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Empirical models to predict feed intake of growing-finishing pigs reared under high environmental temperatures

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ABSTRACT: Several empirical models were proposed to predict feed intake (FI) of growing-finishing pigs reared under high environmental temperatures. However, these models have not been evaluated under conditions different from those in which they were developed. Twelve empirical models were evaluated using a database built after systematic literature review (observed data: 28 studies in which the FI was evaluated in pigs under high environmental temperatures). Model accuracy was assessed using the mean squared of prediction error (MSPE). Analyses were performed considering two scenarios: (1) general population, where all observed data were used in the simulation; (2) reference population, where data were filtered in order to simulate only scenarios with environment (temperature range) and animals (body weight and sex) similar to that used in the model development. Six models estimated FI values similar ($p > 0.05$) to those observed in the general population, while four models produced estimates similar to the observed values in the reference populations. Most models were more accurate when they were simulated using the reference population than when the simulation considered the general database. Moving the simulation from the general database to the reference population reduced up to 98 % of the MSPE, depending on the equation. Empirical models allow to accurately predict FI of growing-finishing pigs exposed to high environmental temperatures, especially in scenarios similar to the ones used for model development. Thus, population characteristics (body weight and sex) and environment (temperature range) must be considered in the model assessment.

Keywords: consumption, heat stress, modelling, precision feeding, swine

Introduction

Precision feeding has great potential to improve sustainability of pig production by ensuring a better adjustment of nutrient supply to animal requirements (Pomar et al., 2011). However, the proper application of precision feeding techniques depends on procedures that accurately predict the voluntary feed consumption (Pomar et al., 1991; Whittemore et al., 1995).

Control mechanisms of feed intake (FI) are complex and influenced by factors that are both extrinsic and intrinsic to the animals (Wellock et al., 2004; Kyriazakis and Whittemore, 2006). The complexity of these physiological processes may hinder FI estimation. Among these factors, environmental temperature is considered one of the most important variables affecting FI in growing pigs (Le Bellego et al., 2002; Renaudeau et al., 2011). The increased heat caused by the digestion process impairs the pig thermal homeostasis. Thus, pigs tend to decrease FI in environments with high temperature (Le Bellego et al., 2002). Due to its great importance to pig production, the effect of environmental temperature on FI has been assessed in many projects, including studies using modeling approach.

Several empirical models were proposed to predict FI based on animal and environmental characteristics. However, these models were usually developed using databases limited to some experimental conditions, which leads to the need for ensuring accuracy of their FI predictions even in different scenarios. Therefore, this study was developed to evaluate the accuracy, trueness, and precision of empirical models in predicting FI of growing-finishing pigs exposed to high environmental temperatures.

Materials and Methods

Description of empirical models

The empirical models proposed to estimate FI of growing-finishing pigs according to the environmental temperature were searched on digital databases. Publications in the last 20 years were considered in the literature review. Twelve empirical models were found in six published papers. All models presented in the original publications were tested in the current study with any previous modification or calibration. These models are presented and labelled in Table 1.

Massabie et al. (1996) proposed two models for barrows and two models for gilts. Equations were based on one study performed for each sex. In these trials, pigs weighing 25-105 kg were exposed to increasing temperatures (16, 20, 24, and 28 °C). The body weight was not considered as an independent variable in these models.

The model proposed by Rinaldo et al. (2000) was obtained using gilts and barrows weighing 35-90 kg, which were reared between 20 and 30 °C. The temperature was used to categorize the model and was not considered as a continuous variable in the model. The body weight was used within a quadratic adjustment to describe FI.

Table 1 – Empirical models predicting feed intake (y) of growing-finishing pigs from environmental temperature (T) and body weight (BW).

References and model labels	Equations[1]	Sex	BW	T
			kg	°C
Massabie et al. (1996)				
Massabie I	$y = -0.051 \times T + 3.53$	Barrows	25 -105	16 - 28
Massabie II	$y = -0.050 \times T + 3.47$	Barrows	25 -105	16 - 28
Massabie III	$y = -0.040 \times T + 3.10$	Gilts	25 -105	16 - 28
Massabie IV	$y = -0.037 \times T + 2.96$	Gilts	25 - 105	16 - 28
Rinaldo et al. (2000)				
Rinaldo	$y = -0.228 \times BW^2 + 42.7 \times BW + 260.3$	Mixed	35 - 90	20 - 30
Quiniou et al. (2000)				
Quiniou	$y = -0.26 \times BW^2 + 73.6 \times BW - 2.40 \times T^2 + 117 \times T - 0.95 \times BW \times T - 1264$	Barrows	30 - 90	19 - 29
Collin et al. (2001)				
Collin I	$y = 97.0 + 5.24 \times (T - 19) - 0.132 \times (T^2 - 19^2) \times BW^{0.83}$	Mixed	15.5 - 25	19 - 35
Collin II	$y = (96.0 + 0.500 - 2.75 \log(1 + \exp^{(T - 24.7)/0.5})) \times BW^{0.83}$	Mixed	15.5 - 25	19 - 35
Renaudeau et al. (2011)				
Renaudeau I	$y = -0.105 \times BW^2 + 58.7 \times BW - 2.40 \times T^2 + 134 \times T - 0.923 \times BW \times T - 1.33$	Mixed	14 - 101.5	14 - 36
Renaudeau II	$y = 1.30 \times BW - 0.215 \times T^2 + 10.1 \times T - 0.045 \times BW \times T + 65.2$	Mixed	14 - 101.5	14 - 36
Renaudeau III	$y = a \times BW^{0.69}$	Mixed	14 - 101.5	14 - 36
NRC (2012)				
NRC	$y = 111 \times BW^{0.803} + 111 \times BW^{0.803} \times (LCT - T) \times 0.025$	Mixed	25 - 90	-

[1]Models predicting feed intake in g d^{-1}, except for the model Renaudeau II in which results are expressed in g d^{-1} kg^{-1} of $BW^{0.60}$; Variables considered in the models: T = environmental temperature (°C); BW = body weight (kg); a = parameter for the relationship between temperature and upper critical temperature.

The model reported by Quiniou et al. (2000) was obtained using barrows weighing 30-90 kg, which were reared from 19 to 29 °C. Body weight and temperature were considered as independent variables in the model, both showing a quadratic fitting.

Two empirical models were proposed by Collin et al. (2001) considering pigs with 15-30 kg of body weight that were exposed to increasing temperatures (19 to 35 °C). Sex was not considered in the modelling procedure. The model Collin I assumed a quadratic fit of FI to environmental temperature, while the model Collin II considered a non-linear regression.

Renaudeau et al. (2011) conducted a meta-analysis using data from 86 studies evaluating the performance of pigs reared under high temperature. Using mixed linear modelling, the authors considered linear and quadratic effects of temperature and body weight and their interaction on FI. Two models (Renaudeau I and II) considered the quadratic effect of body weight, temperature and their interaction to estimate FI. Another model (Renaudeau III) was proposed using a non-linear adjustment that considered the upper critical temperature depending on body weight, followed by the calculation of parameter α, which indicates the magnitude of FI reduction when the upper critical temperature is exceeded.

The model proposed by NRC (2012) also recommended the use of critical temperature. In this model, the critical temperature is linearly related to the body weight (reduced by 0.0375 °C for each increase of 1 kg on body weight). Thus, this model predicts FI considering the environmental temperature, linear critical temperature, and body weight.

Systematic literature review and database building

The empirical models were challenged with a database built with information collected in scientific papers that described the effect of high environmental temperature on pig performance. These papers were systematically searched on digital databases. The criteria for paper selection were: (1) FI data on growing-finishing pigs exposed to high environmental temperatures; (2) *ad libitum* access to feed and water; (3) detailed description of environment and animal characteristics; and (4) dietary metabolizable energy level higher than 3,000 kcal kg^{-1} of feed (Noblet and Van Milgen, 2004).

Forty-six articles published in peer-reviewed scientific journals from 1979 to 2014 matched the first selection criterion. These studies were then evaluated according to other criteria (2, 3, and 4) and 18 articles were removed from the database (two applied feed restriction, 12 showed incomplete information on body weight and temperature, and four studies used metabolizable energy levels lower than 3,000 kcal kg^{-1} of diet). Therefore, 28 studies remained in the database (presented and briefly described in Table 2), totaling 226 observations and 1,968 animals. After selecting the papers, the information related to the proposed theoretical model and other additional variables were copied from sections material and methods and results in the original publication, and transferred to an electronic spreadsheet.

The average initial body weight of pigs used in the database was 48.6 kg (from 14.7 to 103.3 kg) while the average final body weight was 70.9 kg (from 22.3 to 127.5 kg). Average temperature in thermoneutral environments was 21.5 °C (from 18.3 to 25.0 °C) while it

Table 2 – Reference and description of studies included in the database.

References	Temperature range	Body weight		Average daily feed intake
		Initial	Final	
	°C	kg		kg d^{-1}
Batista et al. (2011)	22.7-34.2	30.0	58.3	1.92
Becker et al. (1992)	19.5-31.0	77.5	96.1	2.82
Campos et al. (2014)	24.0-30.0	54.4	64.0	2.43
Christon (1988)	21.0-32.0	40.7	64.1	1.76
Collin et al. (2001)	21.0-35.0	16.6	28.2	1.12
Ferreira et al. (2003)	22.0	15.0	30.2	1.19
Ferreira et al. (2005)	23.0	30.2	60.2	2.04
Ferreira et al. (2006)	32.3	15.2	29.9	1.09
Ferreira et al. (2007)	32.2	29.8	59.9	1.86
Kerr et al. (2005)	22.0-30.0	60.9	67.8	2.28
Kouba et al. (2001)	20.0-31.0	20.1	34.4	1.13
Le Bellego et al. (2002)	22.0-29.0	45.8	82.0	2.46
Le Bellego et al. (2002)	23.0-30.0	44.1	80.7	2.44
Lopez et al. (1991)	20.0-28.8	95.2	101.6	3.35
Lopez et al. (1994)	20.0-31.4	70.9	92.7	2.65
Manno et al. (2005)	22.7-34.2	15.0	30.0	1.06
Manno et al. (2006)	22.8-31.7	29.9	60.0	1.91
Moura et al. (2011)	30.0	69.2	88.6	1.66
Oliveira and Donzele (1999)	22.1-31.7	15.3	29.8	1.21
Rodrigues et al. (2012)	19.0-31.0	68.0	95.4	2.65
Sanches et al. (2010)	31.8	67.3	83.1	1.59
Sobrinho et al. (2013)	32.0	94.9	112.5	2.56
Song et al. (2011)	23.0	96.5	121.0	3.21
Stahly and Cromwell (1979)	22.5-35.0	34.7	67.6	1.83
Tavares et al. (2000)	21.3-32.0	30.6	60.0	2.03
Vaz et al. (2005)	21.8	15.1	29.9	1.15
Weller et al. (2013)	22.0-34.0	22.6	45.0	1.54
Witte et al. (2000)	18.3-32.7	90.3	126.3	3.12

was 31.3 °C (from 27.0 to 35.0 °C) in high-temperature environments. The relative air humidity was reported only in 21 articles, with an average value of 64 % (from 37 to 83 %).

Calculations and statistical procedures

The empirical models were used to generate FI estimates from observed data (pig body weight and environment temperature) presented on the database. Calculations were performed individually for each treatment (i.e. environmental temperature) of the original publication. Repeated-measures over time were considered when available. The observed FI data (results presented in the original publications) were then compared to the estimated FI values (predicted by each empirical model). Comparisons were performed by ANOVA using the General Linear Model procedure (PROC GLM).

Evaluating the model accuracy implies the assessment of closeness between its estimates and the observed values in terms of trueness and precision (Benchaar et al., 1998; Pomar and Marcoux, 2003). In the current study, the observed FI responses (obtained from previously published papers) were compared to the values estimated by the empirical models for the same scenario. Inputs for data modelling (i.e. temperature and body weight) were obtained in the previous published papers. The overall lack of accuracy was evaluated by the magnitude of the mean squared prediction error (MSPE). The MSPE was then decomposed, following the proposition described by Theil (1966), into error of central tendency (ECT), error of regression (ER), and error due to disturbances (ED). The trueness of a measurement indicates the degree of agreement between the expected and reference value. In this study, the lack of trueness (ECT + ER values) was evaluated as the systematic error, which could be easily corrected using linear regression. The lack of precision was evaluated in terms of random error (ED), which indicates the degree of internal agreement between independent measurements made under specific conditions.

The Pearson correlations were calculated considering observed and predicted values. Scatterplot graphs comparing these values were generated and analyzed jointly with linear regressions. In this regard, estimated FI values were regressed (PROC REG procedure) against observed FI values to determine the coefficient of determination (R^2), which indicated the goodness of fit.

The statistical analyses were performed considering two scenarios: (1) general population, in which the entire database (all observed data) was included in the analysis; or (2) reference population, in which the database was filtered in order to perform the simulation using only scenarios with environment (temperature range) and animals (body weight and sex) similar to that used in the models development. All statistical procedures were performed using SAS software (Statistical Analysis System, version 9.3).

Results and Discussion

Results obtained considering the general population (Table 3) and the reference population (Table 4) were used to evaluate the models in terms of lack of accuracy, trueness, and precision. The models with the lowest errors were considered the best predictors (Benchaar et al., 1998; Pomar and Marcoux, 2003).

Half of the evaluated models estimated FI values similar ($p > 0.05$) to those observed in the general population. Comparing estimated and observed values in populations similar to those used for the model development (reference populations) was possible only for seven equations. Simulations were not performed for Massabie III and IV models due to the limited number of observed values in the population similar to the those used for the model development. The Renaudeau I, II, and III models were not tested in reference populations since these equations were obtained by meta-analysis.

The predicted FI from Massabie I, II and III models were similar ($p > 0.05$) to the observed values in general population, while Massabie I and II produced estimates similar to the observed values in reference populations. Although Massabie IV estimated had lower

Table 3 – Agreement between the feed intake (FI) estimated by the empirical models and the observed values in the general population[1].

Model label	n[2]	FI	SD[4]	Estimated *vs* observed FI			MSPE[8]	MSPE		
				p[5]	SEM[6]	r[7]		ECT	ER	ED
		kg d^{-1} [3]								
Observed	226	2.11	0.69							
Massabie I	226	2.17	0.27	0.242	0.025	0.40	0.398	0.003	0.335	0.059
Massabie II	226	2.13	0.26	0.627	0.024	0.36	0.411	0.001	0.351	0.060
Massabie III	226	2.03	0.21	0.099	0.024	0.40	0.405	0.006	0.362	0.037
Massabie IV	226	1.97	0.19	0.004	0.024	0.40	0.420	0.019	0.370	0.031
Rinaldo	226	1.84	0.43	< 0.001	0.028	0.84	0.234	0.071	0.108	0.055
Quiniou	226	1.87	0.63	< 0.001	0.031	0.89	0.157	0.055	0.016	0.085
Collin I	226	2.57	1.02	< 0.001	0.042	0.91	0.444	0.214	0.060	0.170
Collin II	226	2.27	1.04	0.054	0.042	0.90	0.296	0.026	0.065	0.205
Renaudeau I	226	3.40	0.66	< 0.001	0.044	0.92	1.741	1.671	0.006	0.064
Renaudeau II	226	2.07	0.69	0.569	0.032	0.93	0.072	0.001	0.002	0.068
Renaudeau III	226	1.78	0.71	< 0.001	0.034	0.83	0.274	0.110	0.008	0.156
NRC	226	2.10	0.85	0.872	0.036	0.92	0.125	< 0.001	0.008	0.117

[1]General population = all observed data were used in the simulation; [2]n = Number of estimates or observations; [3]Feed intake was estimated individually for each treatment (i.e. environmental temperature) of the original publication; [4]SD = Standard deviation; [5]p = Probability comparing estimated and observed values (*F* test); [6]SEM = Standard error of the mean; [7]Correlation between estimated and observed values; [8]MSPE = mean squared prediction error; composed by ECT = error of central tendency; ER = error of regression; and ED = error due to disturbances.

Table 4 – Agreement between the feed intake (FI) estimated by the empirical models and the observed values in each reference population[1].

Model label	n[2]	Observed FI		Estimated FI		Estimated *vs* observed FI			MSPE[8]	MSPE		
		Mean	SD[3]	Mean	SD	p[5]	SEM[6]	r[7]		ECT	ER	ED
		kg d^{-1}		kg d^{-1} [4]								
Massabie I	38	2.43	0.47	2.44	0.07	0.865	0.038	0.45	0.196	< 0.001	0.192	0.004
Massabie II	38	2.43	0.47	2.34	0.18	0.280	0.041	-0.03	0.266	0.008	0.227	0.031
Rinaldo	148	2.25	0.50	1.99	0.26	< 0.001	0.024	0.62	0.229	0.068	0.120	0.041
Quiniou	40	2.31	0.43	2.09	0.32	0.010	0.044	0.89	0.094	0.051	0.023	0.020
Collin I	42	1.13	0.12	1.15	0.15	0.597	0.015	0.78	0.009	< 0.001	< 0.001	0.009
Collin II	42	1.13	0.12	1.01	0.30	0.021	0.025	0.73	0.064	0.013	0.009	0.041
NRC	150	2.24	0.51	2.23	0.68	0.871	0.035	0.83	0.149	< 0.001	0.003	0.146

[1]Reference population = data were filtered in order to simulate using only scenarios with environment (temperature range) and animals (body weight and sex) similar to that used in the model development; [2]n = Number of estimates or observations; [3]SD = Standard deviation; [4]Feed intake was estimated individually for each treatment (i.e. environmental temperature) of the original publication; [5]p = Probability comparing estimated and observed values (*F* test); [6]SEM = Standard error of the mean; [7]Correlation between estimated and observed values; [8]MSPE = mean squared prediction error; composed by ECT = error of central tendency; ER = error of regression; and ED = error due to disturbances.

(–7 %, $p < 0.05$) FI compared to observed values in general population database, this equation presented the highest precision (i.e., lowest ED = 0.031) among all studied models in this general scenario. Applying the Massabie models to the reference population generated best estimates in terms of accuracy (MSPE = -0.202 and -0.145, respectively for Massabie I and II), precision (ED = -0.055 and -0.029), and trueness (ECT + ER = –0.145 and -0.117) than applying the same models in general database. The ER accounted for most of the error in both simulations (general and reference populations) performed with Massabie models, which may be partially explained by the linearity of the models. In addition, body weight was not accounted in the Massabie models, even though the effects of temperature on animal performance are usually age-dependent (Bruce and Clark, 1979). Another particularity of these models is that pigs used in the model development were exposed to different temperature levels during the whole growing-period.

The FI estimates from the Rinaldo model were lower ($p < 0.05$) than the observed FI in general (–3 %) and reference populations (–12 %). Applying this model to the reference population generated similar accuracy (MSPE = –0.005), precision (ED = -0.014), and trueness (ECT + ER = 0.009) than applying it in general database. Most lack of accuracy of the Rinaldo model was due to the lack of trueness, which may be related to the temperature variation interval (20 to 30 °C) or the tropical humidity condition used for the model development (Rinaldo et al., 2000).

The Quiniou model estimates were lower ($p < 0.05$) than the observed FI in general (–11 %) and reference populations (–10 %). Using the reference population improved accuracy (MSPE = -0.063) and precision (ED = –0.065), but worsened trueness (ECT + ER = 0.003) compared to using the model in general population. It is important to address that housing conditions used to generate the model (respiratory chambers) were not considered when filtering the database (to obtain the reference population) due to the lack of available information. The accuracy of the model was limited by ED when applied to general population, while trueness was the limiting factor when applied to reference population.

The Collin I model estimated higher (+22 %, $p < 0.05$) FI compared to observed values in general database. When applied to reference population, the FI values predicted by Collin I were similar ($p > 0.05$) to the observed values. The estimates from Collin II model were similar ($p > 0.05$) to the observed values in the general population, while lower (–11 %; $p < 0.05$) estimates than the observed values were obtained in reference population. Applying Collin I and II models to reference population improved accuracy (MSPE = –0.435 and –0.232, respectively for Collin I and II), precision (ED = –0.161 and –0.164), and trueness (ECT + ER = –0.272 and –0.069) comparing to the use in the general population. These improvements were particularly relevant for Collin I model and are probably because both models were developed using young pigs and short-term challenge. When applied to general database, the models did not completely estimate FI variation (ED, by definition) observed in heavier pigs.

The estimates from Renaudeau I and III models differed from observed FI in the general database (model I, + 61 %; model III, –16 %; $p < 0.05$). However, the estimates from Renaudeau II model were similar ($p > 0.05$) to the observed values. The Renaudeau II model showed the lowest MSPE among all tested models, while both Renaudeau models showed the lowest ER. The Renaudeau II model showed also the lowest ECT among other Renaudeau models. The importance of ECT may be observed in Figure 1, in which the graphical comparison between estimates from Renaudeau I and II models is presented. Renaudeau III model showed higher ED (0.156) than Renaudeau I and II models (0.064 and 0.068, respectively). Unlike the equations

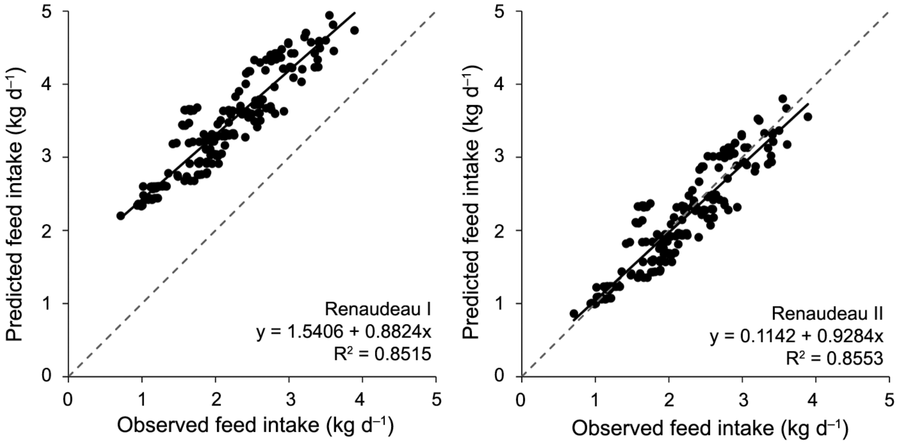

Figure 1 – Agreement between the observed feed intake and estimated values by the models Renaudeau I and Renaudeau II.

presented earlier, the Renaudeau models were obtained by meta-analysis and fitted using variance-covariance components, which is recommended to obtain higher accuracy (St-Pierre, 2001). Therefore, it was expected that estimates from these models would be closer to the general population, as the modelling procedure took into account the variability among studies, and consequently, among different population scenarios.

The FI estimated by the NRC model was similar ($p > 0.05$) to the observed values in general and reference populations. This model presented close MSPE (+0.024), ECT (+0.029), ER (-0.005), and the same ED values when applied in general or reference databases, which indicated that the model consistently predicted FI for both populations. The NRC model showed the lowest ECT among tested models. Although MSPE values were lower compared to most studied models, the major participant in the lack of accuracy of NRC model was the random error (i.e. ED), which is difficult to correct.

The models collected in literature to estimate FI based on independent variables (body weight, temperature) presented linear, exponential, and logarithmic fits. The Renaudeau III model includes parameter α, which describes a negative relation between body weight and FI when the environmental temperature exceeds maximum comfort temperature (upper critical temperature). Some authors reported FI reduction from 40 to 80 g d^{-1} for each 1 °C increase in environmental temperature (Quiniou et al., 2000; Renaudeau et al., 2011). Linear and quadratic fits estimate a constant rate of FI decrease as temperature and body weight increase. The NRC model also considered the critical temperature, which is affected by body weight. In this model, the deviations below the lower critical temperature and above the upper critical temperature (in other words, when comfort temperature is not met) affect pig heat metabolism (production or loss) and FI.

The diversity on experimental characteristics (i.e. other than the aspects considered in the filtering to generate the reference population) may have contributed to the high ED values observed for some models. One of the most important factors to be considered in the development of new models is the adaptation period, since several studies have shown that FI decreases during the first days of exposure to high temperature, but the pigs tend to recover their FI capacity afterwards (Renaudeau et al., 2008; Renaudeau et al., 2010). Therefore, it is not possible to perfectly describe the FI pattern of pigs in the short and long-term stress using only body weight and temperature in the modelling procedures (Whittemore et al., 2001; Renaudeau et al., 2011). Moreover, the susceptibility to temperature effects and time required for recovery may vary among individuals of a given population, which may reduce the precision of the models (Wellock et al., 2003). The use of modelling procedures that consider the variability among animals in the populations challenged by high environmental temperatures (i.e. stochastic approach) would be a major step forward for this area. Therefore, future research projects should be planned to provide the required information for the development of powerful mathematical models, which allow accurate FI estimates for pigs reared under high environmental temperatures, allowing precision feeding strategies to be applied in the field.

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