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Prediction of extruded aquafeed physical quality parameters through a dough viscosity model

Hongyuan Cheng[1,2] | Tor A. Samuelsen[3] | Mette Sørensen[4] | Min Xue[1] | Junguo Li[1]

[1]Feed Research Institute, Chinese Academy of Agriculture Sciences, Beijing, China

[2]National Food Institute, Technical University of Denmark, Kgs. Lyngby, Denmark

[3]Nofima AS, Bergen, Norway

[4]Faculty of Bioscience and Aquaculture, Nord University, Bodø, Norway

Correspondence
Hongyuan Cheng, Feed Research Institute, Chinese Academy of Agriculture Sciences, No. 12, Zhongguancun South Street, Haidian, Beijing 100081, China.
Email: hyc@thermoextrusion.com; chenghongyuan@caas.cn

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Abstract

A widely used dough viscosity model in food extrusion was adopted and employed for the analysis and prediction of extruded aquafeed physical quality parameters. The data for the analysis were collected from previously published articles. The analysis was based on the assumption that pellet physical quality parameters, such as bulk density, oil adsorption, hardness, and durability, are correlated to the dough viscosity property changes in the extrusion process. The physical qualities of feed were modeled using the modified viscosity model. The model was evaluated using the data collected from experiments conducted in three different pilot extrusion systems. The results showed that the new model has the capability to predict the physical quality parameters of extruded aquafeed pellets in the three studied scenarios. The absolute average deviations of the model regression for the pellet qualities were 8.5% for hardness, 4.8% for bulk density, 6.5% for oil adsorption, 15.7% for Holmen durability, and 0.7% for pellet diameter. The new model can correlate the physical qualities of aquafeed pellets across different recipes, extruder configurations, and systems.

Practical Applications

Food or aquatic feed extrusion process operation heavily depends on the operator's experiences and is still a black-box process. In this study, a dough viscosity model was applied to explain the relationship between extrusion variables and extruded pellet physical qualities. The new model can be used for a quantitative description of a feed formulation extrusion process and feed pellet quality optimization.

KEYWORDS

aquafeed, bulk density, durability, extrusion, hardness, model, oil adsorption, viscosity

1 | INTRODUCTION

Extrusion technology is widely employed in the production of texturized products, such as breakfast cereals, pasta, and aquafeeds. Currently, production of these products with predictable and stable quality is still considered as a "black box," where the optimization of process parameters strongly depends on the experience of operators. Due to ingredient and batch-to-batch variation, engineers must frequently optimize extruder settings to produce pellets with desired physical qualities (such as hardness and bulk density) by following their skills. Hence, it is important to develop process models that can quantitatively describe the impacts of ingredients, recipes, and extrusion variables on pellet quality parameters. These models should be able to explain the quantitative influence of the extrusion variables on pellet quality across different recipes, extruder configurations, and systems.

In the extrusion process, ingredient properties and adjustable extruder parameters determine the product quality when the equipment geometry is fixed. Consistency is expected in the production of a specific product with the same extruder operating variables being used in an extrusion line at all times. However, processing characteristics and ingredient technical properties may change from batch to batch due to their variations in chemical composition, agrotechnical conditions, plant variety, or postharvest processing (Glencross, 2020; Thakur & Hurburgh, 2007). As a result, it is impossible to use the same set of extrusion variables to achieve consistent product quality in a specific extrusion line over time for the same recipe production. Therefore, operators need to continuously optimize extruder process parameters based on their experiences in order to meet defined pellet physical quality criteria.

In the case of aquafeeds, the recipes will have to be adjusted to meet the nutritional requirements of different aquatic species, as well as the preferences of organisms for either floating or sinking pellets. Additionally, feed logistics and feeding technology in different rearing conditions like ponds, tanks, or sea cages may also need recipe adjustments. The frequent changes in aquafeed recipes and the introduction of new feed ingredients demand increased efforts to understand and manage the extrusion process effectively.

Statistical methods, namely principal component analysis (PCA) and response surface methodology (RSM), are often used to analyze the relationship between recipe ingredients, extrusion variables, and extrudate or pellet properties, where the extrusion system is treated as a black box. The data-driven RSM and PCA can explain the effects of ingredient and extrusion variables on extrudate quality parameters based on a well-defined experimental design. A limitation of the RSM is that the results are only valid for the studied cases with the specific feed ingredient composition and extruder geometry. Reproducing the results in other extruder systems is often difficult, even for the same feed ingredient formulation. A physical meaning sound method is therefore needed for prediction of pellet quality parameters regardless of feed ingredient composition and extrusion systems.

Several publications have indicated that rheological or viscous behavior of a dough melt can provide valuable insights into the extrusion process and may be used to predict the physical qualities of pellets. Lai and Kokini (1991) reviewed the rheological property changes and models in starch extrusion process. Recently, the viscous behaviors of starch foods were investigated, and a phenomenological model for extrudate expansion was developed (Jebalia et al., 2022; Kristiawan et al., 2016, 2018, 2019). Emin and coworkers studied the shear, viscosity, and reaction behaviors for starch and plant protein extrusion process by numerical and experimental methods (Emin et al., 2017; Emin & Schuchmann, 2013, 2017). Singh and Muthukumarappan (2017) developed a viscosity model for soy white flakes-based aquafeed dough in a single-screw extruder. Ayadi et al. (2013) correlated the product quality and extrusion variables for dried distillers grains with solubles-based Nile tilapia feeds using a material viscous property analysis method. Thomas and van der Poel (2020) investigated the apparent viscosity of feed mash through glass transition concept and the effects of the viscosity changes on the compaction characteristics of the feed mash. Ahmad et al. (2019) applied a capillary rheometer to investigate the apparent viscosity, extrudate physical quality, and microstructure of the sample materials. As can be seen from these articles, the dough viscosity model of Harper and Rhodes (1971) is a widely accepted model for the investigation of rheological properties in food extrusion applications (Lai & Kokini, 1991; Singh & Muthukumarappan, 2017) and was employed in this work.

Extrusion cooking of food and aquafeed is a biochemical reaction process, where biomolecules, such as starch and protein, are converted to new structure molecular chains. Viscosity is one of the basic parameters to measure such variations in the cooking process (Bourne, 2002; Davidson, 1992). For taking viscosity to model the pellet quality parameters, the fundamental consideration is that viscosity is a basic intensive property (like temperature and pressure) and is independent of the size (the extent) of the sample or material. Then, a pellet quality parameter model that is directly proportional to material viscosity is independent of the amount or mass of the extrusion material. The model and its prediction results can be applied to either small- or large-scale extruder. Based on such viscosity model, the extrusion knowledge from a pilot extrusion plant can also be utilized in an industrial-scale extrusion system.

The aim of the present study was to develop a quantitative model to estimate the physical quality parameters of extruded feed pellets based on well-developed rheological concepts and models using published data. It was hypothesized that the formation and shaping of the feed pellets is a result from extrusion process induced pasting or binding behavior of the ingredients in the feed formation. Therefore, the process can be modeled by a viscosity model. The developed model was validated using data on bulk density, hardness, oil adsorption, durability, and pellet diameter from published articles, where the model predicted values were compared with actual values of the pellet quality measurements.

2 | MATERIALS AND METHODS

2.1 | Materials—Literature data

The model was developed using already published dataset generated in well-established pilot-scale facilities. No additional extrusion trials were performed. These pilot-scale plants are Center for Feed Technology (FôrTek, the Norwegian University of Life Sciences, Ås, Norway) (Sørensen et al., 2010, 2011), the Aquafeed Technology Centre (Nofima, Bergen, Norway) (Samuelsen et al., 2018; Samuelsen & Oterhals, 2016), and Skretting Aquaculture Research Centre (Skretting ARC, A Nutreco Company, Stavanger, Norway) (Draganovic et al., 2011). The selected articles addressed various research topics in aquafeed production, such as fishmeal replacement, different starch sources, and extruder screw configuration adjustment. The extruders

TABLE 1 Details of publications from which data were retrieved for the study.

Code	Investigation topic	Extruder and throughput	Reference
TAS1	Microalgae, wheat gluten, and soy protein replacement	Wenger TX52, 150 kg/h	Samuelsen et al. (2018)
TAS2	Fishmeal differences and plasticizers	Wenger TX52, 150 kg/h	Samuelsen and Oterhals (2016)
VD	Wheat gluten, soy protein impact	Thermo Fisher TSE 36, 75 kg/h	Draganovic et al. (2011)
MS1	Pea and wheat starch impact	Buhler, BCTG 62/20, 200 kg/h	Sørensen et al. (2011)
MS2	Starch, screw setup impact	Buhler, BCTG 62/20, 200 kg/h	Sørensen et al. (2010)

used to produce the above-mentioned trial data include a Wenger corotating, fully intermeshing twin-screw extruder (TX-52, Wenger Manufacturing Inc., Sabetha, KS, USA), a five-section Bühler twin-screw extruder (BCTG 62/20 D, Uzwil, Switzerland), and a Thermo Fisher twin-screw extruder (TSE 36 HC Thermo Scientific, UK). These extrusion systems are currently used and accepted to produce results that are upscalable to industrial applications. The selected data source articles are listed in Table 1.

The chemometric information of the feed formulations, the extrusion process parameters, and aquafeed pellet quality parameters was reported in the original published articles and is thus not represented in the current work. The moisture content of the collected data ranged from 0.175 to 0.205 g/g. All the extruded products were salmon feed pellets.

2.2 | Methods

2.2.1 | Model assumptions

The model concept was developed based on the assumption that the raw material viscous property varies with different feed mixtures or formulations in an extrusion process. The viscous property of the melt flow in the die section of the extruder will also vary with the recipe (or formulation) changes and process variables. In the process, the raw material pasting property development will control the quality parameters of extruded pellets or extrudates. Therefore, an adjustment of a recipe in the extrusion process will change not only the ingredient composition but also the dough viscous property that can be calculated by a dough viscosity model.

Based on this assumption, the extruder is treated as a coaxial cylinder-shaped viscometer, where the screw and barrel are considered as an inner and an outer cylinder, respectively. Viscous properties can be assessed using a rheological model at constant screw speed and water content for different recipes. During extrusion cooking, the viscous property of the feed ingredients is not only defined by physical laws but also influenced by chemical reactions and molecule reorganization, such as starch gelatinization, protein plasticization, and new network formation. Finally, the melt rheological property of the recipe mixture entering the extruder die dominates the physical quality parameters of the extrudates and can be considered as a combination of all physicochemical and rheological changes in the process.

In this work, it is hypothesized that the melt rheological property of feed ingredient materials before die plate can be measured or calibrated by the torque of the extrusion process at steady state. It is also hypothesized that the extrudate physical quality parameters, that is, pellet bulk density, hardness, durability, oil adsorption, and pellet diameter, can be correlated to the viscous property of the recipe mixture in the process. A viscosity model can express the viscous or pasting function development of the raw material dough.

2.2.2 | Model construction

In the extrusion process, the melt fluid before the extrusion discharge die can be treated as non-Newtonian shear thinning fluid. The shear thinning fluid is represented by power law model as follows:

$$\eta = m\dot{\gamma}^{n}, \tag{1}$$

where η is the apparent viscosity, N s/m^2, m is the consistency index, N s^n/m^2, $\dot{\gamma}$ is the shear rate, 1/s, and n is the flow behavior index.

To evaluate the viscous property, a viscosity model for cooked cereal dough described by Harper (1981) and Harper et al. (1971) was selected among other similar models (Lai & Kokini, 1991) as it is a widely used model for viscosity calculation in the extrusion process. The model is as follows (Harper, 1981):

$$\eta = \eta^{*}\dot{\gamma}^{n-1}\exp\left(\frac{\Delta E}{RT}\right)\exp(KM), \tag{2}$$

where η is the apparent viscosity, N s/m^2, η^* is the reference apparent viscosity N s/m^2, $\dot{\gamma}$ is the shear rate, 1/s, n is the flow behavior index, ΔE is the energy of activation, J/mol, R is the gas constant, 8.314 J/mol K, T is the absolute die temperature, K, K is a constant, and M is the moisture content, g/g. The effects of moisture and temperature on viscous property changes have been considered in Equation (2).

Aquafeeds are manufactured using a variety of ingredients and optimized based on the least cost formulation and fish size. In the extrusion process, the raw material viscous property development is influenced by each ingredient in the recipe. This contribution of each ingredient to the raw material viscous property can be assessed by either a linear or nonlinear function.

In this work, a viscosity model for binary polymer blends (Carley, 1985) was selected to describe the material (or melt fluid) viscous property during extrusion process. Based on the model of Carley, the viscous property of a recipe can be described as

$$\eta_m = \exp\left(\sum x_i \ln \eta_i\right), \tag{3}$$

where η_m is the melt dough viscosity of a recipe, η_i is the contribution value of ingredient i to the melt viscous property in a recipe and is determined by experimental data, and x_i is the composition of ingredient i, g/g. In this work, Equation (3) is extended to multiple component system application.

In an extrusion cooking process, the melt dough viscosity may not result solely from a simple physical summation of the contribution of each ingredient but may involve a more complicated mechanism (Dogan & Kokini, 2007). Equation (3) is an approximation for the viscosity calculation.

In an extrusion process, the shear rate, $\dot{\gamma}$, can be correlated with screw speed (N_s) as

$$\dot{\gamma} = cN_s^{\alpha}. \tag{4}$$

Here c and α are experimental data determined coefficients.

Combining Equations (2)–(4), we get

$$\eta_m = k_0 \exp\left(\sum x_i \ln \eta_i\right) N_s^{\alpha} \exp\left(\frac{\Delta E}{RT}\right) \exp(k_2 M), \tag{5}$$

where the coefficient $k_0 = c \times \eta^*$, η^* is the reference apparent viscosity N s/m^2, N_s is the screw speed, rpm or 1/s, and k_0 is in N s/m^2.

If the extrudate quality parameters (Y_{prop}) are directly related to the melt dough viscous property, thus,

$$Y_{prop} = k' \eta_m, \tag{6}$$

then Equation (5) becomes

$$Y_{prop} = k_1 \exp\left(\sum x_i \ln \eta_i\right) N_s^{\alpha} \exp\left(\frac{\Delta E}{RT}\right) \exp(k_2 M), \tag{7}$$

where Y_{prop} is an extrudate quality parameter (hardness, oil adsorption, durability, bulk density, etc.), $k_1 = k_0 \times k'$, k_1, η_i, α, ΔE, and k_2 are the experimental data determined parameters and can be obtained from experimental data regression. Equation (7) is the basic model to correlate an extrudate quality parameter with recipe ingredient compositions and extrusion variables. For different extrusion systems and recipes, the model will have different model coefficients that are determined by fitting experimental data.

As Equation (7) is derived from a viscous property concept and shear thinning fluid theory, it is not limited to different recipes, ingredient inclusion levels, and extruders. In other words, the mathematical expression of Equation (7) does not depend on specific recipe or extrusion system. Equation (7) takes into account for the effects of ingredients, screw speed (shear), temperature, and moisture on extrudate quality parameters and aim to explain the extrusion trial results through the mathematical expression.

Equation (7) was used to fit the extrusion process data collected from previous publications (Table 1). The data regression was carried out with optimization tool in Matlab 2014 (The MathWorks, Inc). The least square method of Levenberg and Marquardt was selected. In the regression, the following objective function (obj.) was employed to determine the model coefficients of Equation (7) for each pellet quality parameter.

$$\text{obj.} = \min \sum_{i=1}^{n} \left[Y_{prop,i}^{exp} - Y_{prop,i}^{cal}\right], \tag{8}$$

where $Y_{prop,i}^{exp}$ and $Y_{prop,i}^{cal}$ are respectively experimental and calculated pellet quality parameter. To search possible global minimum, random initial values were employed until the best minimum value was obtained.

3 | RESULTS AND DISCUSSION

3.1 | Model regression with experimental data

Equation (7) was used to regress the experimental feed pellet quality data from five dataset in different published sources (Table 1). In the regression, the five different data sources gave five set of model coefficients for the pellet quality parameters. The obtained model coefficients are given in Tables S1–S5. The model regression results are represented in Figures 1–5. In the results, MS2 refers only to one of the three screw configuration setups employed in Sørensen et al. (2010). The regression deviations for the pellet quality parameters are

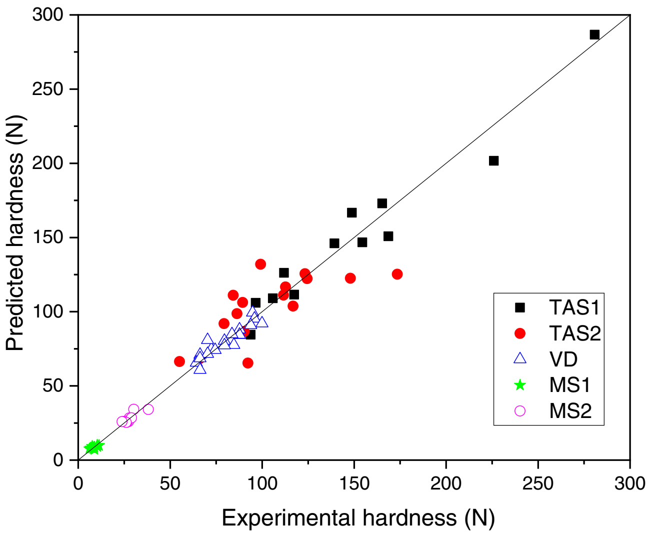

FIGURE 1 Hardness values obtained from experimental data and those determined using Equation (7). Experimental data sources of TAS1, TAS2, VD, MS1, and MS2 are given in Table 1.

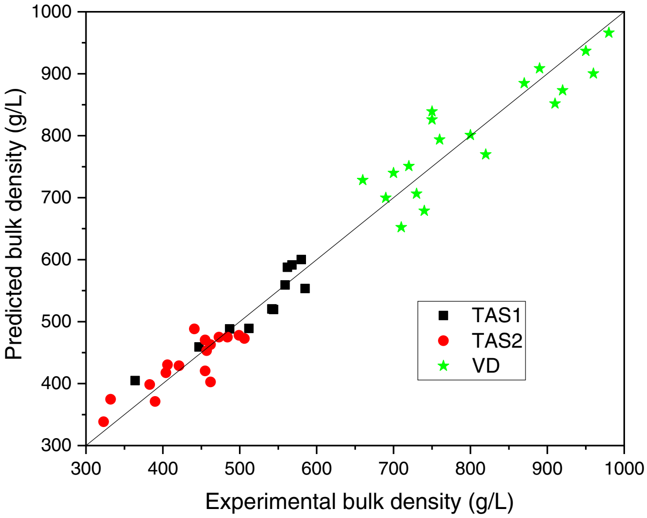

FIGURE 2 Bulk density values obtained from experimental data and those determined using Equation (7). Experimental data sources of TAS1, TAS2, and VD are given in Table 1 (1 kg/m^3 = 1 g/L).

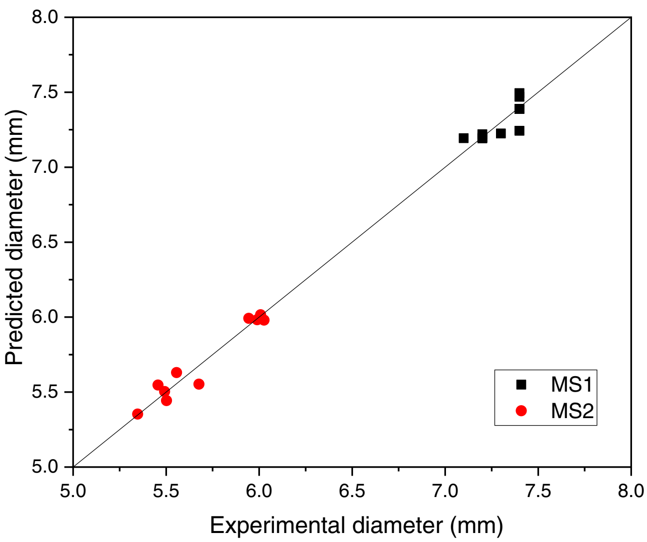

FIGURE 3 Pellet diameter values obtained from experimental data and those determined using Equation (7). Experimental data sources of MS1 and MS2 are given in Table 1.

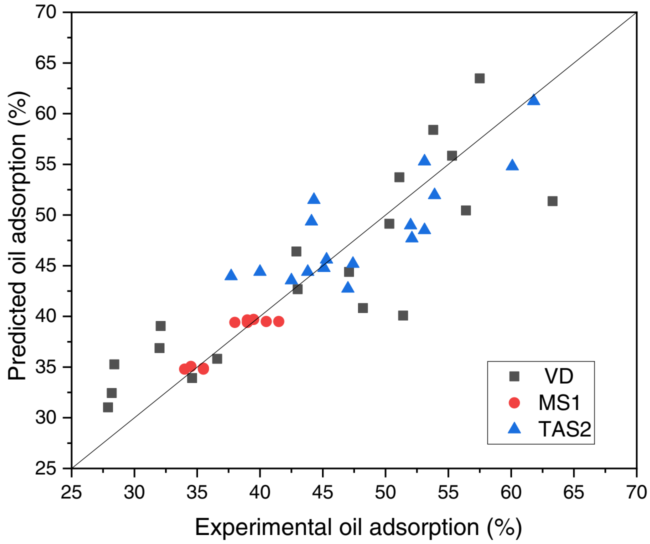

FIGURE 4 Oil adsorption values obtained from experimental data and those determined using Equation (7). Experimental data sources of VD, MS1, and TAS2 are given in Table 1.

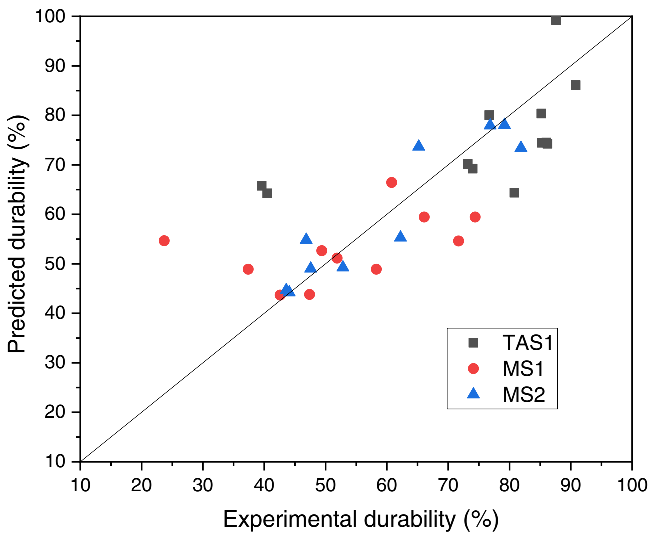

FIGURE 5 Holmen durability values obtained from experimental data and those determined using Equation (7). Experimental data sources of TAS1, MS1, and MS2 are given in Table 1.

represented in Table 2. In Table 2, AAD% is absolute average deviation, which is as follows:

$$\mathrm{AAD\%} = \frac{1}{n}\sum_{n}\left[\frac{\left|Y_{\mathrm{prop}}^{\mathrm{exp}} - Y_{\mathrm{prop}}^{\mathrm{cal}}\right|}{Y_{\mathrm{prop}}^{\mathrm{exp}}}\right]100\%, \quad (9)$$

where $Y_{\mathrm{prop}}^{\mathrm{exp}}$ and $Y_{\mathrm{prop}}^{\mathrm{cal}}$ are the experimental and calculated pellet quality, respectively, and n is the number of experimental runs.

As shown in Table 2, the absolute average deviations of the model regression for the experimental data are 8.5% for hardness, 4.8% for bulk density, 6.5% for oil adsorption, 15.7% for Holmen durability, and 0.71% for pellet diameter. The average R^2 values for the regressions of different pellet quality properties range from 0.70 to 0.86 (Table 2).

In the present work, by combining the dough viscous equation (Equation (2)) and polymer blend equation (Equation (3)), a new equation (Equation (7)) was formulated to calculate the pellet physical quality parameters. Each term of the new equation has its specific physical explanations to take into account the effects of extrusion variables (screw speed, temperature, and moisture content) and the contribution of recipe ingredient. The regression results (Table 2) indicate that the new model can predict the physical quality parameters of extrudates or extruded aquafeed pellets.

TABLE 2 Average absolute deviations of the regression model parameters generated for each dataset of extrusion trials.

Data code[b]	AAD% of model regression[a]				
	Hardness	Bulk density	Oil adsorption	Holmen durability	Diameter
TAS1	7.6	4.1	n.a.	18.7	n.a.
TAS2	14.0	5.1	6.8	n.a.	n.a.
VD	4.2	5.2	10.5	n.a.	n.a.
MS1	11.6	n.a.	2.1	21.6	0.57
MS2	5.3	n.a.	n.a.	6.7	0.84
Average	8.5	4.8	6.5	15.7	0.71
R^2 average	0.7	0.86	0.83	0.79	0.72

Abbreviations: AAD, absolute average deviation; n.a., not available.
[a]AAD% is calculated by Equation (9).
[b]The references of the data TAS1, TAS2, VD, MS1, and MS2 are given in Table 1.

3.2 | Model regression results for pellet quality

3.2.1 | Hardness

A comparison of experimental and model predicted pellet hardness data for the five different datasets is presented in Figure 1. Table S1 presents the obtained model coefficients for prediction of the pellet hardness. The average AAD% of the model regression was 8.5% (Table 2). Figure 1 indicates that the residuals between experimental and predicted hardness are evenly distributed along the central line, and they lie close to the line.

The highest deviation of the predicted pellet hardness was noted for the data of TAS2 (Table 2). In general, pellet hardness depends on the suitable combination of structure forming materials and dispersed phase filling materials (Guy, 2001). In the work of Samuelsen and Oterhals (2016), the feed recipes were arranged to evaluate three types of fishmeal fractions while focusing on the water-soluble protein level as a plasticizer. Fishmeal was the only protein source in the recipes and plays a major role for viscous heat dissipation and structure forming properties. The findings from the present study suggest that the model cannot precisely predict the effect of fishmeal protein networking, aggregation, and reorientation on pellet hardness. Further modifications are needed to enhance the predictive capability of the model in this regard.

3.2.2 | Bulk density, diameter, and oil adsorption capacity

Pellet bulk density is closely related to oil adsorption capacity (Draganovic et al., 2011; Samuelsen et al., 2018; Samuelsen & Oterhals, 2016; Sørensen et al., 2011). Lower bulk density is approximately proportional to higher oil adsorption capacity or free pore space in a pellet, that is, pellet with low bulk density may adsorb more oil.

The experimental and predicted values of extrudate bulk density, pellet diameter, and oil adsorption are presented in Figures 2–4. Tables S2–S4 present the obtained model coefficients for predicting the pellet quality parameters. As shown in Table 2, the model can satisfactorily predict bulk density, oil adsorption capacity, and pellet diameter with average of AAD% of 5.8%, 6.5%, and 0.7%, respectively. Figures 2 and 3 indicate that the errors are small.

Figure 4 and Table 2 show higher deviation associated with oil adsorption based on the data from VD dataset (AAD% = 10.5%). The size of pores within a pellet decides the quantity of oil that can be absorbed into the pores through capillary force. Oil within larger pores is less likely to be retained and tends to leak or escape from these relatively spacious openings. An AAD% of 10.5% for the VD dataset indicates that the model can only approximately predict oil absorption and may not accurately account for the actual quantity of oil in smaller pores in some cases.

In the work of Sørensen et al. (2010, 2011), the extrudate pellet diameter was measured automatically by a texture analyzer in parallel with the hardness analysis. Equation (7) can satisfactorily predict the pellet diameter, as indicated by the AAD% of 0.71 (Table 2). Compared to the extrudate bulk density, the pellet diameter provides only a partial explanation for the floating or sinking ability of an aquafeed pellet. In extrusion operations, pellet diameter is a common metric to assess process performances. Pellet diameter is also a target value determined by the fish size.

3.2.3 | Pellet Holmen durability

The experimental and predicted values of extrudate durability data are presented in Figure 5. Table S5 gives the obtained model coefficients. In the extrusion cooking process, the extrudate durability is controlled by the factors, such as cooking degree (i.e., degree of starch gelatinization and protein plasticization), melt homogeneity, and intermolecular binding network within the produced pellet (Mercier & Feillet, 1975; Samuelsen et al., 2018; Sørensen, 2012).

The predicted Holmen durability has higher AAD% for the datasets TAS1 and MS1 (Table 2). As can be interpreted from Figure 5, some residuals between the experimental and the predicted values are far from the middle line for the dataset of TAS1 (Samuelsen et al., 2018). The extruded feed pellets in the TAS1 experiments were

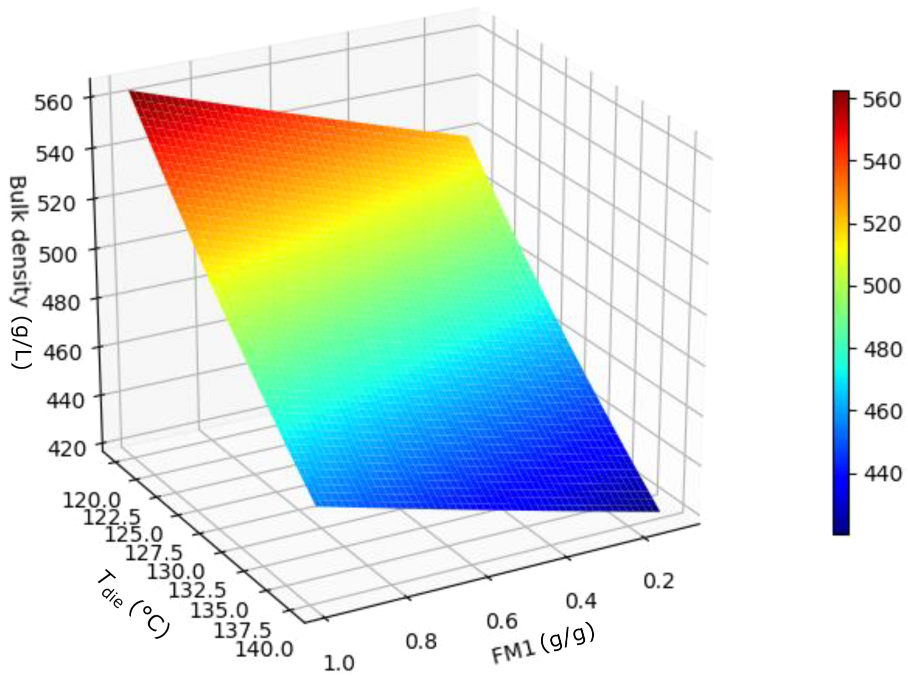

FIGURE 6 Effects of ingredient and die temperature on pellet bulk density. Screw speed = 400 rpm, H_2O content = 172 g/kg, FM1 = 0.14–0.98 g/g, FM2 = 1.0–FM1, FM3 = 0.0 g/g, and T_{die} = 126–137°C. FM1, fish meal 1; T_{die}, die temperature.

formulated with varying levels of the high lipid microalgae, *Schizochytrium* sp. The most deviating values (run 5 and run 8) had high feed mixture lipid content (>19%), and due to the lubrication effects of the lipids in the extruder screws, this resulted in inadequately cooked pellets with poor starch gelatinization. This, in turn, will have a significant impact on pellet durability, shown as deviations from the expected rheological behavior (Harper, 1981). In this scenario, the model's ability to capture the durability behaviors under the influence of lubrication effects will be compromised.

In the prediction of the MS1 dataset, the model exhibited higher deviations, particularly for the low-durability data points. In addition, it is worthy to note that post extrusion operations in aquafeed product, such as drying, may have a pronounced impact on pellet durability (Samuelsen et al., 2021), which cannot be predicted by the model.

3.3 | Model analysis for the effects of ingredients, screw speed, temperature, and moisture content on pellet quality

Using the obtained model regression results for the investigated recipes and extrusion processes, it is possible to analyze the effects of ingredients, screw speed, die temperature, and moisture content on feed pellet quality parameters. For example, in the work of Samuelsen and Oterhals (2016), physical pellet quality was analyzed for the feed pellets produced from three different fish meal inclusion levels in a Wenger TX-52 extruder with a feeding rate of 150 kg/h and a fixed screw speed of 400 rpm. The new model, that is, Equation (7), was used to regress the reported experimental data. A set of model coefficients were obtained (TAS2 in Tables S1–S5). For example, the model coefficients for pellet bulk density calculation are $k_1 = 1.882$, $\eta_1 = 3.730$, $\eta_2 = 3.395$, $\eta_3 = 2.792$, $\Delta E/R = 1724$, $\alpha = 0.0$, and $k_2 = 0.0$. Based on the model coefficients, the effects of ingredients and die temperature on pellet bulk density can be predicted as illustrated in Figure 6. For this calculation, fishmeal 1 (FM1) was set in the range of 0.14–0.98 g/g, with FM3 = 0.0 g/g and FM2 = 1.0–FM1 (TAS2 dataset). The die temperature range was set to 126–137°C (TAS2 dataset). From the study, it can be calculated that bulk density reaches its maximum value when FM1 was included at 0.4 g/g, and a die temperature close to 137°C.

The modeling results can be plotted to study the impact of ingredients, screw speed, temperature, and moisture content on all the modeled physical quality parameters. Often classical (RSM) approach is used to understand the effects of ingredients and process variables on physical quality parameters. However, the RSM model is based on statistical principles other than a physical foundation of the extrusion process, which limits its ability to explore all possible variable combinations, especially across different recipes and extruders. Process modeling can therefore be a better solution. The suggested model in this study is based on assumptions of the physical and chemical principles of the extrusion process and could elaborate the impacts of various factors linked to the process on pellet quality parameters. Compared to RSM modeling, the developed model may give more physical explanations in terms of ingredient combinations in feed formulations and process variables.

3.4 | Model characteristics, limitations, and possible modifications

From the results in Figures 1–5 and Table 2, it is evident that the proposed model can capture the specific aquafeed physical quality parameters across the developed feeds formulated with 31 recipes in three different extrusion systems. The developed model has been validated in the studied cases, which documents that the viscous property changes of the recipes can quantitatively be represented through a classical cereal dough viscosity model. The pellet quality parameters are proportional to dough viscous property development in the extrusion process.

For the calculation of dough melt viscosity, a fragment or group contribution concept was used, where every individual ingredient had its specific contribution to the viscosity of dough mixture. The contribution of a specific ingredient was calculated by its weight fraction (x_i) in a recipe multiplied by its contribution (η_i), that is, $x_i \ln \eta_i$, in Equation (3). The contribution of an ingredient was estimated from experimental data regression. However, it should be pointed out that the viscous effect of the same ingredient is not constant and may change from one batch to another, for example, wheat or fishmeal from different producers or a different batch from the same producer. This within-ingredient variation may cause fluctuations in the viscous contribution to the feed mix. This variation is caused by ingredient varieties, such as their chemical composition, agrotechnical conditions, plant variety, or postharvest processing. Therefore, the contribution coefficient (η_i) of the same ingredient may not be the same across different recipes.

In Equation (7), the dough melt viscosity was calculated by a logarithmic mixing method of Carley (1985), enabling the inclusion of the contributions of different ingredients. Other mixing methods (Dogan & Kokini, 2007) may also be used to calculate the ingredient contribution to the dough viscous property. The activation energy represents the energy changes of starch gelatinization and protein reorganization and is treated as different values for different recipes other than constant in this work.

The model regression results revealed that the model (aside from the model coefficients) is independent of variations in recipe formulations and extruder geometric conditions, which is the notable difference from RSM model. However, it should be acknowledged that the new model validated in this study also has its own set of limitations. The model cannot be used to predict important changes of ingredient characteristics, such as protein reorganization or networking. Another constraint is that a single mathematical expression was applied to correlate five different feed pellet quality parameters. It is worth noting that a specific pellet quality parameter may need a unique approach for precise prediction of its characteristics in the extrusion process. Thus, the generalized model may introduce inaccuracies when predicting a specific pellet quality parameter. Developing tailored models for each pellet quality parameter can be a promising approach to improve the overall model accuracy.

Nevertheless, the new model can serve as a benchmark to facilitate the correlation and comparison of aquafeed physical quality parameters across diverse feed formulations and various extrusion systems. In practical terms, this reference model can be considered as a valuable tool to assess and compare different extrusion systems and recipes. Thus, it can be used to quantitatively transfer the knowledge gained from one system or a recipe in a pilot-scale trial to another including those employed for industrial-scale productions.

4 | CONCLUSION

Employing a widely accepted dough viscosity calculation model, a new model was established to estimate the physical quality parameters, such as bulk density, hardness, oil absorption capacity, durability, and pellet diameter of extruded aquafeeds. The method was validated using pellet physical quality datasets (31 recipes) generated in three different pilot twin-screw extrusion systems. This study documents that the established model can be used to predict pellet quality parameters from the published data without changing its mathematical expression. The absolute average deviations of the model regression for the published datasets (31 recipes) were 8.5% for hardness, 4.8% for bulk density, 6.5% for oil adsorption capacity, 15.7% for Holmen durability, and 0.7% for pellet diameter. The new method can be used to analyze aquafeed extrusion processes regardless of feed ingredient formulations and extruders.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

ORCID

Hongyuan Cheng https://orcid.org/0000-0002-7441-5861

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SUPPORTING INFORMATION

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