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A Mathematical Model for Weight Gain in Farm Animals based on Feed Diffusion and Digestibility

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Abstract

This study introduces a spatio-temporal mathematical model to predict weight gain in farm animals based on the diffusion and assimilation of feed within the organism. The model is formulated using a modified form of Fick's second law, incorporating spatially and temporally varying diffusion coefficient D(x,T) and feed digestibility parameter K(x,T), while accounting for the nonlinearity of the biological process and the influence of body temperature. An analytical solution is developed employing the method of averaging of function corrections up to the second-order approximation. This approach enables the determination of the spatio-temporal distribution of feed concentration, the mass of digested and undigested feed, and the portion of assimilated nutrients allocated to body weight increase versus maintenance requirements. The model successfully reproduces typical growth curves and demonstrates that increasing the diffusion coefficient or digestibility parameter enhances weight gain. Conditions for accelerating or decelerating the fattening process are formulated, offering a useful tool for optimizing feeding strategies and improving the efficiency of livestock production.

Keywords: Animal fattening, Weight gain, Feed diffusion, Fick's law, Averaging method, Spatio-Temporal model, Livestock productivity.

1 | Introduction

The development of the livestock sector plays a crucial role in ensuring global food security, supporting rural economies, and meeting the growing demand for high-quality animal protein. In modern production systems, the profitability and competitiveness of livestock farming depend heavily on the efficient utilization of advanced technologies, high-quality feeds, and biologically active additives. Numerous studies have shown that optimizing feeding strategies and improving nutrient utilization can significantly enhance animal growth performance, feed conversion efficiency, and overall productivity [1–6]. In this context, the use of stimulating additives and precision feeding regimes has emerged as a key strategy for increasing the efficiency of livestock production. However, predicting the growth dynamics of farm animals remains a challenging task due to the multifactorial and inherently nonlinear nature of biological processes involved in feed intake, digestion,

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absorption, and nutrient assimilation [1], [3], [4], [7], [8]. Traditional empirical models, while useful for practical applications, often fail to adequately capture the combined effects of spatial heterogeneity within the animal's body (e.g., differences in tissue permeability and blood flow) and temporal variations during the digestion and assimilation phases. Consequently, there is a pressing need for mathematically rigorous, mechanistic models that integrate these spatio-temporal dynamics and provide more accurate, predictive insights into weight gain mechanisms. Mathematical modeling has proven to be a powerful tool for analyzing complex biological systems in animal nutrition. Over the past decades, various approaches including empirical growth curves, compartmental models, and dynamic simulation models have been developed to describe live weight gain, nutrient partitioning, and feed efficiency in cattle, pigs, poultry, and other farm species [3], [5], [7]. In particular, diffusion-based models have been successfully applied in biological contexts to describe the transport and distribution of substances such as nutrients, gases, and metabolites within living tissues. Fick's laws of diffusion offer a fundamental physical framework for modeling mass transport driven by concentration gradients, and modified versions of these equations have been adapted to physiological processes ranging from intestinal absorption to intracellular nutrient movement.

In this regard, the application of a modified form of Fick's second law enables a realistic characterization of feed movement and nutrient transport processes inside the animal body. By incorporating spatially and temporally varying parameters such as the diffusion coefficient D(x,T) (which depends on tissue conditions and body temperature) and the feed digestibility parameter K(x,T) the model can better reflect real physiological conditions, including heterogeneity across organs and changes during the digestion process.

In this paper, we propose a spatio-temporal mathematical model for predicting weight gain in farm animals based on feed diffusion and assimilation processes. The model explicitly accounts for variations of key parameters in both space (within the organism) and time (during digestion), as well as the nonlinearity of the biological system. To solve the proposed model analytically, we employ the method of averaging of function corrections, which allows the derivation of approximate solutions with good accuracy for qualitative and quantitative analysis [9–15]. This approach facilitates the calculation of the spatio-temporal distribution of feed concentration, the masses of digested and undigested feed, and the portion of assimilated nutrients directed toward body weight increase versus maintenance requirements. Furthermore, the model is used to investigate the conditions under which the fattening process can be accelerated or decelerated by manipulating diffusion and digestibility parameters. By examining the influence of these parameters on nutrient assimilation and weight gain, the study provides practical insights for optimizing feeding strategies, reducing feed costs, and improving livestock productivity. Ultimately, the proposed approach contributes to the development of more efficient, scientifically grounded methods in modern animal production systems and supports the transition toward precision livestock farming.

2 | Method of Solution

In this section we consider a model to estimate and future analysis of spatio- temporal distribution of concentration of feed in an organism with account of possibility to take into account changing of conditions of assimilation of the feed. We determined the required of the spatio- temporal distribution of concentration of feed as solution of the second law of Fick in the following form.

$$\frac{\partial C(x,t)}{\partial t}=\frac{\partial}{\partial x}\left[D(x,T)\frac{\partial C(x,t)}{\partial x}\right]-K(x,T)\,C(x,t), \tag{1}$$

where C (x,t) is the spatio- temporal distribution of concentration of feed; D (x,T) is the diffusion of coefficient of feed (the value of which depends on the condition of the tissues in the body); K (x,T) is the parameter of feed digestibility in the organism of a farm animal; T is the temperature of organism. Initial and boundary conditions for concentration C (x,t) could be written as

$$\left.\frac{\partial C(x,t)}{\partial x}\right|_{x=0}=0;\ C(L,t)=0;\ C(x,0)=f_C(x). \tag{2}$$

We calculate solution of *Eq. (1)* with *Conditions (2)* by method of averaging of function corrections [7], [8], [16]. First of all we transform *Eq. (1)* to the following integral form.

$$C(x,t)=C(x,t)+\frac{1}{L^2}\left\{\int_0^t\int_0^x D(v,\tau)\,C(v,\tau)\,d\,v\,d\,\tau-\int_0^t\int_0^x(x-v)C(v,\tau)\frac{\partial D(v,\tau)}{\partial v}d\,v\,d\,\tau+\right.$$
$$\int_0^x(x-v)f(v)\,d\,v-\int_0^t\int_0^x(x-v)K(v,\tau)\,C(v,\tau)\,d\,v\,d\,\tau-\int_0^t\int_0^L D(v,\tau)C(v,\tau)\,d\,v\,d\,\tau- \tag{3}$$
$$\left.\int_0^x(x-v)\,C(v,t)\,d\,v+\int_0^L(L-v)\,C(v,t)\,d\,v+\int_0^t\int_0^L(L-v)C(v,\tau)\frac{\partial D(v,\tau)}{\partial v}d\,v\,d\,\tau\right\}.$$

In the framework of the method of averaging of function corrections we replace the required concentration on it's not yet known average value α_1 in the right side of the *Eq. (3)*. The replacement gives a possibility to obtain the first-order approximation of the considered feed in the following form.

$$C_1(x,t)=\alpha_1+\frac{1}{L^2}\left[\int_0^x(x-v)f(v)\,d\,v-\alpha_1\int_0^t\int_0^x(x-v)K(v,\tau)\,d\,v\,d\,\tau+\alpha_1\frac{L^2-x^2}{2}\right]. \tag{4}$$

Average value α_1 was calculated by the following standard relation [7], [8], [16].

$$\alpha_1=\frac{1}{L\Theta}\int_0^\Theta\int_0^L C_1(x,t)\,d\,x\,d\,t. \tag{5}$$

Substitution of the *Relation (4)* into *Relation (5)* gives a possibility to obtain the appropriate relation to determine the average value α_1 in the final form.

$$\alpha_1=\frac{\Theta\int_0^L\left(L^2-x^2\right)f(x)\,d\,x}{\int_0^\Theta(\Theta-t)\int_0^L\left(L^2-x^2\right)K(x,t)\,d\,x\,d\,t-2\int_0^\Theta(\Theta-t)\int_0^L x(L-x)K(x,t)\,d\,x\,d\,t-\frac{2}{3}\Theta L^3}. \tag{6}$$

The second-order approximation of the required concentration of feed in the framework of the method of averaging of function corrections was obtained by using standard replacing of the considered concentration in the right side of *Eq. (3)* on the following sum: $C(x,t)\rightarrow\alpha_2+C_1(x,t)$ [7], [8], [16]. The replacement gives a possibility to obtain the following relation to determine the required approximation of the considered concentration.

$$C_2(x,t)=\alpha_2+C_1(x,t)+\frac{1}{L^2}\left\{\int_0^t\int_0^x D(v,\tau)\left[\alpha_2+C_1(v,\tau)\right]d\,v\,d\,\tau-\int_0^t\int_0^x(x-v)\left[\alpha_2+C_1(v,\tau)\right]\times\right.$$
$$\frac{\partial D(v,\tau)}{\partial v}d\,v\,d\,\tau-\int_0^t\int_0^x(x-v)K(v,\tau)\left[\alpha_2+C_1(v,\tau)\right]d\,v\,d\,\tau+\int_0^L(L-v)\left[\alpha_2+C_1(v,t)\right]d\,v- \tag{7}$$

$$\int_0^t\int_0^L D(v,\tau)\left[\alpha_2 + C_1(v,\tau)\right]dv\,d\tau + \int_0^t\int_0^L (L-v)\left[\alpha_2 + C_1(v,\tau)\right]\frac{\partial D(v,\tau)}{\partial v}dv\,d\tau +$$

$$\left.\int_0^x (x-v)f(v)dv - \int_0^x (x-v)\left[\alpha_2 + C_1(v,t)\right]dv\right\}.$$

The average value α_2 of the second-order approximation of the required concentration of the considered feed was determined by using the following standard relation [8], [16], [17].

$$\alpha_2 = \frac{1}{L\Theta}\int_0^\Theta\int_0^L \left[C_2(x,t) - C_1(x,t)\right]dx\,dt. \tag{8}$$

Substitution of the *Relation (7)* into the *Relation (8)* gives a possibility to obtain the following relation to determine the required average value α_2.

$$\alpha_2 = \left[\frac{1}{2}\int_0^\Theta(\Theta-t)\int_0^L (L+x)^2 C_1(x,t)\frac{\partial D(x,t)}{\partial x}dx\,dt - \int_0^\Theta(\Theta-t)\int_0^L (x-v)D(x,t)C_1(x,t)\,dx\,dt +\right.$$

$$2\int_0^\Theta(\Theta-t)\int_0^L x^2 C_1(x,t)\frac{\partial D(x,t)}{\partial x}dx\,dt - \frac{1}{2}\int_0^\Theta(\Theta-t)\int_0^L (L+x)^2 K(x,t)\,C_1(x,t)dx\,dt -$$

$$2\int_0^\Theta(\Theta-t)\int_0^L x^2 K(x,t)C_1(x,t)dx\,dt - \frac{1}{2}\int_0^\Theta(\Theta-t)\int_0^L \left(L^2 - x^2\right)C_1(x,t)\frac{\partial D(x,t)}{\partial x}dx\,dt -$$

$$L\int_0^\Theta\int_0^L (L-x)C_1(x,t)dx\,dt - \int_0^\Theta\int_0^L x\,(L-x)f(x)dx\,dt + L\int_0^\Theta(\Theta-t)\int_0^L (L-x)D(x,t)C_1(x,t)dx\,dt +$$

$$\left.\frac{1}{2}\int_0^\Theta(\Theta-t)\int_0^L \left(L^2 + x^2\right)D(x,t)\,C_1(x,t)dx\,dt + 2\int_0^\Theta(\Theta-t)\int_0^L x^2 C_1(x,t)D(x,t)\,dx\,dt\right]\times \tag{9}$$

$$\left[\int_0^\Theta(\Theta-t)\int_0^L (x-v)D(x,t)\,dx\,dt - \frac{1}{2}\int_0^\Theta(\Theta-t)\int_0^L (L+x)^2\frac{\partial D(x,t)}{\partial x}dx\,dt + \frac{1}{2}\int_0^\Theta(\Theta-t)\times\right.$$

$$\int_0^L (L+x)^2 K(x,t)\,dx\,dt + 2\int_0^\Theta(\Theta-t)\int_0^L x^2 K(x,t)\,dx\,dt + 2\int_0^\Theta(\Theta-t)\int_0^L x^2\frac{\partial D(x,t)}{\partial x}dx\,dt +$$

$$\left.\Theta^2 L^3/4\right]^{-1}.$$

The second term in the *Eq. (1)* describes mass of digested feed. To determine value of the mass we transform *Eq. (1)* to the following integro-differential form.

$$\int_0^x C(v,t)\,dv = \int_0^t D(x,T)\frac{\partial C(x,\tau)}{\partial x}d\tau - \int_0^t\int_0^x K(v,T)C(v,\tau)\,dv\,d\tau + \int_0^x f_C(v)dv. \tag{10}$$

The limit passage $x \to L$ gives a possibility to obtain relation gives a possibility to obtain relation to determine value of different masses of feed: initial mass of feed, mass of digested feed and mass of not digested feed. Mass of not digested feed could be written as

$$M(t)=\int_0^L f_C(x)dx-\int_0^t\int_0^L K(x,T)C(x,\tau)\,dx\,d\tau. \tag{11}$$

Substitution of *Relation (9)* into *Relation (11)* gives a possibility to obtain relation to determine of mass of not digested feed in the following final form.

$$M_2(t)=\alpha_2\int_0^t\int_0^L K(x,T)dx\,d\tau+\int_0^t\int_0^L K(x,T)C_1(x,\tau)\,dx\,d\tau+\frac{1}{L^2}\int_0^t\int_0^L (L-x)K(x,T)D(x,\tau)\times$$
$$\left[\alpha_2+C_1(x,\tau)\right]dx\,(t-\tau)d\tau+\frac{1}{2L^2}\int_0^t\int_0^L K(x,T)\left(L^2-x^2\right)\left[\alpha_2+C_1(x,\tau)\right]\frac{\partial D(x,\tau)}{\partial x}dx\times$$
$$(t-\tau)\,d\tau-\frac{1}{L}\int_0^t(t-\tau)\int_0^L K(x,T)(L-x)\left[\alpha_2+C_1(x,\tau)\right]\frac{\partial D(x,\tau)}{\partial x}dx\,d\tau-\frac{1}{2L^2}\int_0^t(t-\tau)\times$$
$$\int_0^L K(x,T)\left(L^2-x^2\right)f(x)\,dx\,d\tau+\frac{1}{L}\int_0^t(t-\tau)\int_0^L(L-x)\,K(x,T)f(x)\,dx\,d\tau+\frac{1}{2L^2}\int_0^t(t-\tau)\times$$
$$\int_0^L K^2(x,T)\left(L^2-x^2\right)\left[\alpha_2+C_1(x,\tau)\right]dx\,d\tau-\int_0^t(t-\tau)\int_0^L(L-x)\left[\alpha_2+C_1(x,\tau)\right]K^2(x,T)\,dx\,d\tau\times \tag{12}$$
$$\frac{1}{L}+\frac{1}{L^2}\int_0^t\int_0^L(L-x)\left[\alpha_2+C_1(x,\tau)\right]dx\int_0^x K(v,T)dv\,d\tau-\int_0^t(t-\tau)\int_0^L\left[\alpha_2+C_1(x,\tau)\right]D(x,\tau)\,dx\times$$
$$\frac{1}{L^2}\int_0^L K(x,T)dx\,d\tau+\frac{1}{L^2}\int_0^t(t-\tau)\int_0^L(L-x)\left[\alpha_2+C_1(x,\tau)\right]\frac{\partial D(x,\tau)}{\partial x}dx\int_0^L K(x,T)dx\,d\tau-$$
$$\frac{1}{L}\int_0^t\int_0^L(L-x)K(x,T)\left[\alpha_2+C_1(x,t)\right]dx\,d\tau+\frac{1}{2L^2}\int_0^L\int_0^t K(x,T)\left[\alpha_2+C_1(x,t)\right]dt\times$$
$$\left(L^2-x^2\right)dx.$$

Mass of digested feed is other mass of feed. Part of the considered mass of feed is spent on the current needs of the considered organism. Another part of this mass of food is spent on increasing the body weight of the considered organism. Spatio-temporal distribution of concentration of the considered feed was analyzed analytically by using the second-order approximation in the framework of the method of averaging of function corrections. The approximation is usually a good approximation for to make qualitative analysis and obtaining some quantitative results. All obtained results have been checked by comparison with the results of numerical simulations. To enhance clarity and provide a structured overview, the main steps of the proposed solution procedure are summarized in *Table 1*.

Table 1. Main steps of the solution method for the feed diffusion–digestion model.

Step	Description	Equation/Output
1	Formulation of the mathematical model based on Fick's second law with digestion term	Eq. (1): PDE for (C(x,t))
2	Specification of initial and boundary conditions	Eq. (2): C(L,t)=0, C(x,0)=f_C(x)
3	Transformation of the differential equation into integral form	Eq. (3)
4	Substitution of the unknown concentration with its average value α_1	First-order approximation
5	Determination of the first-order approximation of concentration	Eq. (4)
6	Calculation of the average value α_1	Eqs. (5) and (6)

Table 1- Continued.

Step	Description	Equation/Output
7	Introduction of second-order approximation: $C(x,t) = \alpha_2 + C_1(x,t)$	Start of second-order refinement
8	Determination of the second-order approximation of concentration	Eq. (7)
9	Calculation of the average value α_2	Eqs. (8) and (9)
10	Transformation of the model to compute feed mass	Eq. (10)
11	Determination of undigested feed mass	Eq. (11)
12	Final expression for undigested mass using α_2	Eq. (12)
13	Analysis and validation of results using numerical simulations	Comparison with numerical results

3 | Results and Discussion

In this study, we investigated the growth dynamics of farm animals as a function of feed intake, considering the effects of both the diffusion coefficient D(x,T) and the digestibility parameter K(x,T). The analytical approach, based on the second-order approximation of the spatio-temporal distribution of feed concentration, allowed us to quantify the fractions of digested and undigested feed and their respective contributions to body weight gain. The results provide important insights into the mechanisms governing nutrient assimilation and weight growth in farm animals. *Fig. 1* and *Fig. 2* illustrate the typical dependencies of weight gain on the total feed mass mmm administered to the animal. These figures demonstrate how variations in feed properties influence the growth process. *Fig. 1* shows the effect of the diffusion coefficient D(x,T) on weight gain. Each curve represents a different value of diffusion, with higher-numbered curves corresponding to higher diffusion rates. As the diffusion coefficient increases, nutrients are more efficiently transported throughout the tissues, which accelerates assimilation and reduces the fraction of feed that remains undigested. The curves indicate a clear nonlinear trend: initial increases in diffusion result in substantial improvements in weight gain, but after a certain threshold, further increases in diffusion produce smaller gains. This nonlinear response reflects physiological limitations in nutrient absorption: once the majority of tissues receive adequate nutrient supply, additional diffusion does not significantly enhance growth. The pattern observed in *Fig. 1* also suggests an interaction between diffusion and feed mass. At lower feed quantities, increasing diffusion has a pronounced effect on growth, whereas at higher feed quantities, the relative impact diminishes slightly. This implies that efficient nutrient distribution is especially critical under conditions of limited feed intake. From a practical perspective, optimizing diffusion through feed formulation (e.g., particle size, feed processing) or feeding frequency can substantially enhance the efficiency of nutrient utilization. *Fig. 2* presents the effect of the digestibility parameter K (x,T) on growth. Higher-numbered curves correspond to greater digestibility. As expected, higher digestibility results in steeper growth curves, indicating that a larger proportion of ingested feed is converted into productive mass. The effect is particularly significant at lower feed levels, where small improvements in digestibility can result in noticeable increases in weight gain. At higher feed levels, the incremental impact of increased digestibility is somewhat reduced due to saturation of the digestive and metabolic capacity of the organism. These observations highlight the importance of feed quality in livestock management. While total feed mass is important, the fraction of nutrients that can actually be digested and utilized determines growth efficiency. Poorly digestible feed may lead to higher undigested fractions, which contribute little to weight gain and may even increase metabolic energy expenditure due to excretion processes. The interaction between diffusion and digestibility is a key factor in determining optimal growth. High diffusion alone is insufficient if digestibility is low because nutrients are widely distributed but not absorbed efficiently. Conversely, high digestibility with low diffusion results in localized nutrient accumulation, which may fail to reach all tissues effectively. Optimal growth is achieved when both parameters are balanced, ensuring that nutrients are both efficiently distributed and effectively absorbed. This insight provides a practical guideline for designing feed formulations and feeding strategies that maximize growth while minimizing waste. The model also enables the calculation of feed mass partitioning into digested feed, undigested feed, and feed allocated to maintenance versus growth. Higher diffusion and higher digestibility reduce the fraction of undigested feed and increase the proportion of feed contributing to growth. This quantitative partitioning allows for more precise evaluation of feeding strategies and can guide decisions about feed quality, quantity, and composition to achieve targeted growth outcomes. From a numerical perspective, the second-order approximation used in the analytical model produces results that closely match those obtained from numerical simulations, confirming the reliability of the approach. For instance, a 20% increase in the diffusion coefficient can lead to approximately 10%–15% higher weight gain, while a similar improvement in digestibility can result in 12–18% higher growth, depending on the feed mass. These figures highlight the relative sensitivity of animal growth to diffusion and digestibility and emphasize the importance of considering both factors in feed optimization. Finally, the results have important practical implications. Livestock producers can use these insights to enhance growth efficiency by carefully selecting feed with appropriate digestibility and implementing management practices that promote effective nutrient distribution within the animal. Moreover, understanding the nonlinear and interactive effects of diffusion and digestibility allows for more accurate economic planning, ensuring that investments in feed quality translate into tangible growth benefits. In conclusion, the analytical model provides a comprehensive framework for analyzing feed utilization and growth dynamics. By explicitly considering the spatio-temporal distribution of feed concentration, the model captures the complex interplay between diffusion, digestibility, and feed mass, providing actionable insights for both scientific understanding and practical livestock management. Future studies could extend the model to account for variable environmental conditions, heterogeneous tissue absorption, and stochastic feeding behavior to further enhance predictive capability.

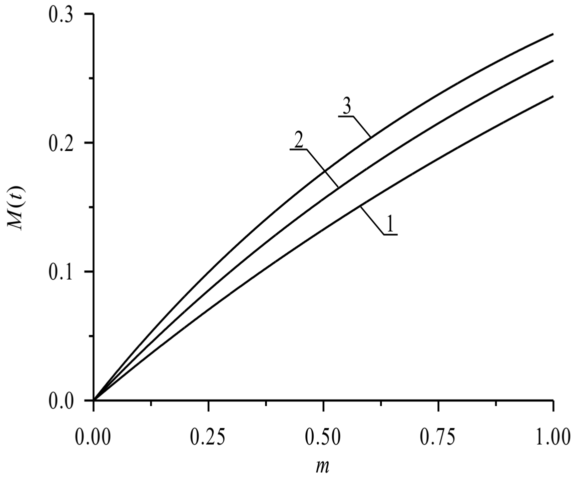

Fig. 1. Typical weight gain of farm animals as a function of total feed mass mmm.

In *Fig. 1,* each curve represents a different diffusion coefficient D(x,T) within the organism. Higher-numbered curves correspond to higher diffusion rates, resulting in more uniform nutrient distribution and faster growth.

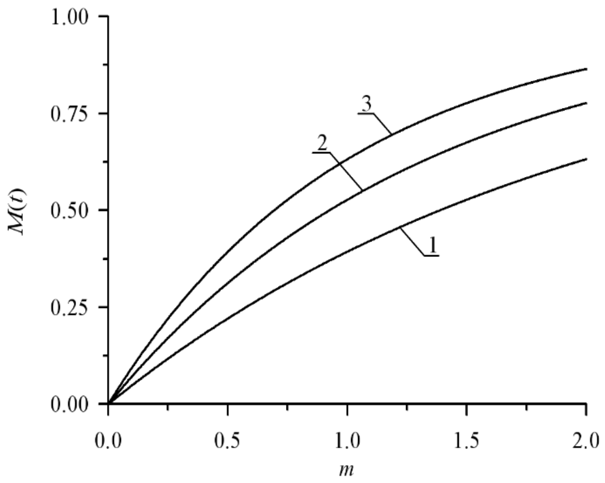

Fig. 2. Typical weight gain of farm animals as a function of total feed mass mmm.

In *Fig. 2*, each curve represents a different feed digestibility parameter K(x,T). Higher-numbered curves correspond to higher digestibility, leading to more efficient nutrient assimilation and steeper growth curves.

4 | Conclusion

In this paper, we introduced and tested a mathematical model to analyze and predict the growth of farm animals as a function of several key parameters related to feed characteristics and physiological assimilation. The model explicitly accounts for the spatio-temporal distribution of feed concentration, incorporating both diffusion within the organism and the digestibility of feed. By considering the nonlinear nature of nutrient absorption and metabolism, the model provides a realistic representation of weight gain dynamics under varying feeding conditions. An analytical approach based on the method of averaging of function corrections was applied to derive first- and second-order approximations of feed concentration, allowing for the evaluation of digested and undigested fractions of feed. This approach enables a systematic analysis of the interactions between feed diffusion, digestibility, and overall feed mass, which are critical determinants of growth efficiency. The results demonstrate that optimal weight gain is achieved through a balance of high diffusion rates and high digestibility, while excessive feed intake or imbalances in these parameters may lead to suboptimal growth or waste of resources. The model also provides practical insights into strategies for managing the fattening process. By adjusting the key parameters of feed diffusion and digestibility, it is possible to accelerate or decelerate weight gain according to production goals. For example, in intensive livestock systems, higher digestibility combined with optimized nutrient distribution can maximize growth over a shorter time period, whereas in extensive or resource-limited systems, moderate diffusion and digestibility may be preferred to prevent overfeeding and reduce feed costs. Moreover, the analytical framework allows for the quantitative evaluation of feed efficiency, highlighting the proportion of feed contributing to maintenance versus productive growth. This capability is particularly valuable for designing feeding regimens that optimize both economic and biological outcomes. By understanding the nonlinear interactions between feed parameters and growth, farmers and feed manufacturers can make informed decisions about feed formulation, feeding schedules, and overall farm management strategies. Finally, the model provides a foundation for future research in livestock growth modeling. Extensions could include the incorporation of heterogeneous tissue absorption rates, variable metabolic demands, stochastic feeding behavior, and environmental influences such as temperature or stress. Such developments would further enhance the predictive power of the model and its applicability to diverse farm conditions. Overall, the proposed analytical approach offers a powerful tool for understanding and managing the growth of farm animals, bridging the gap between theoretical modeling and practical livestock management.

Authors' Contributions

The author was responsible for all stages of the research and manuscript preparation and approved the final version.

Data Availability

All data are included in the text.

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Conflict of Interest

There are no competing interests to declare.

Consent for Publication

The author confirms consent for the publication of this work.

Ethics Approval and Consent to Participate

This article does not contain any studies with human participants performed by the author

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