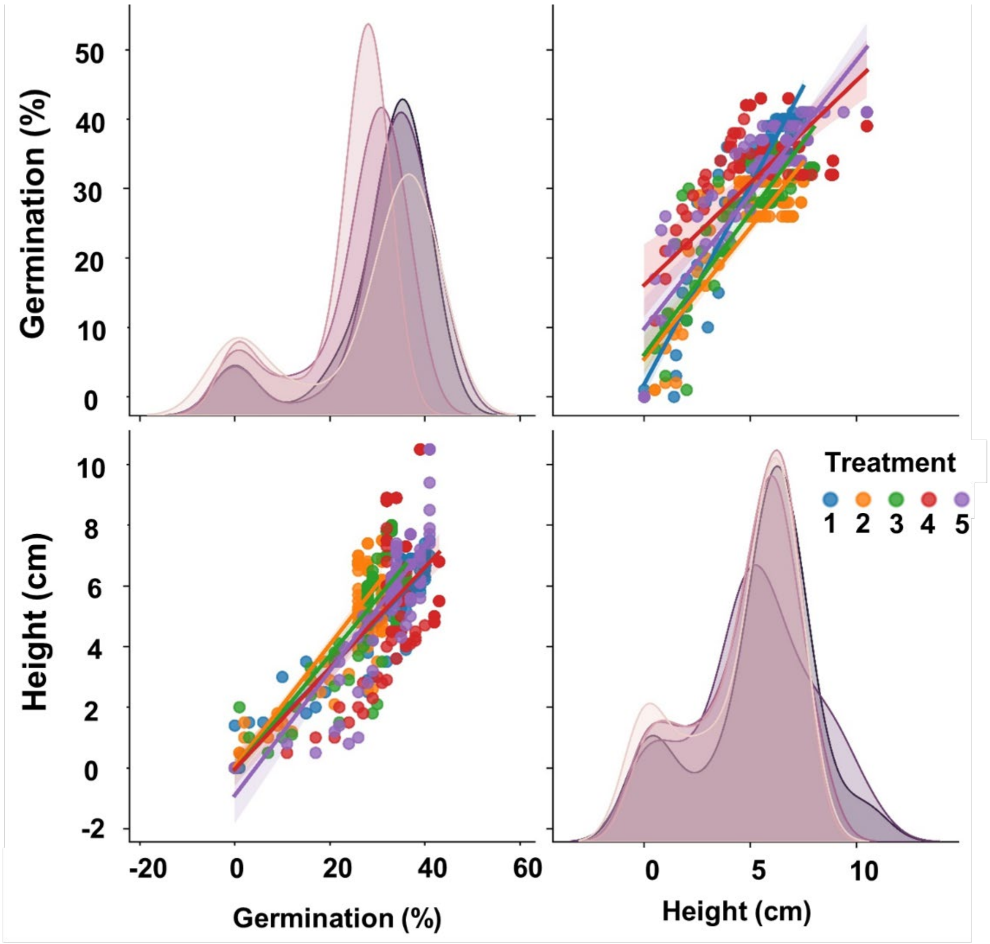


Figure 5. Relationship between germination rate of L. leucocephala and plant height according to treatment

Table 1 and Table 2 show the prediction equations with estimated parameters for the models adjusted to the germination rate and plant height of *L. leucocephala*, in each of the experimental substrates. In Figure 6, the germination rate data with the evaluated sigmoidal models are presented, and Table 1 shows the maximum R^2 values and minimum AIC values of all the most efficient models to predict the germination rate in five different substrates.

Table 1.
Prediction equations with best fit for germination rate of L. leucocephala, according to experimental substrates.

Treatment	Model	Prediction equation	Statistics	
			R^2	AIC
T1: 100% virgin forest land	Von Bertalanffy	y = 43.028 * (1 - exp(-0.114(x - 2.557)))	0.93	306.43
T2: 50% compost and 50% sand	Gompertz	y = 28.408 * exp(-exp(-(1.512(x - 5.123))))	0.97	152.01
T3: 50% compost and 50% virgin forest land	Gompertz	y = 31.764 * exp(-exp(-(2.140(x - 5.349))))	0.97	188.78
T4: 0% compost, 25% sand and 25% sawdust	Gompertz	y = 36.634 * exp(-exp(-(1.426(x - 4.036))))	0.95	233.25
T5: 50% compost, 25% sand and 25% rice straw	Gompertz	y = 35.903 * exp(-exp(-(1.757(x - 4.066))))	0.95	233.64

R^2: Coefficient of determination, AIC: Akaike criterion, * in each equation indicates multiplication.

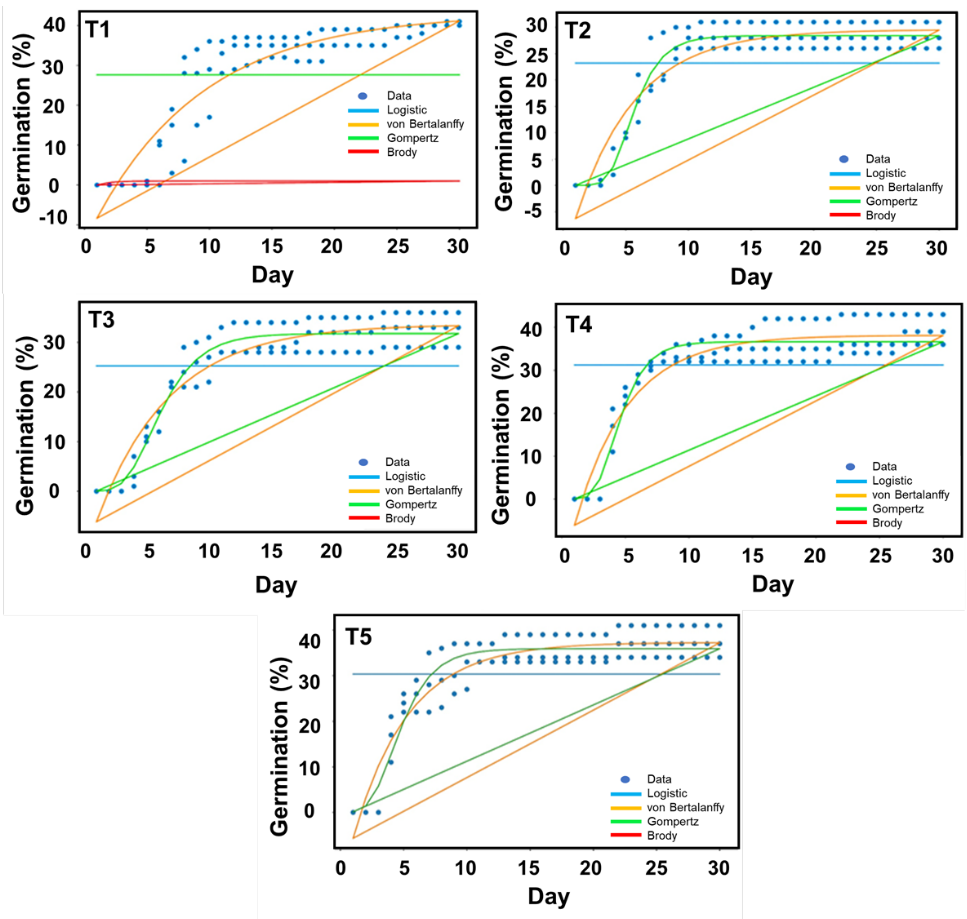


Figure 6. Prediction models for the germination rate (%) of L. leucocephala in different substrate treatments. T1 = 100% virgin forest land, T2 = 50% compost and 50% sand, T3 = 50% compost and 50% virgin forest land, T4 = 50% compost, 25% sand and 25% sawdust, T5 = 50% compost, 25% sand and 25% rice straw

In Figure 7, the plant height growth curves are presented up to 30 days of age, with all the sigmoidal models evaluated. Likewise, Table 2 shows the maximum R^2 values and minimum AIC values of the models that predicted best on five different substrates. The von Bertalanffy model is more appropriate to predict this variable in substrates with compost and another input other than virgin forest land.

Table 2.
Prediction equations with best fit for plant height of L. leucocephala at 30 days of growth, according to experimental substrates.

Treatment	Model	Prediction equation	Statistics	
			R^2	AIC
T1: 100% virgin forest land	Logistic	y = 6.614 / (1 + exp(-(2.716(x - 9.721))))	0.97	-86.2
T2: 50% compost and 50% sand	Von Bertalanffy	y = 7.865 * (1 - exp(-0.086(x - 1.871)))	0.99	-182.3
T3: 50% compost and 50% virgin forest land	Gompertz	y = 6.917 * exp(-exp(-(4.893(x - 7.269))))	0.96	-66.32
T4: 0% compost, 25% sand and 25% sawdust	Von Bertalanffy	y = 8.353 * (1 - exp(-0.093(x - 1.937)))	0.87	66.18
T5: 50% compost, 25% sand and 25% rice straw	Von Bertalanffy	y = 8.737 * (1 - exp(-0.090(x - 1.907)))	0.95	68.94

R^2: Coefficient of determination, AIC: Akaike criterion, * in each equation indicates multiplication.

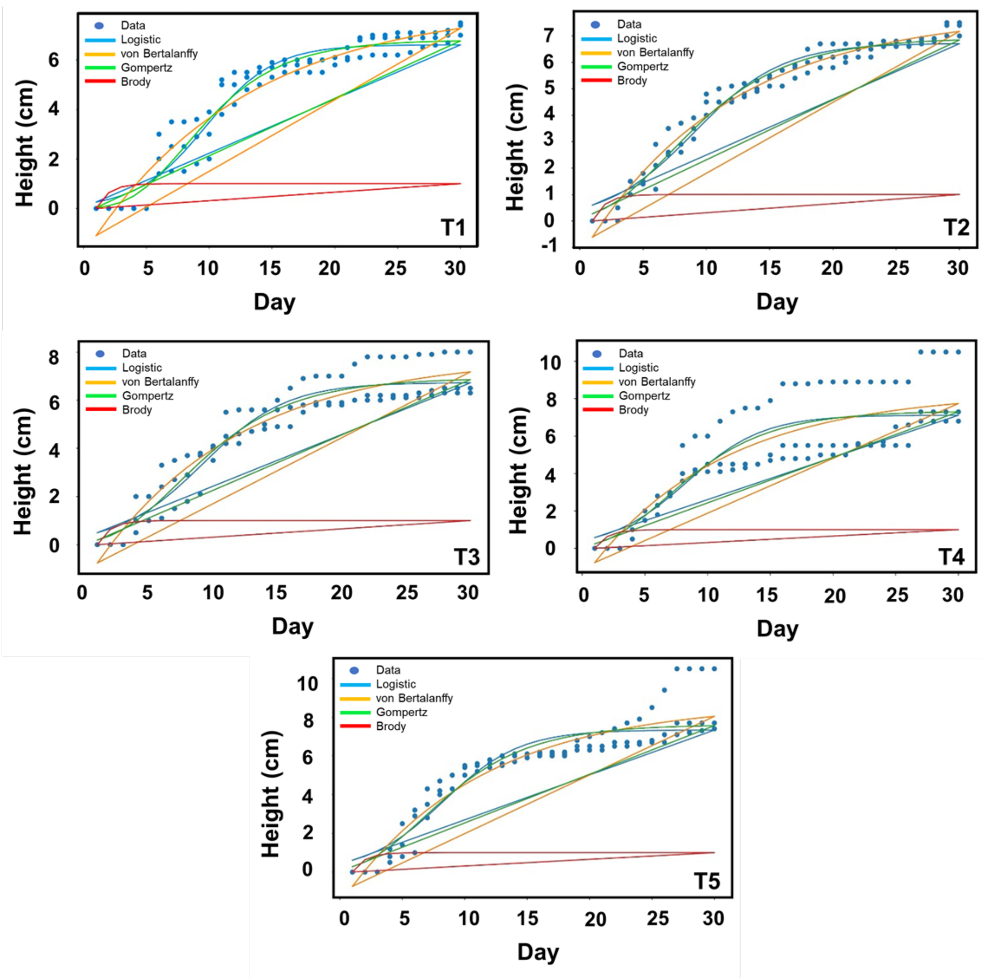


Figure 7. Plant height prediction models (cm) of L. leucocephala at 30 days of age, in different substrate treatments. T1 = 100% virgin forest land, T2 = 50% compost and 50% sand, T3 = 50% compost and 50% virgin forest land, T4 = 50% compost, 25% sand and 25% sawdust, T5 = 50% compost, 25% sand and 25% rice straw

Discussion

The present study evaluated the germination behavior and early growth of Leucaena leucocephala under different substrate compositions during the nursery phase, a critical stage for seedling establishment prior to transplanting. The experimental period was intentionally limited to the first 30 days after sowing, as this timeframe corresponds to the phase in which germination dynamics, initial seedling vigor, and substrate performance are most relevant for nursery management decisions.

The lowest germination rates of *L. leucocephala* were observed in T2 and T3, whereas the highest germination percentages were obtained in T1 and T4. These results are consistent with previous studies reporting that germination success is highly influenced by substrate physical and chemical characteristics, such as aeration, moisture retention, and nutrient availability. Sánchez-Gómez et al., (2018) reported lower germination percentages when applying seed scarification techniques, such as removal of the outer seed layer or hot water treatment, suggesting that both substrate composition and seed handling practices can substantially influence germination outcomes.

The average plant height 30 days after sowing was 7.7 cm, which falls within the range reported by Rangel et al. (2017), who observed seedling heights between 7 and 11 cm depending on nitrogen availability. In the present study, no significant differences in plant height were detected among substrates during the nursery phase, indicating that early seedling elongation is less sensitive to substrate composition under controlled conditions. Nevertheless, other studies have demonstrated that organic residues, such as palm by-products and plant-based compounds, can influence the early development of *L. leucocephala* seedlings depending on their source, rate, and interaction within the substrate matrix (Amaral et al., 2016).

The use of. *L. leucocephala* as a forage resource plays a fundamental role in improving livestock productivity, particularly in tropical systems, due to its high adaptability, nutritional value, and ecological benefits (Díaz et al., 2009; Bermúdez and Araica 2022). Predicting germination and growth of forage species constitutes a valuable strategy for ensuring forage availability and optimizing production (Iraola et al., 2015), thereby supporting long-term monitoring and management strategies for *L. leucocephala* establishment and productivity (Chiou et al., 2013).

Sigmoidal growth models are widely used to describe biological growth processes occurring under favorable environmental conditions. In this study, treatments T2 and T3 exhibited the highest coefficients of determination ($R^2 = 0.97$), whereas the highest Akaike Information Criterion (AIC) value was observed in T1 (AIC = 306). While high R^2 values indicated a good statistical fit, the simultaneous presence of elevated AIC values suggests that model complexity may limit biological interpretability of predictive robustness. Because AIC penalizes overparameterized models, low AIC values combined with high R^2 provide a more reliable criterion for model selection (Quiñones-Huatangari et al., 2023). Consequently, models showing high R^2, but high AIC values may not adequately describe the germination behavior of *L. leucocephala*, particularly when restricted to early-stage data.

The Gompertz model proved more suitable for describing germination dynamics in compost-based substrates, likely due to its capacity to represent self-regulated biological processes characterized by rapid initial growth followed by gradual deceleration. In contrast, the

Von Bertalanffy model demonstrated better performance in substrates composed of virgin forest soil, reflecting growth patterns associated with metabolic scaling and resource assimilation. This model has been widely applied to describe growth in diverse biological systems, including Atlantic herring (*Clupea harengus*) (Burbank et al., 2023), trout (*Oncorhynchus mykiss*), red deer (*Cervus elaphus*) (Vindenes et al., 2023), and Ashidan Yak (*Bos grunniens*) (Meng et al., 2023), and Kivircik lamb (Ozturk et al., 2023). Understanding growth processes is fundamental across biological disciplines and production systems, and nonlinear models have long been used to simulate growth trajectories in plants and animals (Fitzhugh Jr 1976; Lee et al., 2020).

Plant height is a key variable at the time of transplanting, as seedlings are subsequently exposed to more valuable and challenging field conditions. In this study, treatment T2 exhibited the highest R^2 value (0.99), for plant height prediction. Substrates containing virgin forest soil were better described by the Logistic and Gompertz models, which represent growth patterns characterized by an initial lag, an exponential growth phase, and eventual stabilization as environmental constraints increase (Ulloa and Rodríguez 2010). The Logistic model has been widely applied in population growth studies, epidemiological modeling (Wu et al., 2020), habitat distribution analysis (Ghorbani et al., 2020), and forage production systems (Njarui et al., 2017), supporting its relevance for early plant growth modeling.

Although the substrate composed of 100% virgin forest soil resulted in the highest germination performance, its use raises important environmental and sustainability concerns related to soil extraction and ecosystem disturbance. From an applied perspective, compost-based substrates combined with sand and agricultural residues, such as sawdust or rice straw, represent more sustainable alternatives that provide competitive germination performance while minimizing environmental impact. These findings support the formulation of nursery substrates based on locally available organic materials for silvopastoral species.

Overall, the results of this research highlight the usefulness of integrating experimental nursery data with nonlinear predictive models to optimize seedling production strategies for *L. leucocephala*. However, it is important to emphasize that the applicability of the models developed in this study is restricted to the nursery phase evaluated (0–30 days). Extrapolation to later developmental stages or field conditions should be undertaken with caution. Future studies incorporating longer evaluation periods, post-transplant growth, and additional morphological or physiological variables would strengthen predictive modeling across successive growth stages.

Study Limitations

While primary forest soil showed the highest germination rates, its use presents an environmental limitation because its extraction is unsustainable and can compromise the ecological functions of the forest soil. Consequently, the results associated with this substrate should be interpreted as a reference for optimal soil conditions for germination, rather than as a practical recommendation for nurseries. Furthermore, future studies could explore sustainable alternatives that fully replicate the physical, chemical, and biological properties of this soil and validate the results under larger-scale production conditions or in later stages of development. Additionally, further research is needed to translate these findings into management recommendations applicable to nurseries and silvopastoral systems, prioritizing environmentally responsible and technically feasible substrates.

Conclusions

The results of this study indicate that substrate composition significantly influences the germination of *Leucaena leucocephala* during the nursery phase, with compost-based substrates combined with sand and sawdust or rice straw providing high germination performance and representing environmentally sustainable alternatives to virgin forest soil. Although no significant differences in early plant height were observed within the first 30 days after sowing, nonlinear sigmoidal models proved useful for describing germination dynamics and initial seedling growth; however, models exhibiting high R^2 values together with elevated AIC values should be interpreted with caution due to potential overparameterization. The application of predictive modeling at the nursery stage offers a practical tool to support seedling production planning, substrate selection, and transplant scheduling, thereby contributing to the efficient establishment of *L. leucocephala* and the broader adoption of sustainable silvopastoral systems in tropical livestock production.

Author contribution. All persons entitled to authorship have been so named, and all authors have seen and agreed to the submitted version of the manuscript. J. A. S-U.: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft; M. E. M-P.: Data curation, Formal analysis, Supervision, Writing – review & editing; H. A. Q-C.: Methodology, Investigation, Writing – original draft; G. T. S. P.: Methodology, Investigation, Writing – original draft; H. V. V. P: Investigation, Writing – original draft; Writing – review & editing; D. J. G-B.: Methodology, Investigation, Writing – original draft; J. L. M. Q.: Supervision, Writing – review & editing.

Conflict of interest. The authors declare no conflict of interest.

Funding. This research was funded by Project “Mejoramiento de la disponibilidad y acceso del material genético mediante el uso de técnicas de biotecnología reproductiva en ganado bovino tropical en las regiones de San Martín, Loreto y Ucayali–PROMEG–Tropical” with CUI N°. 2338934 and We also express our gratitude to the Vicerrectorado de Investigación at the “Universidad Nacional Toribio Rodríguez de Mendoza de Amazonas” for financing the Article Processing Changes (APC).

Acknowledgements. The authors are grateful to Cesar Uribe for assistance with data collection, care and irrigation of *L. leucocephala* in the nursery. In addition, the authors thank

Jhonsy Omar Silva López and Carlos I. Arbizu for his support in preparing the map and the revision of English, respectively.

References

Alemán-Ramirez, J.L., Okoye, P.U., Torres-Arellano, S., Mejía-Lopez, M. & Sebastian, P.J. (2022). A review on bioenergetic applications of *Leucaena leucocephala. Industrial Crops and Products, 182*, 114847. https://doi.org/10.1016/j.indcrop.2022.114847.

Amaral, F.H., Nóbrega, J.C., Nóbrega, R.S. & Amorim, S.P. (2016). Growth of *Leucaena leucocephala* (Lam.) de Wit favored by organic waste in the Brazilian semiarid region. *Revista Brasileira de Engenharia Agrícola e Ambiental, 20*, 612-617. https://doi.org/10.1590/1807-1929/agriambi.v20n7p612-617.

Andrew, S.M. (2023). Production and nutritional value of Pleurotus floridanus grown on rice straw supplemented with *Leucaena leucocephala* foliage. *Environmental and Sustainability Indicators*, *17,* 100223. https://doi.org/10.1016/j.indic.2022.100223.

Archontoulis, S.V. & Miguez, F.E. (2015). Nonlinear regression models and applications in agricultural research. *Agronomy Journal, 107*, 786-798. https://doi.org/10.2134/agronj2012.0506.

Bacab, H.M., Madera, N.B., Solorio, F.J., Vera, F. & Marrufo, D.F. (2013). Los sistemas silvopastoriles intensivos con *Leucaena leucocephala*: una opción para la ganadería tropical. *Avances en Investigación Agropecuaria, 17*, 67-81.

Benincasa, P., Falcinelli, B., Lutts, S., Stagnari, F. & Galieni, A. (2019). Sprouted grains: A comprehensive review. *Nutrients, 11*, 421. https://doi.org/10.3390/nu11020421.

Bermúdez, C.G. & Araica, G.M. (2022). Sistemas silvopastoriles: una alternativa para la ganadería bovina sostenible. *La Calera, 22*, 46-52. https://doi.org/10.5377/calera.v22i38.14193.

Blanco, A.M., Chantre, G.R., Lodovichi, M.V., Bandoni, J.A., López, R.L., Vigna, M.R., Gigón, R. & Sabbatini, M.R. (2014). Modeling seed dormancy release and germination for predicting Avena fatua L. field emergence: A genetic algorithm approach. *Ecological Modelling*, *272*, 293-300. https://doi.org/10.1016/j.ecolmodel.2013.10.013.

Boris, S.T. & Chan, J.S. (2008). Scale mixtures distributions in statistical modelling. *Australian & New Zealand Journal of Statistics*, *50*, 135-146. https://doi.org/10.1111/j.1467-842X.2008.00504.x

Burbank, J., McDermid, J.L., Turcotte, F. & Rolland, N. (2023). Temporal Variation in Von Bertalanffy Growth Curves and Generation Time of Southern Gulf of St. Lawrence Spring and Fall Spawning Atlantic Herring (*Clupea harengus*). *Fishes, 8*, 205. https://doi.org/10.3390/fishes8040205.

Chará, J., Rivera, J., Barahona, R., Murgueitio, E., Deblitz, C., Reyes, E., Maurício, R. M., Molina, J. J., Flores, M., & Zuluaga, A. (2024). Intensive silvopastoral systems: Economics and contribution to climate change mitigation and public policies. In Integrating landscapes: Agroforestry for biodiversity conservation and food sovereignty (pp. 613–634). *Springer*. https://doi.org/10.1007/978-3-031-54270-1_21.

Chauhan, B.S., Manalil, S., Florentine, S. & Jha, P. (2018). Germination ecology of Chloris truncata and its implication for weed management. *PLoS One, 13*, e0199949. https://doi.org/10.1371/ journal.pone.0199949

Chiou, C.R., Wang, H.H., Chen, Y.J., Grant, W.E. & Lu, M.L. (2013). Modeling potential range expansion of the invasive shrub *Leucaena leucocephala* in the Hengchun peninsula, Taiwan. *Invasive Plant Science and Management, 6*, 492-501. https://doi.org/10.1614/IPSM-D-13-00010.1

Coşkun, Y. (2018). Evaluation of different sigmoidal growth models and climate parameters for dry matter accumulation of oat. *Genetika*, *50*, 1045-1054. https://doi.org/10.2298/GENSR1803045C.

Dagogo, J.E., Nduka, C. & Ogoke, U.P. (2020). Comparative Analysis of Richards, Gompertz and Weibull Models. *IOSR Journal of Mathematics, 16*, 15-20.

Díaz, A., Castillo, E., Martín, P.C. & Hernández, J.L. (2009). Ceba de toros mestizos lecheros, en silvopastoreo con leucaena, acceso a banco de biomasa y suplemento activador del rumen. *Revista Cubana de Ciencia Agrícola, 43*, 235-238.

Durand-Chávez, L.M., Vásquez, H.V., Ushiñahua-Ramírez, D., Carrasco, W., Depaz-Hizo, B. A. & Saucedo-Uriarte, J.A. (2022). Yield Performance of Forage Shrubs and Effects on Milk Production and Chemical Composition under the Tropical Climatic Conditions of Peru. *Sustainability, 14*, 12774. https://doi.org/10.3390/su141912774.

Dzib-Castillo, B. B., Casanova-Lugo, F., Pozo-Leyva, D., Costa, R. L. D., Macario-González, L., Gimenes, F. M. A., Lara-Pérez, L. A., & Chay-Canul, A. J. (2025). Productivity and nutritional quality of pastures in a silvopastoral system under two harvest intervals in southeastern Mexico. *Agroforestry Systems*, *99*, 137. https://doi.org/10.1007/s10457-025-01235-3.

Fitzhugh, H.A. (1976). Analysis of growth curves and strategies for altering their shape. *Journal of Animal Science, 42*, 1036-1051. https://doi.org/10.2527/jas1976.4241036x

Ghasami, S., Maleki, M. & Khodadadi, Z. (2020). Leptokurtic and platykurtic class of robust symmetrical and asymmetrical time series models. *Journal of Computational and Applied Mathematics, 376,* 112806. https://doi.org/10.1016/j.cam.2020.112806.

Ghorbani, A., Samadi, S., Moameri, M. & Esfanjani, J. (2020). Predicting the distribution of *Leucanthemum vulgare* Lam. using logistic regression in Fandoghlou rangelands of Ardabil province, Iran. *Journal of Rangeland Science, 10*, 98-111.

Guterres, L., Duarte, M.C., Catarino, S., Roxo, G., Barnabé, J., Sebastiana, M., Monteiro, F. & Romeiras, M.M. (2022). Diversity of Legumes in the Cashew Agroforestry System in East Timor (Southeast Asia). *Foods, 11*, 3503. https://doi.org/10.3390/foods11213503.

Hadi, M.H. & Gonzalez-Andujar, J.L. (2009). Comparison of fitting weed seedling emergence models with nonlinear regression and genetic algorithm. *Computers and Electronics in Agriculture, 65*, 19-25. https://doi.org/10.1016/j.compag.2008.07.005.

Iraola, J., García, Y., Muñoz, E., Fraga, L.M., Barros-Rodríguez, M., Hernández, J.L. & Moreira, E. (2015). Modeling of live weight per age in fattening bovines under a silvopastoral system with *Leucaena leucocephala* hala. *Revista Cubana de Ciencia Agrícola, 49*, 307-315.

Jayanthy, V., Geetha, R., Rajendran, R., Prabhavathi, P., Sundaram, S.K., Kumar, S.D. & Santhanam, P. (2014). Phytoremediation of dye contaminated soil by *Leucaena leucocephala* (subabul) seed and growth assessment of Vigna radiata in the remediated soil. *Saudi Journal of Biological Sciences, 21*, 324-333. https://doi.org/10.1016/j.sjbs.2013.12.001.

Kamar, S.H. & Msallam, B.S. (2020). Comparative study between generalized maximum entropy and Bayes methods to estimate the four parameter weibull growth model. *Journal of Probability and Statistics, 2020*(1), 7967345. https://doi.org/10.1155/2020/7967345.

Kaps, M., Lamberson, W.R. (2017). Biostatistics for Animal Science. *CABI Publishing, Oxfordshire* OX10 8DE, UK, 2017.

Lee, L., Atkinson, D., Hirst, A.G. & Cornell, S.J. (2020). A new framework for growth curve fitting based on the von Bertalanffy Growth Function. *Scientific Reports, 10*, 7953. https://doi.org/ 10.1038/ s41598-020-64839-y.

Lim, T. K. (2012). *Edible medicinal and non-medicinal plants*. (Vol. 1, pp. 285-292). Dordrecht, The Netherlands: Springer.

Marques, A.R. Lima, L.L., Garcia, Q.S. & Atman, A.P. (2020). A novel cellular automata approach: seed input/output of the alien species *Leucaena leucocephala* in the soil and the effects of climate changes. *Plant Ecology, 221*, 141-154. https://doi.org/10.1007/s11258-019-00999-w.

Meng, G., La, Y., Bao, Q., Wu, X., Ma, X., Huang, C., Chu, M., Liang, C. & Yan, P. (2023). Early Growth and Development and Nonlinear Model Fitting Analysis of Ashidan Yak. *Animals, 13*, 1545. https://doi.org/10.3390/ani13091545.

Nehdi, I.A., Sbihia, H., Ping, C.B. & Al-Resayes, S.I. (2014). *Leucaena leucocephala* (Lam.) de Wit seed oil: Characterization and uses. *Industrial Crops and Products, 52*, 582-587. https://doi.org/10.1016/j.indcrop.2013.11.021.

Njarui, D.M., Gatheru, M., Gichangi, E.M., Nyambati, E.M., Ondiko, C.N. & Ndungu-Magiroi, K.W. (2017). Determinants of forage adoption and production niches among smallholder farmers in Kenya. *African Journal of Range & Forage Science, 34*, 157-166. https://doi.org/10.2989/10220119.2017.1387814.

Normaniza, O., Faisal, H.A. & Barakbah, S.S. (2008). Engineering properties of *Leucaena leucocephala* for prevention of slope failure. *Ecological engineering, 32*, 215-221. https://doi.org/10.1016/j.ecoleng.2007.11.004.

Ozturk, N., Kecici, P.D., Serva, L., Ekiz, B. & Magrin, L. (2023). Comparison of Nonlinear Growth Models to Estimate Growth Curves in Kivircik Sheep under a Semi-Intensive Production System. *Animals, 13*, 2379. https://doi.org/10.3390/ani13142379.

Pandey, V.C. & Kumar, A. (2013). *Leucaena leucocephala*: an underutilized plant for pulp and paper production. *Genetic resources and crop evolution, 60*, 1165-1171. https://doi.org/10.1007/s10722-012-9945-0.

Pramod, S., Rajput, K.S. & Rao, K.S. (2019). Immunolocalization of β-(1–4)-D-galactan, xyloglucans and xylans in the reaction xylem fibres of *Leucaena leucocephala* (Lam.) de Wit. *Plant Physiology and Biochemistry, 142*, 217-223. https://doi.org/10.1016/j.plaphy.2019.07.013.

Prasad, J. V. N. S., Korwar, G. R., Rao, K. V., Mandal, U. K., Rao, G. R., Srinivas, I., Venkateswarlu, B., Rao, S. N., & Kulkarni, H. D. (2011). Optimum stand density of Leucaena leucocephala for wood production in Andhra Pradesh, southern India. *Biomass and Bioenergy*, *35*(1), 227–235. https://doi.org/10.1016/j.biombioe.2010.08.012.

Quiñones-Huatangari, L., Huaccha-Castillo, A.E., Fernandez-Zarate, F.H., Morales-Rojas, E., Marrufo-Jiménez, J.D. & Mejía-Córdova, L.L. (2023). Analysis of Germination Curves of Cinchona officinalis L. (Rubiaceae) Using Sigmoidal Mathematical Models. *International Journal of Agronomy, 6*, 1360608. https://doi.org/10.1155/2023/1360608.

Rangel, W.M., Thijs, S., Janssen, J., Oliveira, S.M., Bonaldi, D.S., Ribeiro, P.R., Jambon, I., Eevers, N., Weyens, N., Vangronsveld, J. & Moreira, F.M. (2017). Native rhizobia from Zn mining soil promote the growth of *Leucaena leucocephala* on contaminated soil. *International journal of phytoremediation, 19*, 142-156. https://doi.org/10.1080/15226514.2016.1207600.

Ritz, C., Pipper, C.B. & Streibig, J.C. (2013). Analysis of germination data from agricultural experiments. *Journal of Agronomy, 45*, 1-6. https://doi.org/10.1016/j.eja.2012.10.003.

Rivera-Herrera, J.E., Molina-Botero, I., Chará-Orozco, J., Murgueitio-Restrepo, E. & Barahona-Rosales, R. (2017). Intensive silvopastoral systems with *Leucaena leucocephala* (Lam.) de Wit: productive alternative in the tropic in view of the climate change. *Pastos y Forrajes*, *40*, 171-183.

Saucedo-Uriarte, J. A., Diaz-Quevedo, C., Milla Pino, M. E., Durand Chávez, L. M., Linares Rivera, J. L., Vásquez Pérez, H. V. & Quispe-Ccasa, H. A. (2023). Sustentabilidad productiva de la instalación de sistemas silvopastoriles: una revisión sistemática basada en la realidad de Perú y Colombia. *Ciencia y Tecnología Agropecuaria*, *24*(2), e3048. https://doi.org/10.21930/rcta.vol24_num2_art:3048.

Sánchez-Gómez, A., Rosendo-Ponce, A., Vargas-Romero, J.M., Rosales-Martínez, F., Platas-Rosado, D.E. & Becerril-Pérez, C.M. (2018). Energía germinativa en guaje (*Leucaena leucocephala* cv. Cunningham) con diferentes métodos de escarificación de la semilla. *Agrociencia, 52*, 863-874.

Sarabia-Salgado, L., Solorio-Sánchez, F., Ramírez-Avilés, L., Rodrigues Alves, B.J., Ku-Vera, J., Aguilar-Pérez, C., Urquiaga, S. & Boddey, R.M. (2020). Increase in milk yield from cows through improvement of forage production using the N2-fixing legume *Leucaena leucocephala* in a silvopastoral system. *Animals,* 10, 734. https://doi.org/10.3390/ani10040734.

Sharma, A.R. & Behera, U.K. (2010). Green leaf manuring with prunings of *Leucaena leucocephala* for nitrogen economy and improved productivity of maize (*Zea mays*)–wheat (*Triticum aestivum*) cropping system. *Nutr. Cycl. Agroecosyst.* 86, 39-52. https://doi.org/10.1007/s10705-009-9272-9
Smithers, E.T., Luo, J. & Dyson, R.J. (2019). Mathematical principles and models of plant growth mechanics: from cell wall dynamics to tissue morphogenesis. *J. Exp. Bot.* 70, 3587-3600. https://doi.org/10.1093/jxb/erz253.
Tan, L., Chen, S., Wang, T. & Dai, S. (2013). Proteomic insights into seed germination in response to environmental factors. *Proteomics, 13,* 1850-1870. https://doi.org/10.1002/pmic.201200394.
Ulloa, J.T. & Rodríguez, J.A. (2010). El modelo logístico: Una alternativa para el estudio del crecimiento poblacional de organismos. *Revista Electrónica de Veterinaria*, *11*, 3.
Vindenes, Y., Langvatn, R., Mysterud, A. (2023). Shifting seasonality of annual growth through ontogeny for red deer at northern latitudes. *Ecosphere*, *14*, e4639. https://doi.org/ 10.1002/ecs2.4639
Wu, K., Darcet, D., Wang, Q. & Sornette, D. (2020). Generalized logistic growth modeling of the COVID-19 outbreak: comparing the dynamics in the 29 provinces in China and in the rest of the world. *Nonlinear dynamics, 101*, 1561-1581. https://doi.org/10.1007/s11071-020-05862-6.

MODELOWANIE MATEMATYCZNE KIEŁKOWANIA I WZROSTU *LEUCAENA LEUCOCEPHALA* PRZY RÓŻNYCH PODŁOŻACH I WARUNKACH SZKÓŁKARSKICH

Streszczenie. Produkcja zwierzęca w regionach tropikalnych ma głównie charakter ekstensywny i w dużym stopniu opiera się na pastwiskach rodzimych lub monokulturowych. Jednak często okazują się one niewystarczające dla wyżywienia przeżuwaczy. Włączenie *Leucaena leucocephala* do systemów sylwopastoralnych jest obiecującą strategią ze względu na wysoką jakość paszową tej rośliny, jednak informacje dotyczące jej wczesnego rozwoju w warunkach szkółkarskich są nadal ograniczone. Celem niniejszego badania było modelowanie dynamiki kiełkowania oraz wczesnego wzrostu siewek *L. leucocephala* w różnych składach podłoża w fazie szkółkarskiej. Procent kiełkowania oraz dzienną wysokość roślin rejestrowano w okresie 30 dni. Wpływ badanych czynników oceniono za pomocą analizy wariancji (ANOVA), natomiast dynamikę wzrostu opisano przy użyciu nieliniowych modeli sigmoidalnych (Gompertza, logistycznego, von Bertalanffy'ego oraz Brody'ego). Stwierdzono istotne różnice w tempie kiełkowania między podłożami ($p<0,05$), podczas gdy nie zaobserwowano istotnego wpływu podłoża na wysokość roślin w okresie oceny ($p>0,05$). Spośród analizowanych modeli funkcje von Bertalanffy'ego, Gompertza oraz logistyczna zapewniły najlepsze dopasowanie do danych dotyczących wysokości roślin na podstawie kryteriów R^2 i AIC. Chociaż niektóre modele wykazały wysokie wartości R^2 dla kiełkowania, podwyższone wartości AIC sugerują ich ograniczoną adekwatność biologiczną. Wyniki te podkreślają użyteczność modelowania predykcyjnego przy podejmowaniu decyzji dotyczących zarządzania szkółką, optymalizacji doboru podłoża oraz ułatwianiu wprowadzania *L. leucocephala* do zrównoważonych systemów sylwopastoralnych.

Słowa kluczowe: *Leucaena leucocephala*, modele sigmoidalne, kiełkowanie, wysokość roślin, system produkcyjny, zrównoważony rozwój.