

Analysis of influential points in decreasing curves applied to corn kernel drying

Abstract – The objective of this work was to identify and evaluate influential points for the analysis of corn kernel drying curves. Classical influential points derived from nonlinear models fitted to drying kinetics were analyzed. In addition, a new influential point was proposed to determine the time to interrupt drying, when moisture content reached 13%. The Lewis, Overhults, Page, three-parameter simple exponential, and Midilli models were applied to corn kernel drying data. The selection of the best models was based on the adjusted coefficient of determination and the Akaike information criterion. The times associated with the influential points were estimated using the confidence intervals obtained with the bias-corrected and accelerated bootstrap method. Among the evaluated models, the Page model allowed the identification of all influential points and provided a physically consistent interpretation of drying behavior. Initial influential points represented a higher kinetic efficiency, while the asymptotic deceleration point indicated transition to a stabilization regime. The proposed influential point shows narrow confidence intervals and a low model dependence, indicating robustness and operational relevance.

Index terms: *Zea mays*, bootstrap method, curve fitting, drying kinetics, moisture content, nonlinear regression models.

Análise de pontos influentes em curvas de decrescimento aplicadas à secagem de grãos de milho

Resumo – O objetivo deste trabalho foi identificar e avaliar pontos influentes para análise de curvas de secagem de grãos de milho. Foram analisados pontos influentes clássicos derivados de modelos não lineares ajustados à cinética de secagem. Além disso, foi proposto um novo ponto influente para determinar o tempo de interromper a secagem, quando o teor de umidade atingisse 13%. Os modelos de Lewis, Overhults, Page, exponencial simples de três parâmetros e de Midilli foram aplicados aos dados de secagem de grãos de milho. A seleção dos melhores modelos foi baseada no coeficiente de determinação ajustado e no critério de informação de Akaike. Os tempos associados aos pontos influentes foram estimados com os intervalos de confiança obtidos por meio do método bootstrap, com correção de viés e aceleração. Entre os modelos avaliados, o modelo de Page permitiu a identificação de todos os pontos influentes e forneceu uma interpretação fisicamente consistente do comportamento de secagem. Os pontos influentes iniciais representaram maior eficiência cinética, enquanto o ponto de desaceleração assintótica indicou a transição para o regime de estabilização. O ponto influente proposto apresenta intervalos de confiança estreitos e baixa dependência do modelo, indicando robustez e relevância operacional.

Termos para indexação: *Zea mays*, método bootstrap, ajuste de curvas, cinética de secagem, teor de umidade, modelos de regressão não linear.

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Received

August 19, 2025

Accepted

April 8, 2026

How to cite

GONZAGA, N. de A.; GENARO, R.; SILVA, E.M.; MUNIZ, J.A.; FERREIRA, D.F. Analysis of influential points in decreasing curves applied to corn kernel drying. *Pesquisa Agropecuária Brasileira*, v.61, e04220, 2026. DOI: <https://doi.org/10.1590/S1678-3921.pab2026.v61.04220>.

Introduction

Several specific technical parameters, such as air temperature and grain moisture content, must be monitored and controlled during grain drying to prevent quality and preservation losses (Timm et al., 2020a, 2020b). Considering its kinetics, the drying rate gradually decreases until moisture reduction stabilizes near a lower asymptote, mimicking growth processes where acceleration tends to zero (Mischan et al., 2011). This behavior underscores the need of defining a drying endpoint criterion.

In food drying studies, nonlinear models have been shown to be efficient tools, providing good data fit and biologically meaningful parameter estimates (Furtado et al., 2019; Costa et al., 2022; Gonzaga et al., 2024a, 2024b, 2026). In this scenario, identifying influential points (including inflection point, maximum acceleration point, maximum deceleration point, and asymptotic deceleration point) is highly useful. In grain drying, for example, the asymptotic deceleration point marks the optimal time to end the process, beyond which the moisture removal rate becomes negligible, marking an asymptotic behavior (Teixeira et al., 2021).

In growth modeling, influential points indicate points of acceleration and deceleration in the increase of the study variable (Teixeira et al., 2021). However, when transposing this approach to decreasing curves, the patterns shift: maximums become minimums and vice versa, mirroring the dynamics of processes involving the reduction in a given magnitude over time, such as organic matter breakdown, depletion of natural resources, and population decline (Gomez et al., 2020). For this reason, influential points are not widely used in the case of decreasing curves, but in growth studies on fruits, vegetables, and animals (Sari et al., 2018; Carini et al., 2020; Diel et al., 2020; Teixeira et al., 2021). For growth curves, the critical points can be determined mathematically based on the function fitted to observational data (Mischan et al., 2011).

The objective of this work was to identify and evaluate influential points for the analysis of corn (*Zea mays* L.) kernel drying curves.

Materials and Methods

The used data were sourced from the research conducted by Timm et al. (2023). The P3016VYHR

yellow flint corn hybrid (Pioneer, Corteva Agriscience, Santa Cruz do Sul, RS, Brazil) was harvested during the 2019/2020 growing season in the municipality of Canguçu, in the state of Rio Grande do Sul, Brazil. Following harvest, the kernels were promptly packed in plastic bags and transported to a laboratory.

Kernels with an initial moisture content of $31.90 \pm 0.20\%$ on a wet basis were dried in a fixed-bed dryer at 80°C and 0.5 m s^{-1} airflow until reaching $13.00 \pm 0.20\%$, also on a wet basis (Timm et al., 2023). Corn kernel drying was described by the five following nonlinear models: Lewis (Lewis, 1921), Overhults (Souza et al., 2015), Page (Sun et al., 2016), three-parameter simple exponential (Ertekin & Yaldiz, 2004), and Midilli (Midilli et al., 2002), using the respective equations:

$$RU_i = \exp(-kt_i) + \varepsilon_i$$

$$RU_i = \exp(-(kt_i)^c) + \varepsilon_i$$

$$RU_i = \exp(-kt_i^c) + \varepsilon_i$$

$$RU_i = k_0 \exp(-kt_i) + a + \varepsilon_i$$

$$RU_i = k_0 \exp(-kt_i^c) + at_i + \varepsilon_i$$

where RU_i is the dimensionless moisture ratio at time t_i (min); k_0 is the initial condition; k is the drying rate; c is a dimensionless parameter; a is a constant; ε_i and ε_i are residuals with zero mean and variance.

The influential points used for the drying kinetics were: inflection point, maximum acceleration point, maximum deceleration point, and asymptotic deceleration point. The inflection point, where the second derivative equals zero indicating a change in curve concavity, was determined according to Mischan et al. (2011) and Teixeira et al. (2021). The maximum acceleration and deceleration points correspond to the maximum and minimum values of the model's acceleration, respectively, as identified by Mischan et al. (2011). The asymptotic deceleration point, showing process stabilization near the asymptote, was defined as in Mischan et al. (2011) and Mischan & Pinho (2014). An additional influential point was proposed here to indicate the time to interrupt drying, when moisture content reached the 13% recommended for safe storage (Mantovani & Pimentel, 2017; Timm

et al., 2023). This additional point was calculated by inverting the fitted model, $t = f^{-1}(0.13)$, or by the bisection method for models without an analytical inverse, such as that of Midilli (Burden & Faires, 1985). The relative position and sequence of these points within a sigmoidal drying curve are illustrated in Figure 1, aiding the interpretation of the drying phases from initial acceleration to asymptotic stabilization.

The estimates of the maximum acceleration and deceleration points can be obtained by calculating the third derivative of each studied model and identifying its two roots, whereas the asymptotic deceleration point can be determined by calculating the fourth derivative and setting it to zero.

For the Lewis model, the second, third, and fourth derivatives were obtained by the following equations, respectively:

$$\frac{d^2f(t)}{dt^2} = k^2 \exp(-kt)$$

$$\frac{d^3f(t)}{dt^3} = -k^3 \exp(-kt)$$

$$\frac{d^4f(t)}{dt^4} = k^4 \exp(-kt)$$

Since $k \neq 0$ and $\exp(-kt) \neq 0$ for any finite time t , none of the derivatives equal zero. This reflects the purely exponential nature of the Lewis model, which lacks inflection points or changes in the acceleration sign. Consequently, it is not possible to define inflection point, maximum acceleration, maximum deceleration, or asymptotic deceleration using the standard derivative root criterion. Furthermore, the model describes a drying process with a continuously decreasing rate and no distinct transitional phases.

For the Overhults model, the influential points were determined analytically. The inflection point was given by:

$$t = \left(\frac{c-1}{ck^c} \right)^{\frac{1}{c}}$$

Solving $f'''(t) = 0$ leads to a quadratic equation in $z = (kt)^c$.

For , the positive root

$$t_{\text{crit}} = \left(\frac{1}{k} \right) * \left[\frac{\left(3(c-1) + \sqrt{((5c-1)(c-1))} \right)}{2c} \right]^{\frac{1}{c}}$$

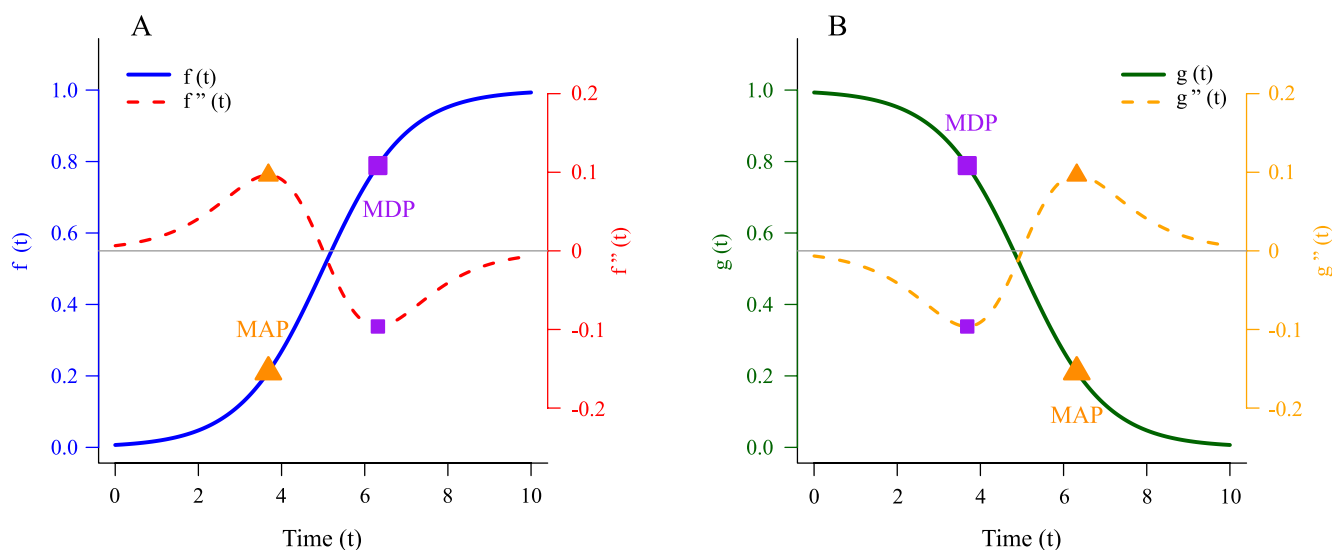


Figure 1. Schematic representation of critical points in sigmoidal corn (*Zea mays*) kernel drying curves, as follows: A, growth curve (increase in moisture content) and corresponding acceleration curve, highlighting the maximum acceleration point (MAP) and the maximum deceleration point (MDP); and B, decay curve (decrease in moisture content) and corresponding acceleration curve, also indicating the MAP and MDP. In both cases, the inflection point corresponds to the transition between the acceleration and deceleration phases of the process.

was identified as the maximum acceleration point, as confirmed by $f^4(t_{\text{crit}}) < 0$.

The asymptotic deceleration point, from $f^4(t) = 0$, is:

$$t_{\text{ADP}} = \left(\frac{1}{k}\right) * \left[\frac{\left(2(c-1) + \sqrt{((c-1)(3c-1))}\right)}{c} \right]^{\frac{1}{c}}$$

For the Page model, the influential points were also derived analytically. The inflection point was given by:

$$t = \left(\frac{c-1}{kc}\right)^{\frac{1}{c}}$$

The condition $f'''(t) = 0$ leads to the quadratic equation $c^2z^2 - 3c(c-1)z + (c-1)(c-2) = 0$, where $z = kt^c$. In addition, the two-time solutions

$$t = \left[\left(\frac{1}{k}\right) * \left(\frac{(3(c-1) \pm \sqrt{5c^2 - 6c + 1})}{2c} \right) \right]^{\frac{1}{c}}$$

correspond to the maximum and deceleration points. The asymptotic deceleration point was obtained from $f^4(t) = 0$, which reduces to the cubic equation $c^3z^3 - 6c^2(c-1)z^2 + 7c(c-1)(c-2)z - (c-1)(c-2)(c-3) = 0$. For $c > 1$, the solution is simplified to:

$$t_{\text{ADP}} = \left[\left(\frac{1}{k}\right) * \left(\frac{(6(c-1) + \sqrt{(c-1)(c+7)})}{2c} \right) \right]^{\frac{1}{c}}$$

For the three-parameter simple exponential model, the inflection point was analytically determined by the equation:

$$\frac{d^2f(t)}{dt^2} = k_0 k^2 \exp[-kt]$$

Since $k_0 \neq 0$, $k \neq 0$, and $\exp[-kt] \neq 0$, there was no influential point.

The maximum acceleration and deceleration points were determined using the critical point equation:

$$\frac{d^3f(t)}{dt^3} = -k_0 k^3 \exp[-kt]$$

However, since $k_0 \neq 0$, $k \neq 0$, and $\exp[-kt] \neq 0$, there was no maximum acceleration or deceleration point in the model.

Mathematically, the asymptotic deceleration point is described as:

$$\frac{d^4f(t)}{dt^4} = k_0 k^4 \exp[-kt]$$

Since all terms remained nonzero, the aforementioned point does not exist in the three-parameter simple exponential model.

For the Midilli model, the inflection point was obtained by:

$$\frac{d^2f(t)}{dt^2} = 0 \Rightarrow t = \left(\frac{c-1}{kc}\right)^{\frac{1}{c}}$$

The third derivative was used to locate the maximum acceleration and deceleration points. Setting $f'''(t) = 0$ and substituting $z = kt^c$ resulted in the quadratic equation $-c^2z^2 + 3c(c-1)z - (c-1)(c-2) = 0$, whose positive roots correspond to:

$$t_{1,2} = \frac{1}{k^{\frac{1}{c}}} \left[\frac{3(c-1) \pm \sqrt{5c^2 - 6c + 1}}{2c} \right]^{\frac{1}{c}}$$

The asymptotic deceleration point was derived from the fourth derivative, resulting in the cubic equation: $-c^3z^3 + 7c^2(c-1)z^2 - 6c(c-1)(c-2)z + (c-1)(c-2)(c-3) = 0$, where $z = kt^c$; this point was defined as the largest real positive root.

In addition to the points determined by the analytical calculations, the Newton-Raphson numerical method (Nocedal & Wright, 2006) was applied to all models to check the accuracy of the analytically obtained results.

Given a model $f(t)$, an expression for t is determined such that, for a given value of y , $t = f^{-1}(y)$. According to Mantovani & Pimentel (2017) and Timm et al. (2023), $y = 0.13$ is considered the ideal value for defining the additional influential point in drying processes. Thus, this point was obtained for each model using the relation $t = f^{-1}(y)$. The four following equations, respectively,

present the analytical expressions of $f - 1(y)$ for the Lewis, Overhults, Page, and three-parameter simple exponential models:

$$t = \frac{-\log(0.13)}{k}$$

$$t = \frac{(-\log(0.13))^{\frac{1}{c}}}{k}$$

$$t = \left(\frac{-\log(0.13)}{k} \right)^{\frac{1}{c}}$$

$$t = \frac{-1}{k} \log \left(\frac{0.13 - a}{k_0} \right)$$

For the Midilli model, the used equation had no analytical solution, making it impossible to explicitly isolate t . Therefore, in this case, the additional influential point was determined using the bisection method.

Confidence intervals for the influential points were estimated by the bias-corrected and accelerated bootstrap method (Efron & Tibshirani, 1993; Ferreira, 2013), used to construct confidence intervals by resampling the data multiple times and fitting the model at each resampling, allowing more robust estimates of uncertainty (Ferreira, 2013). Model parameters were estimated via the least squares method, implemented

with the Gauss-Newton algorithm (Seber & Wild, 2003). The best models were selected based on the Akaike information criterion (Akaike, 1974) and adjusted coefficient of determination (Mischak & Pinho, 2014), with the lowest and highest values, respectively. Once selected, the drying curve and derivatives of each model were plotted. All statistical analyses were performed using the R software (R Core Team, 2024).

Results and Discussion

The drying rate parameter (k) of drying kinetics was consistent across the evaluated models, reflecting moderate kinetic conditions under the specific experimental setup (Table 1), in alignment with findings of studies on controlled-temperature drying (Costa et al., 2022; Gonzaga et al., 2024a). Other authors have linked parameter variations to differing air temperature, airflow, and initial moisture (Pereira Junior et al., 2025).

Most tested parameters presented intervals excluding zero, which indicates statistical significance. However, in the Midilli model, parameters k_0 and c were not significant since their intervals included 1, suggesting a limited contribution to explaining drying dynamics, while also supporting the observation that extra parameters do not always enhance model interpretability (Costa et al., 2022). Although narrow confidence intervals denote numerical precision,

Table 1. Estimates and 95% confidence intervals for the parameters of the models fitted to the drying kinetics of corn (*Zea mays*) kernels.

Model ⁽¹⁾	Parameter ⁽²⁾	Estimate	Lower limit	Upper limit
Lewis	k	0.0302	0.0295	0.0309
Overhults	k	0.0299	0.0293	0.0304
	c	1.0634	1.0318	1.0958
Page	k	0.0239	0.0212	0.0269
	c	1.0634	1.0318	1.0958
TPSE	k	0.0266	0.0259	0.0274
	k_0	1.0489	1.0392	1.0587
	a	-0.0541	-0.0648	-0.0438
Midilli	k	0.0300	0.0270	0.0333
	k_0	1.0000	0.9910	1.0109
	c	0.0979	0.9499	1.0103
	a	-0.0005	-0.0006	-0.0003

⁽¹⁾ TPSE, three-parameter simple exponential. ⁽²⁾ k , c , k_0 , and a , empirical parameters of the equations.

they do not alone ensure a meaningful physical interpretation, a key consideration for the analysis of influential points. This is an indicative that the identification of influential points in decreasing drying curves remains limited in the literature on drying. Therefore, the bootstrap confidence intervals for the times related to the influential points identified in the drying curves constitute a central contribution of the present study (Table 2).

For the Overhults, Page, and Midilli models, the inflection point occurred early, marking the transition to kinetic stabilization, consistent with diffusion-controlled drying where initial surface moisture removal causes rapid rate changes (Gomez et al., 2020; Rickli et al., 2023). The subsequent maximum acceleration point was identified within 1–13 min, representing the period of the most rapid rate increase and optimal energy efficiency, indicating the importance of early-stage dynamics for overall efficiency (Gomez et al., 2020). The Page model uniquely identified the asymptotic deceleration point at advanced stages, signaling the onset of dominant internal diffusion resistance. The model's ability to detect this point later than the others underscores its capacity to represent final-stage kinetics, a phase that is qualitatively linked to reduced shrinkage and damage risk (Gomez et al., 2020); however, the asymptotic deceleration point or model dependence are still little quantified in the literature. In the present work, the identified point was shown to be highly model dependent, which establishes the Page model as the most suitable for a reliable physical interpretation of the mentioned critical stage, with implications for defining optimal drying conditions.

The proposed additional influential point, defined by a moisture ratio corresponding to 13%, exhibited

narrow and overlapping confidence intervals across all models, ranging approximately from 58 to 70 min. This result shows that this new point is robust and weakly dependent on the chosen model structure. Unlike derivative-based influential points, the additional influential point incorporates a technologically meaningful threshold widely adopted for safe grain storage. Furthermore, its consistent estimation across models indicates that drying stabilization occurs within a well-defined time window, reinforcing the relevance of this new point for operational decision-making (Gomez et al., 2020).

As observed analytically, the Lewis and three-parameter simple exponential models did not provide confidence intervals for the influential, maximum acceleration, and asymptotic deceleration points, which were consequently not identified in the model's drying curves. However, since both models provided an interval for the additional operational point, they are more suited for describing the latter part of the drying curve.

All models showed high values for the adjusted coefficient of determination (>0.996), confirming a good data fit (Table 3). However, differences were observed regarding the Akaike information criterion. Although the Midilli and three-parameter simple exponential models resulted in lower values, they were not selected for the dynamic analysis: the first produced complex values for influential points, compromising interpretability, whereas the second failed to identify such points. In contrast, the Page model, despite having a slightly higher Akaike information criterion, consistently identified all influential points and allowed the direct estimation of the bootstrap confidence interval. Therefore, its selection is justified on methodological and interpretative grounds, aligning

Table 2. Bootstrap confidence intervals for the times (in minutes) at the influential points of the models fitted to the drying kinetics of corn (*Zea mays*) kernels⁽¹⁾.

Model	IP	MAP	ADP	P1
Lewis	-	-	-	(66.07, 68.56)
Overhults	(2.29, 6.76)	(3.55, 13.29)	(34.78, 45.26)	(63.37, 67.00)
Page	(0.06, 2.74)	(1.31, 11.41)	(49.27, 63.16)	(58.93, 70.70)
TPSE	-	-	-	(63.72, 66.01)
Midilli	(0.13, 2.70)	(1.17, 12.18)	(6.95, 26.31)	(64.60, 70.00)

⁽¹⁾IP, inflection point; MAP, maximum acceleration point; ADP, asymptotic deceleration point; and P1, proposed additional influential point, to indicate when to interrupt drying.

with studies prioritizing model interpretability over purely statistical metrics (Costa et al., 2022; Gonzaga et al., 2024a).

Table 3. Evaluators of the goodness-of-fit of the models fitted to the drying kinetics of corn (*Zea mays*) kernels⁽¹⁾.

Model	R ₂ adj	AIC
Lewis	0.9966	-134.4544
Overhults	0.9982	-146.7625
Page	0.9982	-146.7625
TPSE	0.9996	-183.1653
Midilli	0.9996	-185.8832

⁽¹⁾R₂adj, adjusted coefficient of determination; and AIC, Akaike information criterion.

The drying dynamics were objectively interpreted using the four derivatives of the Page model (Figures 2 and 3). The first confirmed the highest initial drying rate, typical of diffusion-controlled processes (Gomez et al., 2020). The second enabled the identification of the influential and maximum acceleration points, characterizing the initial high-efficiency phase (Khalili et al., 2014). The third and fourth derivatives approached zero as drying progressed, indicating a transition to a stabilization regime limited by internal diffusion. The additional influential point proposed here (13% moisture) occurred near the asymptotic region of the curve, supporting its use as a practical threshold for safe storage and energy efficiency in industrial drying (Gomez et al., 2020). These results

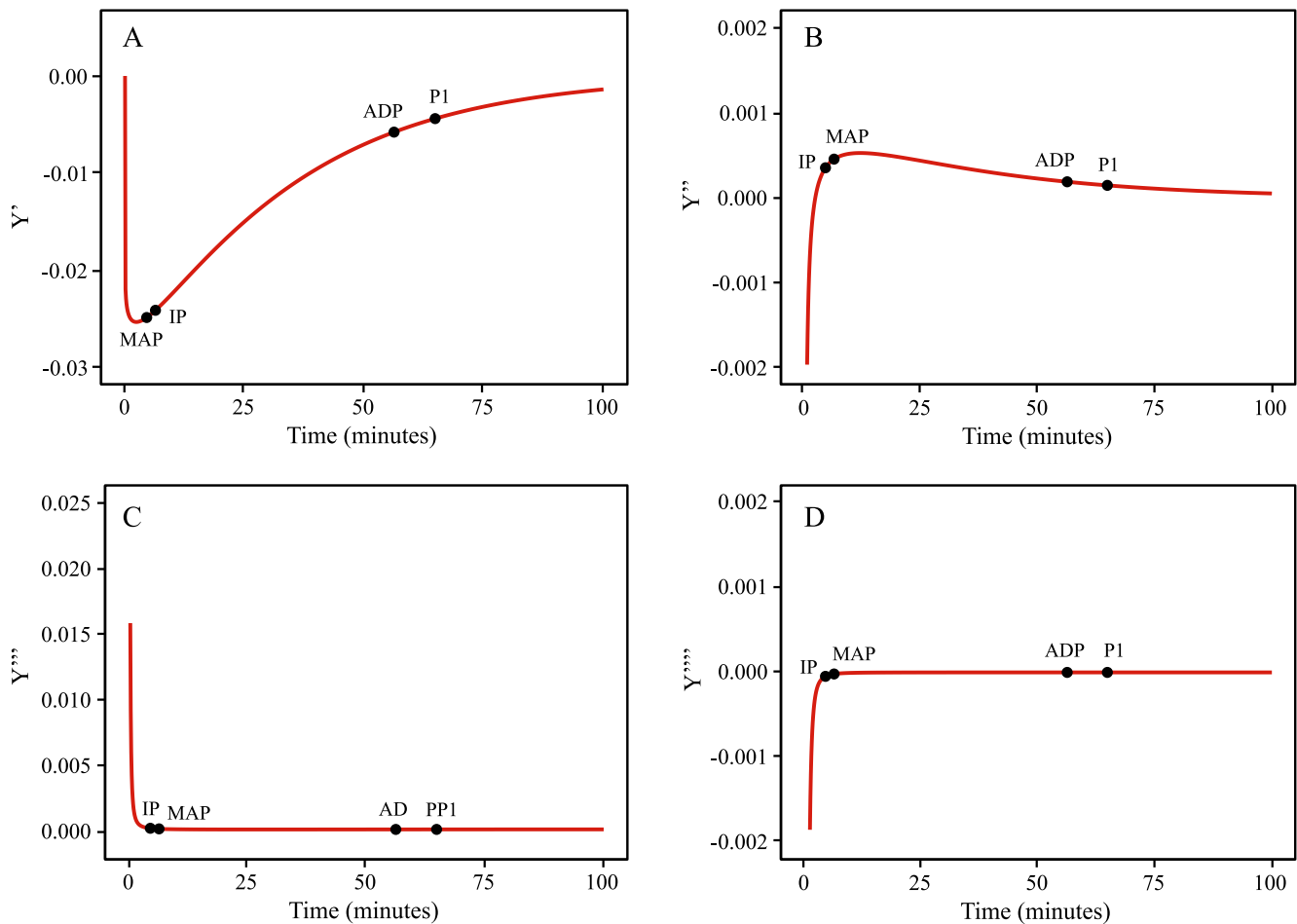


Figure 2. First (A), second (B), third (C), and fourth (D) order derivatives of the Page model used to describe the drying process of corn (*Zea mays*) kernels. IP, inflection point; MAP, maximum acceleration point; ADP, asymptotic deceleration point; and P1, proposed additional influential point, to indicate when to interrupt drying.

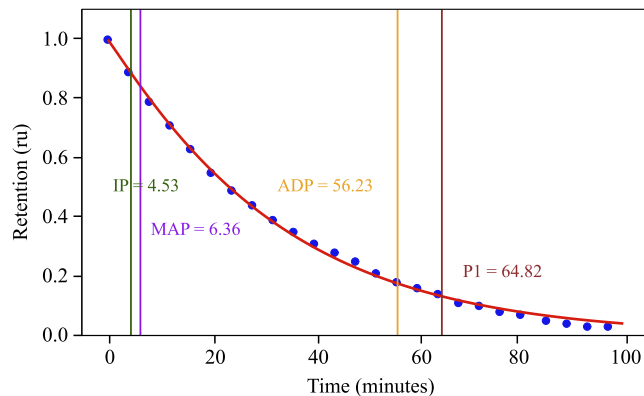


Figure 3. Drying curve of the Page model fitted to corn (*Zea mays*) kernel drying data. IP, inflection point; MAP, maximum acceleration point; ADP, asymptotic deceleration point; and P1, proposed additional influential point, to indicate when to interrupt drying.

are an indicative that the analysis of influential points complements traditional goodness-of-fit criteria by providing quantitative information on critical stages of the drying process, with a direct application in the definition of more efficient operating conditions.

Conclusions

1. The analysis of influential points enables an objective and quantitative identification of critical stages in corn (*Zea mays*) drying.
2. The Page model presents a mathematical structure suitable for describing drying kinetics and estimating influential points with a consistent physical interpretation.
3. The Lewis and three-parameter simple exponential models show limitations for a dynamic interpretation of the drying process.
4. The proposed additional operational influential point, defined by a moisture content of 13%, is a technically sound criterion for determining when to interrupt drying, contributing to optimizing the drying process and defining safer conditions for corn storage.

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Chief editor: Edemar Corazza

Edited by: Daniel Kinpara

Data availability statement

Data available upon request: research data are only available upon reasonable request to the corresponding author.

Declaration of use of AI technologies

During the preparation of this work, the author(s) used DeepSeek in order to correct grammatical errors and improve linguistic clarity. After this use, the author(s) reviewed and edited the content as needed and take(s) full responsibility for it.

Conflict of interest statement

The authors declare no conflicts of interest.

Acknowledgments

To Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), for financial support.

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