

AN APPROACH TO THE USE OF MATHEMATICAL AND COMPUTATIONAL MODELS IN UNDERSTANDING AND VALIDATING AGRICULTURAL PROCESSES AND TECHNOLOGIES

UMA ABORDAGEM NO USO DE MODELOS MATEMÁTICOS E
COMPUTACIONAIS NA COMPREENSÃO E VALIDAÇÃO DE PROCESSOS E
TECNOLOGIAS NA AGRICULTURA

UN ENFOQUE PARA EL USO DE MODELOS MATEMÁTICOS Y
COMPUTACIONALES EN LA COMPRENSIÓN Y VALIDACIÓN DE PROCESOS Y
TECNOLOGÍAS EN LA AGRICULTURA

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ABSTRACT

The growing demand for more efficient and sustainable agricultural systems has expanded the use of mathematical modeling as a tool to support research and decision-making. In this context, this paper presents a narrative literature review of various mathematical models, encompassing both traditional approaches and more recent techniques used in agriculture. Conventional models include biometric and regression analyses, which are widely employed to evaluate cultivar performance, identify relationships between agronomic variables, and estimate the efficiency of management practices. The review also discusses applications of differential equations and Fick's laws of diffusion, used to describe processes such as the progression of foliar diseases and soil nutrient dynamics. Furthermore, it addresses the increasing use of computational tools and methods, such as fuzzy logic, artificial neural networks, and genetic algorithms. These techniques have shown promise in analyzing complex agricultural systems, particularly in situations involving large datasets, non-linear relationships, and various sources of uncertainty. Overall, the studies analyzed demonstrate that combining different modeling strategies contributes to a broader understanding of agricultural processes. Mathematical modeling serves as a vital instrument for supporting the development of technologies and practices aimed at the sustainability of production systems.

Keywords: Correlation and Regression. Differential Equations. Fuzzy Logic. Neural Networks. Genetic Algorithm.

RESUMO

A crescente demanda por sistemas agrícolas mais eficientes e sustentáveis tem ampliado o uso da modelagem matemática como ferramenta de apoio à pesquisa e à tomada de decisão. Nesse sentido, este trabalho apresenta uma revisão narrativa da literatura sobre diferentes modelos matemáticos, reunindo abordagens tradicionais e técnicas mais recentes utilizadas na agricultura. Entre os modelos convencionais, destacam-se as análises biométricas e de regressão, amplamente empregadas para avaliar o desempenho de cultivares, identificar relações entre variáveis agrônomicas e estimar a eficiência de práticas de manejo. Também são discutidas aplicações de equações diferenciais e das leis de difusão de Fick, utilizadas na descrição de processos como a evolução de doenças foliares e a dinâmica de nutrientes no solo. Além disso, a revisão aborda o uso crescente de ferramentas e métodos computacionais, como lógica fuzzy, redes neurais artificiais e algoritmos genéticos. Essas técnicas têm se mostrado promissoras na análise de sistemas agrícolas complexos, especialmente em situações que envolvem grande volume de dados, relações não lineares e diferentes fontes de incerteza. De modo geral, os estudos analisados evidenciam que a combinação de diferentes estratégias de modelagem contribui para uma compreensão mais ampla dos processos agrícolas. A modelagem matemática é um importante instrumento para apoiar o desenvolvimento de tecnologias e práticas voltadas à sustentabilidade dos sistemas produtivos.

Palavras-chave: Correlação e Regressão. Equações Diferenciais. Lógica Fuzzy. Redes Neurais. Algoritmo Genético.

RESUMEN

La creciente demanda de sistemas agrícolas más eficientes y sostenibles ha impulsado el uso de la modelización matemática como herramienta para la investigación y la toma de decisiones. En este sentido, este trabajo presenta una revisión narrativa de la literatura sobre diferentes modelos matemáticos, reuniendo enfoques tradicionales y técnicas más recientes utilizadas en la agricultura. Entre los modelos convencionales, destacan los análisis biométricos y de regresión, ampliamente utilizados para evaluar el rendimiento de los cultivos, identificar relaciones entre variables agronómicas y estimar la eficiencia de las prácticas de manejo. También se analizan las aplicaciones de ecuaciones diferenciales y leyes de difusión de Fick, empleadas en la descripción de procesos como la evolución de enfermedades foliares y la dinámica de nutrientes del suelo. Asimismo, la revisión aborda el uso cada vez mayor de herramientas y métodos computacionales, como la lógica difusa, las redes neuronales artificiales y los algoritmos genéticos. Estas técnicas han demostrado ser prometedoras en el análisis de sistemas agrícolas complejos, especialmente en situaciones que involucran grandes volúmenes de datos, relaciones no lineales y diversas fuentes de incertidumbre. En general, los estudios analizados muestran que la combinación de diferentes estrategias de modelización contribuye a una comprensión más amplia de los procesos agrícolas. La modelización matemática es una herramienta importante para apoyar el desarrollo de tecnologías y prácticas orientadas a la sostenibilidad de los sistemas de producción.

Palabras clave: Correlación y Regresión. Ecuaciones Diferenciales. Lógica Difusa. Redes Neuronales. Algoritmo Genético.



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INTRODUCTION

Mathematical modeling is a powerful tool that enables the understanding, simulation, optimization, and validation of real processes and systems. Furthermore, due to its low cost and ability to simulate different environments, mathematical modeling stands out not only as a complement to research but also as a protagonist in various fields of scientific inquiry (Bassanezi, 2009; Rosa, Orey, 2012; Lopatiev *et al.*, 2017; Soltani *Et al.*, 2018). Mathematical modeling is essential for the advancement of scientific knowledge, enabling new discoveries and the development of systems to support decision-making (Bassanezi, 1994; Tedeschi, 2006; Klering *et al.*, 2016; Screminn *et al.*, 2023). In the study and interpretation of biosystems, where properties and interactions are often complex, mathematical modeling has enabled a better understanding of the relationships between the variables involved in the processes being analyzed (Silva, Mattos, 2017; Sarstedt, Mooi, 2019).

In the agricultural sector, modeling serves as a reliable method for making predictions about crop productivity and quality, enabling a description of the dynamics of biological and environmental relationships with technologies, aiming to simulate scenarios (Kocira, 2018; Mellaku *et al.*, 2022). Therefore, it represents a field of knowledge that seeks to create a mathematical representation of a real problem, generating opportunities for interpretations and analyses (Aguirre, 2000; Sausen *et al.*, 2015). Moreover, it allows for the interpretation of phenomena, identifying characteristics, revealing trends, and strengthening more reliable decision-making (Tedeschi & Menendez, 2020; Oliveira & Santos, 2022).

The study of agrarian systems can present high complexity due to the large number of variables, making it difficult to construct models aimed at simulation and the search for optimization of problems (Campos *et al.*, 2016; Dornelles *et al.*, 2023). Due to this, modeling has enabled the study of cultivar behavior in response to climatic variations, the validation of new management technologies, crop simulation and forecasting, cost reduction and production maximization optimization, plant selection in breeding programs, and has assisted in pest control decision-making, among others (Audsley, Milne, Paveley, 2005; Barioni *et al.*, 2011; Alessi *et al.*, 2018; Kraisig *et al.*, 2018).

The aim of this article is to present both conventional models and those gaining widespread use—due to the range of possibilities they offer—that can be applied in the pursuit of more efficient and sustainable agricultural processes.

METHODOLOGY

This research is a qualitative narrative literature review, aiming to develop the state of the art on mathematical models designed for efficient computational simulations, capable of capturing the multifaceted interactions and nonlinear effects characteristic of agroecosystems, which have become the subject of growing interest. These models have been gaining widespread use due to the range of possibilities they offer, and they can be applied to oat cultivation in the context of advances in cleaner, more efficient, and sustainable processes. The focus is on advancing these scientific sources to assist in understanding more sustainable agricultural practices.

In this perspective, the following topics are presented: 'Biometric techniques as support for the initiation of mathematical modeling,' 'The use of regression for modeling behavior and

simulation,' 'Real systems represented by differential equations,' 'Mathematical model of mass flow by diffusion: Fick's laws,' 'Process simulation through computational intelligence: fuzzy logic,' 'Pattern recognition and simulation through artificial intelligence: neural networks,' and 'Process optimization using genetic algorithms: stochastic search.

The research was conducted through online access to databases such as Google, Google Scholar, SciELO, Elsevier, PubMed, Scopus, Web of Science, and the Portal de Periódicos of the Coordination for the Improvement of Higher Education Personnel (CAPES). Articles published between the years 1980 and 2025 were used, gathered from June 2024 to July 2025. For this, scientific papers in any language were selected and read, covering various fields such as mathematical and computational modeling in agronomy. Since this is a narrative-type review, there were no specific criteria for the acceptance or exclusion of papers, nor were specific years defined for the selection and reading to compose the development of the discussion addressed in this research.

This methodological configuration is described in the work developed by Rother (2007), who states that qualitative narrative review articles provide broad and adequate knowledge for the development of a specific subject, whether from a theoretical or contextual perspective. These articles basically consist of an analysis of the literature published in books, printed and/or electronic journal articles, accompanied by the authors personal interpretation and critical analysis, taking into account the development of the 'state of the art.

RESULT AND DISCUSSION

Biometric Techniques as Support for the Initiation of Mathematical Modeling

Procedures based on biometric techniques are useful for interpreting biological phenomena, guiding research strategies, constructing and validating model prediction parameters, and consequently developing more efficient models aimed at more accurate and sustainable management practices (Cruz, 2006; Mantai *et al.*, 2017; Scarton *et al.*, 2025). From this perspective, correlation analyses improve the understanding of the associations among the studied traits, providing support to comprehend the magnitude and direction of these relationships. In this way, when a large number of variables are measured, it becomes desirable to understand how they are related.

Correlation tests are used in studies where there is interest in understanding the relationship between variables. One of the most well-known correlation tests is Pearson's linear correlation coefficient, which is used to determine the degree of linear relationship between two variables (Dalchiavon & Carvalho, 2012; Sari *et al.*, 2017; Bandeira *et al.*, 2024). Also from this perspective, canonical correlations allow for the establishment of interrelationships between groups of traits involved. This method analyzes the interrelationships among groups with varying numbers of traits, with the associations being explainable through a few canonical correlations (Cruz *et al.*, 2012; Pradebon *et al.*, 2025). However, a simple correlation does not detect the influence of a third variable or group of variables on this relationship, which may lead to incorrect conclusions. In this context, path analysis allows correlations to be broken down into direct and indirect effects, thereby unfolding the direct relationships.

Path analysis was developed by Wright (1921 and 1923) and represents a multivariate analysis technique that specifically examines the relationship between a set of explanatory variables and a dependent variable (Cruz, 2006; Sari *et al.*, 2017; Pradebon *et al.*, 2025). Furthermore, adaptability and stability analyses are of great importance for identifying more stable and efficient management technologies for grain production (Cavalcante *et al.*, 2014; Arenhardt *et al.*, 2015; Carvalho, I. R. *et al.*, 2023). These models allow, through the quantification of their parameters, the identification of genotypes and management practices that are more productive and exhibit predictable behavior under environmental conditions (Pereira *et al.*, 2013; Silva *et al.*, 2016; Olivoto & Nardino, 2021). In variable selection, there is also the Stepwise technique, which aims to establish the relationship between a set of explanatory (independent) variables and a main (dependent) variable (Boligon *et al.*, 2010; Fukushima *et al.*, 2016; Reginatto *et al.*, 2024).

Many researchers use correlation models, path analysis, multivariate analysis, Stepwise methods, and adaptability and stability analyses to identify potential variables as a basis for validating more efficient cultivars or management practices and selecting indicators for use in mathematical modeling. In this regard, Vieira *et al.* (2007) used correlation models to identify that thousand-grain weight is the component with the greatest potential for selecting genetic constitutions related to the grain productivity of wheat and oats. Junying *et al.* (2010) found positive correlations between oat grain yield and panicle weight as well as the number of grains per panicle. Mantai *et al.* (2016a), using path analysis, developed a multiple linear regression model to simulate oat grain yield. Marolli *et al.* (2017) used the Stepwise technique to select

potential variables for simulating oat yield under conditions involving the use of growth regulators, regardless of the nitrogen fertilizer dose. Mittelman *et al.* (2001) estimated heritability and examined the effect of selection on oat height and the duration of the vegetative cycle.

One of the areas of biometric application in modeling is focused on the joint analysis of variables, so that their effects should not be interpreted separately. Known as multivariate data analysis, this field consists of statistical techniques that simultaneously analyze multiple variables and measurements on an individual or object of study (Neisse, Hongyu, 2016; Howsmon *et al.*, 2017; Pradebon *et al.*, 2025). These methods are widely used in the study of biosystems because this field can involve a large number of variables that directly and indirectly influence processes and response variables, making it impossible to assess their effects in isolation. In agriculture, these methods help study the relationships among two or more variables, as well as determine the magnitude of influence that independent variables have on dependent variables. Additionally, it serves as a basis for variable selection in the development of simulation models, assessing the importance of variables involved in the system (Kurek *et al.*, 2001; Maciel *et al.*, 2018; Pradebon *et al.*, 2025).

Some multivariate methods can analyze genetic diversity among plants based on morphological traits. Thus, together with multivariate clustering methods, it is possible to identify groups of cultivars with greater genetic resistance to diseases, aiding in the selection of plants for genetic improvement (Martins *et al.*, 2013; Carmona *et al.*, 2015; Chagas *et al.*, 2016; Maciel *et al.*, 2018).

The Use of Regression for Behavior Modeling and Simulation

One of the most commonly used modeling techniques in the study of biosystems is regression analysis. Regression analysis allows the relationship of one or more independent variables to a dependent variable, facilitating the understanding of interactions that occur during different processes, simplifying the approach while maintaining the reliability of the results presented (Chatterjee, Hadi, 2012; Sarstedt, Mooi, 2019; Fachi *et al.*, 2020; Sgarbossa *et al.*, 2024).

Among regression models, the linear and quadratic models stand out. The linear regression model enables estimating the rate that represents the dependence between the response

variable and the explanatory variable, providing support to measure the efficiency of a process through this relationship. In agricultural studies, in some cases, this rate helps characterize the maximum agronomic efficiency of cultivars (Arenhardt *et al.*, 2017; Alessi *et al.*, 2018; Sgarbossa *et al.*, 2024).

Quadratic regression analysis allows the optimization of different processes either by maximizing or minimizing the variable of interest. In estimating an optimal point, where economic factors are not considered, the maximum technical efficiency is determined. However, when product cost and consumption factors for a given situation are involved, the maximum economic efficiency is estimated (Silva *et al.*, 2015; Uchôa *et al.*, 2018; Peter *et al.*, 2024). In the agricultural field, Costa *et al.* (2017) demonstrated the possibility of using the linear model to represent the estimation of the grain productivity rate. Scremin *et al.* (2017) used this same type of modeling to estimate daily biomass gain per hectare in white oats. Mamann *et al.* (2017) used quadratic regressions to estimate the optimal nitrogen dose for grain production and yield expectation when using biopolymers added to the soil. Brezolin *et al.* (2017) and Costa *et al.* (2017) demonstrated the possibility of using quadratic regressions to simulate grain yield and estimate the optimal fertilizer point. Santos *et al.* (2013) used regressions to analyze the dynamics of nitrogen use in black oat as a soil cover in no-till planting systems.

Multiple linear regression is a distinct regression model because it allows the inclusion of both controlled and uncontrolled effects in the simulation process, enabling a satisfactory explanation of the relationship between these effects and the dependent variable (Brezolin *et al.*, 2016; Scremin *et al.*, 2017; Pansera *et al.*, 2021). Thus, it is cited in numerous applications across various fields (Mamann *et al.*, 2017; Marolli *et al.*, 2018; Peter *et al.*, 2024). Multiple linear regression supports the optimization of simulations for predicting agricultural yields and more sustainable management in the soil-plant-atmosphere interaction (Carmona & Berlato, 2002; Scremin *et al.*, 2017; Marolli *et al.*, 2021).

The use of response surface regression also stands out as an efficient optimization technique that enables simulations of important processes related to resource use efficiency in agriculture. This model allows the simulation of the variable of interest considering two quantitative effect factors, proposing the optimization of the combined elements (Brezolin *et al.*, 2017; Alessi *et al.*, 2021). Scremin *et al.* (2017), using response surface methodology in studies with oats, observed optimized combinations of hydrogel and nitrogen at 60 and 80 kg ha⁻¹, respectively, in the soybean/oat system. Similarly, Mamann *et al.* (2017b), using response surface

in wheat, suggested the combination of 64 and 88 kg ha⁻¹ of hydrogel and nitrogen, respectively, for maximum technical efficiency in grain yield in the soybean/wheat system

Araújo *et al.* (2016) analyzed acerola juice pasteurization using response surface methodology, varying the time and temperature of the heat treatment. Tonon *et al.* (2006) used response surface to evaluate the influence of variables on the osmotic dehydration of tomatoes. Mattos Junior *et al.* (2004), using response surface methodology, assessed nutrient demand and established fertilizer doses to maximize tangerine yield and quality. Therefore, the use of regression models aims to analyze the behavior of the study object and promote simulations, aiding decision-making, while the use of response surface methodology allows the evaluation of factor effects and their interactions on the response variable, assisting in process optimization.

Regression analysis can also support models that enable the interpretation and evaluation of adaptability and stability traits of cultivars in response to meteorological variations and treatment factors. Among the models, those of Eberhart & Russell and Cruz, Torres & Vencovsky can be mentioned, which estimate the mentioned characteristics through the calculation of an environmental index, allowing for the interpretation and description of more efficient, adapted, and stable processes (Carvalho *et al.*, 2014; Lara *et al.*, 2019; Moura *et al.*, 2021).

Reais Systems Represented by Differential Equations

Several real-world systems can be represented by a differential equation. This equation, which contains an unknown function and some of its derivatives, can be formulated either through intuitive reasoning about the phenomenon or based on a physical law supported by experimental evidence. One of the applications of differential equations is in representing the progression of foliar diseases (Stewart, 2013; Montanher, 2021).

Solving a differential equation that represents the progression of a foliar disease makes it possible to highlight the relationship between the disease and time. In addition, it can facilitate the understanding and analysis of experimental data, as well as enable predictions of future epidemic levels, allowing for the development of control strategies (Chang, Phin, Mun, 2018; Mcharo *et al.*, 2024). In the literature, different models are used to represent disease progression, such as the Monomolecular, Exponential, Logistic, Gompertz, and Richards models (Campbell, Madden, 1990; Medina *et al.*, 2009; Hinnah *et al.*, 2018).

"Due to their specific characteristics, each model is applied according to the features of

the epidemic, making them more efficient in representing the progression of the targeted disease. When a disease progress curve is available, a quantitative indicator of the plant's resistance to the pathogen can be calculated based on the area under the disease progress curve (Jeger, Viljanen-Rollinson, 2001; Chang, Phin, Mun, 2018; Mcharo *et al.*, 2024). Measuring a single resistance component provides an important indicator during cultivar selection and speeds up the selection process in breeding programs (Chaves, Martinelli, Federizzi, 2004; Alves *et al.*, 2017; Garcia-Abadillo *et al.*, 2023). In addition to disease progress simulation models, the literature includes models capable of predicting the onset of an infection/epidemic (Bebber, Castillo, Gurr, 2017).

Models for predicting the onset of an infection or disease risk are widely disseminated in the literature and often are based on disease progress models. In foliar diseases affecting different cultivars, disease onset prediction models are based on meteorological factors such as precipitation, relative humidity, and temperature, as these are key factors in the development and initiation of various diseases (Xu, 1999; Audsley, Milne, Paveley, 2005; Pereira *et al.*, 2023). In oat cultivation, the main diseases affecting the crop are leaf rust and helminthosporiosis. Both are fungal, polycyclic diseases caused by the fungi *Puccinia coronata* Cda. f.sp. *avenae* and *Drechslera avenae* (Eidam) El Sharif, respectively (Nerbass Junior *et al.*, 2010; Nazareno *et al.*, 2017). Leaf rust is the main disease of oats, potentially causing a significant reduction in grain yield. The parasite causing the disease survives in the field through infection of volunteer plants that remain after harvest (Chaves, Martinelli, 2004; Nazareno *et al.*, 2017; Tremea *et al.*, 2024). It is a polycyclic disease that completes its cycle in 7 to 10 days in regions with leaf wetness periods of 6 hours and average temperatures between 16 and 18 °C. Similarly, the pathogen causing helminthosporiosis survives in crop residues, infected seeds, and volunteer plants. The disease symptoms are broad, elliptical leaf spots with yellow, brown, or purple coloration. Under favorable conditions, the fungus advances to the bracts and panicles, establishing itself in the grains, where it persists from one year to the next. The greatest damage potential of this disease occurs at temperatures between 18 and 28 °C, associated with a minimum of 30 hours of leaf wetness, particularly during the final stages of the crop (Kimati *et al.*, 1997; Nazareno *et al.*, 2017; Basso *et al.*, 2022). Thus, the logistic model, suitable for polycyclic diseases, can help in understanding the behavior and development of leaf rust and helminthosporiosis in different oat cultivars.

The determination of the AUDPC can quantify a resistance indicator for each cultivar, aiding in the identification of cultivars most resistant to foliar diseases. The epidemic risk

prediction models of Audsley, Milne, and Paveley, as well as the generic infection model, can enable prior and real-time knowledge of pathogen infestation among cultivars based on local meteorological conditions, providing support for control decision-making. Magarey, Sutton, and Thayer (2005) proposed a generic mathematical model for foliar fungal diseases in various plants. This model is based on temperatures and minimum and optimal relative humidity values required to maintain leaf surface wetness, conditions essential for pathogen development. Audsley, Milne, and Paveley (2005) proposed a decision support model for managing foliar disease in wheat, based on the logistic disease progress model.

Similarly, Xu (1999) proposed a prediction model for powdery mildew epidemics in apple trees, based on the logistic model, considering precipitation, relative humidity, and temperature. Mohapatra *et al.* (2008) successfully tested the suitability of the Logistic and Gompertz models in representing rice blast in 42 rice genotypes. Aghajani, Nafaine, and Alizadeh (2010) used the Logistic, Monomolecular, Exponential, and Gompertz models to represent the progress of *Sclerotinia* stem rot in canola, identifying the model that best fit the data representation.

Chang, Phin, and Mun (2018) applied the Monomolecular, Exponential, Logistic, and Gompertz models to represent the progress of black pod disease in cocoa plants, along with the calculation of the AUDPC, to quantify the plants' resistance to the pathogen. Chaves, Martinelli, and Federizzi (2004) demonstrated quantitative resistance to leaf rust in 31 white oat genotypes through the calculation of the AUDPC. Mukherjee, Mohapatra, and Nayak (2010) estimated the AUDPC in rice, considering only two data points. Chaves, Martinelli, and Federizzi (2004) demonstrated quantitative resistance to leaf rust in 31 white oat genotypes through the calculation of the AUDPC. Mukherjee, Mohapatra, and Nayak (2010) estimated the AUDPC in rice, considering only two data points. Jeger and Viljanen-Rollinson (2001) validated the estimation of the AUDPC from two points as an indicator equivalent to quantitative resistance calculated from multiple repetitions. Alves *et al.* (2017) estimated the AUDPC of tomato late blight using artificial neural networks. Bebbber, Castillo, and Gurr (2017), based on the generic infection model, modeled the risk of coffee rust considering local meteorological data.

Mathematical Model of Mass Flow by Diffusion: Fick's Laws

Mathematical models are essential for understanding numerous phenomena (Rosa *et al.*, 2006). The success of models developed to describe solute transport in soil largely depends on

the reliability of the transport variables involved (Alcântara & Camargo, 2001; Prezott *et al.*, 2012; Santos *et al.*, 2023). The diffusive mass transfer process was studied by Adolf Fick (1829–1901), and it indicates that diffusion occurs due to the concentration gradient present in a fluid; that is, the solute dissolved in water moves from an area of higher concentration to an area of lower concentration, aiming to equalize the concentration throughout the fluid mass (Pizarro, 2009; Do Rosário *et al.*, 2015).

The equations developed for mathematical models of solute transport in soil have been used to: (a) evaluate the time required for a solution with a given concentration to reach a certain depth, and (b) calculate the concentration in the solution at a given time and depth, knowing the concentration in the input liquid (Alcântara & Camargo, 2001; Santos *et al.*, 2023). The factors controlling the final fate of an element—whether it will precipitate as an insoluble phase, be adsorbed onto the surface of another phase, or be released, transported, and eventually absorbed by plants—depend essentially on geological, climatic, physicochemical, and biological conditions (Bini *et al.*, 2011; Haddad *et al.*, 2013; Qim *et al.*, 2023).

Among the main physical attributes that influence the transport mechanism are the relative distribution of soil pore size, its degree of water saturation, and the amount of water percolating through the soil profile, which depends on the amount and intensity of rainfall and the soil's water retention capacity. The main chemical aspects are the concentration of the soil solution, pH, cation exchange capacity, dissolution/precipitation reactions, and ionic exchanges between nutrients in the solution and those in the solid phase during the transport process (Bolzani; Oliveira; Lautenschlager, 2012; Andreguetto *et al.*, 2015; Peter *et al.*, 2024).

Mass flow occurs by diffusion, known as Fick's laws. These laws have been used in various fields to solve different problems. Andrade *et al.* (2000) and Nilsson *et al.* (2000) state that the behavior of chloride penetration in concrete, after the formation of the peak, continues with behavior similar to the solution of Fick's second law, considering the chloride content at the peak as constant. Where the effective diffusivity equation is the analytical solution to Fick's second law (Brooker *et al.*, 1992; Kumar *et al.*, 2023).

Oliveira *et al.* (2004) state that diffusion was the main transport mechanism of K in the soil, contributing 72 to 96% of the total absorbed by cotton plants. Rosa *et al.* (2006), using Fick's second law, demonstrate that the migration of packaging components is strongly dependent on their initial concentration profile of chemical components present in the packaging. Brito *et al.* (2011), using Fick's law, modeled the differential equation of the diffusion model of molecules

through a cell membrane. Silva *et al.* (2014) determined the effective diffusivity of pigeon pea grain through Fick's second law.

Process Simulation by Computational Intelligence: Fuzzy Logic

Walter *et al.* (2010) highlight that models simulating development can be used to assess crop performance under different conditions, regardless of how they are generated and tested. In this sense, the mathematical modeling of productive processes has been gaining ground in agricultural research (Lara & Pedreira, 2011; Reginatto *et al.*, 2024).

Siqueira *et al.* (2000) verified, through simulation in wheat, corn, and soybean, projections for the year 2050 based on meteorological variations. An ideal development model should be capable of quantitatively describing how genetic and environmental factors interact throughout the crop development cycle (Franceschi *et al.*, 2010; Costa *et al.*, 2017; Peter *et al.*, 2024). Before the emergence of methods based on Computational Intelligence, only statistical methods were used for forecasting (Medeiros *et al.*, 2016). Therefore, new data processing and simulation techniques, such as fuzzy logic and artificial neural networks, have been used to estimate parameters or explain the development of complex systems.

Computational intelligence techniques, such as artificial neural networks and fuzzy logic, have been gaining prominence for managing large amounts of linear and nonlinear data and do not depend on complex simulation models. Fuzzy models are techniques that allow the description of complex systems with linear and nonlinear behaviors, produced from rules that must be developed by experts, providing their experience to the creation of an inference system of the type 'If <condition> Then <result>' (Silva *et al.*, 2014a; Barros & Bassanezi, 2010; Reginatto *et al.*, 2024).

Medeiros *et al.* (2016) successfully used artificial neural networks and fuzzy logic to define energy system planning, providing necessary information for experts in the electrical sector to allocate available resources. Soares *et al.* (2015) developed a simulation model using artificial neural networks to estimate corn productivity, considering leaf area index, total green matter, plant height, and the number of plants per square meter.

Vendruscolo *et al.* (2015) used artificial neural networks to develop a model for estimating the height of eucalyptus trees. Villela *et al.* (2007) modeled, using fuzzy set theory, the fuzzy medical diagnosis of childhood diseases such as chickenpox, mumps, whooping cough,

and meningitis. Brezolin *et al.* (2020), aiming to use fuzzy logic to simulate wheat productivity under conditions of nitrogen use along with air temperature and rainfall effects, found that the membership functions and linguistic values established for the input and output variables are suitable for the use of fuzzy logic. Fuzzy logic efficiently simulates wheat grain productivity under nitrogen usage conditions, air temperature, and rainfall in cropping systems.

Pattern Recognition and Simulation by Artificial Intelligence: Neural Networks

Artificial Neural Networks (ANNs) are a tool within the field of artificial intelligence capable of learning and generalizing knowledge through logical-mathematical structures, using experimental data (Fernandes, 2005; Dornelles *et al.*, 2018; Lu *et al.*, 2024). This designation stems from the fact that its structure is based on the connection of biological neurons. Learning in an artificial neural network is carried out through the successive presentation of examples (samples), allowing information to be extracted regarding the relationships existing between the variables that influence a particular event or dependent variables (Silva *et al.*, 2018; Xu *et al.*, 2024). In this way, the use of ANNs enables the development of simulation models capable of estimating results based on common characteristics identified in the input variables (Soares *et al.*, 2015; Lu *et al.*, 2024).

Artificial neural networks (ANNs) are computational models inspired by the biological nervous system, meaning they learn from experience (Wasserman, 1989; Bucene & Rodrigues, 2004; Argenta *et al.*, 2020). The ability to learn through examples and generalize the learned information is the main appeal of solving problems using ANNs. The generalization, which is associated with the network's capacity to learn from a limited set of examples and subsequently provide coherent responses to unknown data, demonstrates that ANNs go beyond simply mapping input-output relationships. Networks are organized according to the number of layers that make up their typological structure. Thus, there are single-layer neural networks, consisting of a group of neurons arranged in only one layer, and multilayer networks, formed by the combination of several single-layer networks (Soares *et al.*, 2015; Xu *et al.*, 2024).

According to Silva *et al.* (2009), obtaining the appropriate neural network architecture depends on numerous trials to generate satisfactory results, since this process is random; that is, the number of neurons per layer is not based on any criterion, but rather on trial and error. One aspect to consider is that the Neural Network can accept different input data. Thus, data collected

in the field, such as topographic conditions and measurements, soil parameters, biomass values, crop development stages, etc., can also be used as a source for defining and contextualizing a specific target, which is important in the task of memorizing thematic features (Depiné *et al.*, 2013; Argenta *et al.*, 2020). In light of this, it is believed that ANNs can predict the productivity, chemical quality, and industrial quality of wheat grains considering the use of nitrogen and hydrogel combined with actual cultivation conditions, especially climatic factors. Supporting this, Mumbach *et al.* (2017) state that the increase in yield of a given crop results from the combination of various factors, including the use of cultivars adapted to local conditions, good soil fertility, weather conditions, and rigorous pest and disease management. Oliveira *et al.* (2013) used artificial neural networks in the classification of autotetraploids of banana (*Musa acuminata* Colla). Aruda *et al.* (2013) employed ANNs to obtain a digital soil map by using correlations between mapping units and environmental covariates.

Silva *et al.* (2014) found satisfactory output performance using neuro-fuzzy modeling to estimate wheat productivity based on nitrogen fertilization. Soares *et al.* (2015), studying maize productivity using ANNs, observed no difference between the estimated and observed grain yield values. The excellent results already achieved through artificial neural networks are due to their intrinsic characteristics that make them suitable for solving different problems. Artificial intelligence can accurately assist in understanding and optimizing cultivation technologies by precisely simulating important variables in complex systems of plant production (Soares *et al.*, 2015; Xu *et al.*, 2024).

Process Optimization by Genetic Algorithms: Stochastic Search

Within the scope of artificial intelligence are optimization methods. These techniques are used in different fields of knowledge in order to find a solution to a given problem, identifying the optimal point that either maximizes or minimizes the variable of interest. One of the optimization techniques based on artificial intelligence that has been used is the genetic algorithm method (Fonseca *et al.*, 2017; Metawa *et al.*, 2017; Doumpos *et al.*, 2023). Considered a stochastic search method, genetic algorithms represent an optimization process based on the biological processes of species evolution, mathematically simulating Darwin's theory (Salvino *et al.*, 2015; Metawa *et al.*, 2017; Doumpos *et al.*, 2023).

Starting from the generation of a population formed by a random set considered as

possible solutions to the problem, this population is evaluated during the evolutionary process, where individuals with the best evaluation scores are selected to generate a new population. These selected individuals may undergo modifications in their fundamental characteristics through crossover, mutations, or genetic recombinations, producing offspring for the next generation. This process is repeated until a satisfactory solution to the problem is found. In this way, the main advantage of using the genetic algorithm is that it is a general-purpose technique that can be applied to solve problems across various fields of knowledge (Sivanandam & Deepa, 2008; Abdelrazek *et al.*, 2024).

Genetic algorithms are stochastic search methods that represent an optimization process based on the biological processes of species evolution, mathematically simulating Darwin's theory (Salvino *et al.*, 2015; Rocha *et al.*, 2025). According to experts, optimization has been applied internationally since the 1980s, due to advances in computational technology. Furthermore, the authors highlight that only from the second half of the 2000s has there been a growing interest in studies in the field of optimization. Therefore, the main advantage of using the genetic algorithm is that it is a general-purpose technique, allowing it to solve problems across various fields of knowledge (Sivanandam & Deepa, 2008; Abdelrazek *et al.*, 2024).

Salvino *et al.* (2015) found that the use of the genetic algorithm is a tool capable of optimizing processes in which the number of variables is quite significant (ROCHA *et al.*, 2025). Fonseca *et al.* (2017) used the optimization process, which proved to be an effective strategy for identifying formal design solutions that meet two proposed objectives: finding a building volumetry with good thermal performance and reduced costs within a set of predetermined conditions. Gasparetto *et al.* (2010) applied the genetic algorithm technique to analyze risk factors associated with malaria incidence. Costa Filho & Poppi (2002) used genetic algorithms for variable selection in infrared spectroscopy for the simultaneous determination of glucose, maltose, and fructose.

Leite *et al.* (2006) found, through the genetic algorithm technique, an individualized representation of the power plants. In addition to being relatively simple to apply, the increase in the number of plants did not affect the efficiency of the algorithm—something that often occurs when traditional optimization techniques are used. Almeida & Kagan (2010) applied genetic algorithms and fuzzy sets in the design of systems for monitoring short-duration voltage variations in electric power transmission networks. Konzen *et al.* (2003) used genetic algorithm and tabu search methods to optimize the quality of active ingredients in pharmaceuticals.

Catarina *et al.* (2002) used genetic algorithms to optimize the profit of an agricultural property. Furthermore, the authors compared the optimization results obtained using the genetic algorithm with those obtained through a deterministic method, the Simplex method, and found that the genetic algorithm was more efficient.

CONCLUSION

Mathematical models aiming for efficient simulations, describing complex interactions along with the nonlinear effects of agroecosystems, have been increasingly sought after. These models have primarily contributed to the physiological understanding of crops and the development and validation of new technologies, a condition that has been evolving as experimentation efforts increase.

Natural phenomena along with biological processes, as they represent data that behave imprecisely, require efficient models that facilitate the understanding of these connections, with the possibility of simulations a fundamental strategy in scientific and technological advancement in the pursuit of increasingly sustainable agriculture.

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