Shelf-life predictive models for Australian beef and lamb products in overwrap trays and modified atmosphere packs: development and evaluation

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Abstract

The Australian red meat industry has a reputation for producing meat with excellent shelf-life, which services both domestic and export markets in the retail and further processing sectors. However, this reputation is constantly challenged throughout supply chains due to unexpected temperature fluctuations and transit delays. Such incidences can result in unnecessary product wastage or markdowns, or otherwise require timely and costly evaluation of its sensory and microbiological condition to decide its disposition. To address this challenge within export markets, shelf-life predictive models for vacuum-packed (VP) beef and lamb primals were previously developed and are being adopted as a rapid, reliable and cost-effective decision-support tool to predict the remaining shelf-life, providing enormous economic benefits to the industry. This tool has the potential to provide further benefits to the Australian meat industry by expanding its applicability to retail-ready products within domestic markets. To this end, we used the data generated previously (Rood et al., publication in preparation) to develop predictive models for the shelf-life remaining for Australian beef and lamb products (*i.e.,* mince and steak) in overwrap (OW) trays and modified atmosphere packs (MAP, 20% CO_2 and 80% O_2). The remaining shelf-life is predicted based on the products initial total bacterial count or *Pseudomonas* numbers, and time:temperature parameters. The models were then validated using independent data and have bias and accuracy factors ranging from 0.93 to 1.03, and 1.10 to 1.11, respectively, when used for predicting the shelf-life of OW and MAP products. This indicates a good agreement between the observed and predicted shelf lives and generally underpredict the shelf-life of products with approximately ≤ 10% deviation, providing 'fail-safe' predictions. These new models together with the existing models for shelf-life prediction of VP red meat were incorporated into a 'ready to use' decision-making tool (known as 'Shelf-life Calculator for Red Meat') for the Australian red meat industry to effectively and reliably manage diverse supply chains to ensure high quality meat products with excellent shelf-life.

1. Introduction

The Australian red meat industry has a reputation for producing meat with excellent shelf-life, which services both domestic and export markets in the retail and further processing sectors (contributing $18.5 billion to Gross Domestic Product in 2017/2018) (Small et al., 2012). This reputation is constantly challenged by the need to minimise the loss of product shelf-life along different supply chains through unexpected temperature fluctuations and transit delays, and to meet a wide range of shelf life-related specifications imposed by intended international markets.

It is well established that the shelf-life of meat depends upon the degree of bacterial contamination obtained during processing and a range of intrinsic (meat biochemistry) and extrinsic (storage conditions) factors, of which temperature is considered the most important factor (Nychas et al., 2008). Chill storage temperature (-1.5 to 0°C) is the most common approach to maximise the shelf-life of fresh meat products by slowing bacterial growth rates (Borch et al., 1996; Doulgeraki et al., 2012). However, even small increases in storage temperature have been shown to significantly reduce the shelf-life, for instance, at temperatures of 0°, 2° or 5°C, the storage life was reduced by about 30, 50 or 70%, respectively, compared with storage at -1.5°C (Gill et al., 1988).

Temperature abuse, defined by Mills et al., (2014) as higher than 5°C during any stage of the cold chain, is onerous for the supplier. It can result in unnecessary product wastage and markdowns or, otherwise requires evaluation of its sensory and microbiological condition to decide its disposition. In many instances, the time taken to conduct an evaluation (*i.e.*, locate consignment, select and sample representative units, and await test results) increases the likelihood that the contents might be deemed sensorially unacceptable or do not comply with market specifications (Huynh et al., 2016). It is, therefore, critical for the success of the Australian red meat industry to be able to assure quality shelf-life remaining for products in diverse supply chains, and to improve the accuracy and timeliness with which a disposition decision can be made.

To address this challenge, shelf-life predictive models for vacuum-packed (VP) beef and lamb primals were successfully developed to predict the remaining shelf-life rapidly and accurately. These models were developed based on the growth rate of microorganism`s present (total viable count, TVC) and processes of spoilage (based on odour) as a function of temperature (Huynh et al., 2016; Kaur et al. 2021). The models have been validated by independent data from commercially available products in both simulated and commercial cold chains, both within Australia and internationally, and are being adopted as a reliable and cost-effective decision-support tool, providing enormous economic benefits to the industry. However, the focus of this tool to date has been on the shelf-life prediction of Australian VP beef and lamb in supply chains, especially for distant markets. To provide additional benefits to the Australian meat industry, this tool has potential to be further developed for red meat in common retail packaging formats within domestic markets, such as modified atmosphere packs (MAP, 20% CO_2 and 80% O_2) and overwrap (OW) trays (aerobic conditions).

Previously, we assessed the microbiological and sensorial qualities of beef and lamb products in MAP (*i.e.,* mince) and OW trays (*i.e.,* mince and steak) sourced from several Australian processors at different storage temperatures (ranging from 0°C to 12°C) (Rood et al., publication in preparation). These trials involved products with and without prior wet aging in VP at low temperatures (between 0°C and 4°C) for different durations (up to 35 days for beef and 14 days for lamb). In contrast to VP formats, it was found that colour quality was the most appropriate indicator for determining the shelf-life of all MAP and OW products, and the rate of colour quality loss was not affected by the wet aging durations tested, or product type (*i.e.,* mince or steak for OW). Furthermore, the end of shelf-life of OW products corresponded to the time taken for *Pseudomonas* spp. to reach a certain population level of. This agrees well that this organism is a specific spoilage organism (SSO) for chilled foods under aerobic conditions (Gill et al., 1977). The findings of those trials indicated the feasibility of developing models for separately predicting the shelf-life of MAP and OW products based on the rate of colour quality loss and time taken to reach *Pseudomonas* numbers that correspond to spoilage, respectively, as functions of temperature. To this end, we used the data from Rood et al. (publication in preparation) to develop predictive models for the shelf-life of beef and lamb products in MAP (*i.e.,* mince) and OW trays (*i.e.,* mince and steak) with prior wet aging durations up to 35 days for beef and 14 days for lamb. This paper describes the development of these models and the evaluation of their performance in simulated supply chains, with the overall aim to incorporate these new models together with the existing models for shelf-life prediction of VP red meat into a 'ready-to-use' decision-making tool for the Australian red meat industry.

2. Materials and methods

2.1 Model development

2.1.1 Model development for OW products based on pseudomonas levels

Data for specific growth rates of *Pseudomonas* on OW beef and lamb steak and mince at different storage temperatures (ranging from -0.5°C to 12°C) were obtained from Rood et al. (publication in preparation). To describe the effects of storage temperature on the rates of *Pseudomonas* growth, linear regression analysis was performed for each meat type (Ratkowsky et al., 1982) and the following model derived:

$$\sqrt{\mu_{Pseudomonas}} = (a \times T) + b \qquad \text{(Eq. 1)}$$

where $\mu_{Pseudomonas}$ is the specific growth rate of *Pseudomonas* (in days); *a* is the slope of the regression line; *T* is the temperature at which meat is stored (°C); and *b* is the regression coefficient.

Given the observed lag phase of *Pseudomonas* growth and the consistent relative lag time (RLT) observed across all product types and storage temperature (Rood et al., manuscript in preparation), the increase in *Pseudomonas* numbers over a given period of time could be estimated based on the growth rate from Equation 1 and the average relative lag time (RLT) as follows:

for: $t \geq (RLT/GT)$: $$Log_{10}\,N_t = Log_{10}\,N_o + 0.301 \times \left[\frac{\left(t - \left(\frac{RLT}{GT}\right)\right)}{GT}\right]$$

else $$Log_{10}\,N_t = Log_{10}\,N_o \qquad \text{(Eq. 2)}$$

where N_t is the number of *Pseudomonas* spp. after a period of time (t); N_o is the starting number (CFU/cm^2 or g); RLT is the observed relative lag time; GT (day) is generation time estimated based on the predicted growth rate from Equation 1 (*i.e.,* GT = 0.301/ $\mu_{Pseudomonas}$); and t is time in day.

Based on the growth data for *Pseudomonas* spp. (parameters obtained from Equation 1) and its levels at which the spoilage of beef and lamb products occurred (based on colour), the remaining shelf-life of a given OW product could be predicted using the following equation:

$$SL_{remaining} = \left[\frac{Log_{10}\ N_{spoilage} - Log_{10}\ N_t}{0.301}\right] \times GT_T \qquad \text{(Eq. 3)}$$

where $SL_{remaining}$ is the remaining shelf-life of a given OW product at a given temperature (T); $N_{spoilage}$ is the *Pseudomonas* numbers at the time of spoilage for OW products; N_t is the observed *Pseudomonas* numbers ($\log_{10}$ CFU/cm^2 or g) of that product after lag time is considered; GT_T (day) is estimated based on the predicted growth rate from Equation 1 (*i.e.,* GT = 0.301/GR) at a given temperature (T); and T is the expected future storage temperature (˚C).

2.1.2 Model development of MAP products based on rate of quality loss

The shelf-life of MAP products could be predicted based on the rate of colour quality loss as a function of temperature (Rood et al., manuscript in preparation). Accordingly, Equation (4) can then be expressed as:

$$SL = [\frac{1}{a \times (T - T_{\min})}]^2 \quad \text{(Eq. 4)}$$

where *SL* is the shelf-life of MAP products in (days); *a* is the slope of the regression line; *T* is the temperature at which meat is stored (°C); and $T_{\min}$ is the minimum temperature where the rate of colour loss is zero.

Equation (4) was further modified to predict remaining shelf-life by accounting for the observed initial TVC (at the time of packaging). This was achieved by calculating a correction factor that considers the initial TVC numbers and the calculated TVC numbers of a given product at the time of spoilage at a given temperature. This correction factor was then incorporated to Equation (4) to predict the remaining shelf-life ($SL_{\text{remaining}}$; day).:

$$SL_{\text{remaining}} = [\frac{N_0 - (N_{\text{obs}}) + N_{\text{s}}}{N_{\text{s}}}] \times [\frac{1}{a \times (T - T_{\min})}]^2 \quad \text{(Eq. 5)}$$

where N_0 is the initial TVC that was typically observed on MAP products based on the previous data of Rood et al. (publication in preparation) (log CFU/g); N_{obs} is the observed initial TVC (log CFU/g); and N_{s} is the nominal population level on MAP beef and lamb at the time of spoilage (log CFU/g). The N_{s} value was estimated by extrapolation of the regression line of TVC data to the time at which spoilage occurs at -0.5°C.

2.1.3 Production of a model interface

Based on the developed Equations (2) and (3) for OW, and (4) and (5) for MAP products a model interface was produced in MS 365 ®Excel to predict the remaining shelf-life of beef and lamb products in OW (*i.e.*, mince and steak) and MAP (*i.e.*, mince) with or without prior wet aging for up to 35 days for beef and 14 days for lamb.

2.2 Validation of the developed models in simulated supply chains

2.2.1 Validation shelf-life trials

Microbiological and sensorial assessments for MAP mince and OW mince and steak were conducted in accordance with Rood et al. (manuscript in preparation). Shelf-life trials were conducted at either constant (ranging from -0.5 to 12°C) or dynamic temperature profiles. The dynamic temperatures tested were representative of time:temperature profiles for domestic supply chains, which were obtained from industry partners (Table 1). This is with the exception of the final retail holding temperature, which was modified to represent different scenarios, including 'worse case'.

Table 1: Dynamic temperature profiles used for shelf-life validation trials simulating domestic supply chains.

Supply chain phase	Scenario 1		Scenario 2		Scenario 3	
	Temperature (°C)	Duration (h)	Temperature (°C)	Duration (h)	Temperature (°C)	Duration (h)
Chiller storage	2.4	10	2.4	10	2	17.5
Truck	0.3	1	0.3	1	1.5	1
Warehouse storage	1.7	20	1.7	20	1.7	21.25
Retail	8	Indefinitely	6	Indefinitely	4	Indefinitely

2.2.2 Determination of the shelf-life

The shelf-life of each product type was determined from colour assessments as described previously (Rood et al., manuscript in preparation). Specifically, products that were rated as 'marginal – colour off' were considered as commercially unacceptable and the time taken to reach that endpoint was recorded as the shelf-life of the product. Due to the variability of product characteristics even within the same trial, the shelf-life was determined when at least one of the replicates were rated as unacceptable at any given time point and subsequent time points.

2.2.3 Comparison between observed and predicted shelf-life

The shelf-life of each product type was estimated using the developed predictive models based on initial TVC or *Pseudomonas* numbers, and time:temperature history. The performance of the developed models to predict the shelf-lives of different products was evaluated using the methods described by Ross (1996). Bias and accuracy factors for the models were calculated from observed and predicted shelf lives (days) of each packaging type.

3. Results and Discussion

Shelf-life predictive models for VP beef and lamb primals were previously developed based on the growth rate of TVC and processes of spoilage (based on odour) as a function of temperature (Huynh et al., 2016; Kaur et al. 2021). The models have been validated by independent data from commercially available products in both simulated and commercial cold chains and are being adopted as a reliable and cost-effective decision-support tool to predict the remaining shelf-life rapidly and accurately. To provide additional benefits to the Australian meat industry, this study developed shelf-life predictive models for red meat in common retail packaging formats, such as OW trays and MAP, to be incorporated into the decision-support tool.

To develop shelf-life predictive models for OW and MAP beef and lamb products, a comprehensive study was conducted to determine the microbiological and sensory qualities of meat as they relate to spoilage (Rood et al., manuscript in preparation). That study, consistent with previous studies, indicated that the rate of quality loss could be predicted as a function of temperature (Gill et al., 1988; Kaur et al., 2021). It was also evident that the spoilage process was different between MAP and OW trays. These results were expected given the unique selection pressures created by the different gaseous atmospheres between MAP and OW packaging formats (Kameník et al., 2014; Kiermeier et al., 2013; Taylor et al., 1990). Specifically, *Pseudomonas* spp. is a specific spoilage organism (SSO) for chilled foods under aerobic conditions, such as OW meat. However, its growth is suppressed by CO_2 under MAP conditions (Gill et al., 1977). Accordingly, separate shelf-life predictive models were developed for each packaging format.

3.1. Development of shelf-life predictive models for OW beef and lamb products

Given that the growth rates of *Pseudomonas* were similar at a given temperature regardless of their source, type of product (mince or steak) and meat type (beef or lamb) (Rood et al., manuscript in preparation), the growth rate data generated was combined and was fitted with the square root model of Ratkowsky et al., (1982) to describe the effects of storage temperature on the growth rate of *Pseudomonas* on OW products. This was in accordance with Equation (1). However, the RLT and the *Pseudomonas* numbers at the time of spoilage were found to be different between meat type. Beef had a larger RLT and higher *Pseudomonas* spoilage threshold compared to lamb (Rood et al., manuscript in preparation). This indicated the need to develop two different models. Table 2 shows the model parameters for different meat types in accordance with Equations (1) and (2).

Table 2.

Estimated values of the parameters of Equation (1) and (2) for OW beef and lamb products (mince and steak), based growth rate of *Pseudomonas*.

Product type	*a*	*b*	T_{min} (°C)[a]	RLT
OW beef	0.0145	0.1566	-10.8000	5.3406
OW lamb	0.0145	0.1566	-10.8000	4.2066

[a] T_{min} is the theoretical minimum temperature and was estimated by extrapolation of the regression line to $\sqrt{\mu_{\text{quality loss}}/\mu_{Pseudomonas}} = 0$.

With the parameters obtained above, models specifically to predict the remaining shelf-life of OW beef and lamb products were developed and can be defined by their respective Equations (6) and (7).

$$SL_{remaining\ (beef)} = \left[\frac{6.933 - Log_{10}\,N_t}{0.301}\right] \times GT_T \qquad \text{(Eq. 6)}$$

$$SL_{remaining\ (lamb)} = \left[\frac{6.291 - Log_{10}\,N_t}{0.301}\right] \times GT_T \qquad \text{(Eq. 7)}$$

where $SL_{remaining}$ is the remaining shelf-life of a given OW product at a given temperature (T); $N_{spoilage}$ is the *Pseudomonas* numbers at the time of spoilage for OW beef (6.933 $\log_{10}$ CFU/cm^2 or g) or lamb (6.291 $\log_{10}$ CFU/cm^2 or g) (Rood et al., manuscript in preparation); N_t is the observed *Pseudomonas* numbers ($\log_{10}$ CFU/cm^2 or g) after lag time is considered; GT_T (h) is estimated based on the predicted growth rate from Equation 1 (*i.e.,* GT = $0.301/\mu_{Pseudomonas}$) at a given temperature (T); and T is the expected future storage temperature (˚C).

3.2 Development of shelf-life predictive models for MAP beef and lamb products

Similar to Section 3.1, we applied the square root model of Ratkowsky et al., (1982) to the relevant data of Rood et al. (manuscript in preparation) to describe the effects of storage temperature on the rates of quality loss for MAP (based on colour scores) as described in Equation (4). Table 3 shows the model parameters (*a* and $T_{\min}$) for MAP products for different meat types. It was found that different meat types (beef and lamb) have different model parameters. This was likely due to differences in their biochemistry, particularly glycogen and lactic acid contents, as well as pH, where beef (pH 5.5-5.8) tends to be lower compared to lamb (pH 5.6-6.8) (Carse & Locker, 1974). Such differences can affect the growth of bacteria with consequential effects on shelf-life. Accordingly, two separate models were developed to predict the shelf-life of beef and lamb in MAP. A similar observation was also made for the development of shelf-life predictive models for VP beef and lamb primals (Huynh et al., 2016; and Kaur et al., 2021)

Table 3.

Estimated values of the parameters of Equation (4) for MAP beef and lamb mince based on rate of quality loss.

Product type	*a*	$T_{\min}$ (°C)[a]
MAP beef	0.0059	-8.4641
MAP lamb	0.0064	-7.6875

[a] $T_{\min}$ is the theoretical minimum temperature and was estimated by extrapolation of the regression line to $\sqrt{\mu_{\text{quality loss}}/\mu_{Pseudomonas}} = 0.$

With the parameters (a and T_{min}) obtained above, predictive models for the shelf-life of MAP products were developed in accordance with Equation (4). However, such models could not be used to specifically predict the remaining shelf-life. This requires a number of factors (*i.e.,* N_0, and N_s) to be determined based on previous data from Rood et al. (publication in preparation) for the shelf-life of MAP products (*i.e.,* as defined in Equation (5)). Specifically, N_0 is the initial TVC for MAP beef and lamb based on the experimental data for a given product stored at -0.5˚C (4.1 and 4.6 log CFU/g, respectively); N_{obs} is the observed initial TVC (log CFU/g) of the product in question; and N_s is the nominal population level of MAP beef and lamb at the time of spoilage (log CFU/g). The N_s value was estimated by extrapolation of the regression line of observed TVC data to the time at which spoilage occurs at -0.5˚C. The extrapolated N_s value was estimated to be 8.77 log CFU/g for beef and 8.46 log CFU/g for lamb. These, taken together, were used to develop models to predict the remaining shelf-life of MAP beef (Equation (8)) and lamb (Equation (9)) as follows:

$$SL_{\text{remaining}} = [\frac{4.10 - (N_{obs}) + 8.77}{8.77}] \times [\frac{1}{0.059 \times (T - -8.464)}]^2 \qquad \text{(Eq. 8)}$$

$$SL_{\text{remaining}} = [\frac{4.64 - (N_{obs}) + 8.43}{8.43}] \times [\frac{1}{0.0064 \times (T - -7.688)}]^2 \qquad \text{(Eq. 9)}$$

The developed models were incorporated into a software tool (implemented in MS 365 ®Excel) that allows prediction of remaining shelf-life of beef and lamb MAP (mince) and OW (steak and mince) reprocessed from VP primals aged up to 35 days for beef and 14 days for lamb. To use this tool, the user selects the meat type (beef or lamb), packaging format (OW or MAP), and product type (mince or steak), enters the starting bacterial numbers (*Pseudomonas* for OW or TVC for MAP), and a time:temperature profile, typically collected by a temperature logger. The tool then predicts the remaining shelf-life of the product based on assessment of predicted growth and colour kinetic responses.

3.3 Shelf-life data for model validation

The shelf-life validation data obtained for various OW (n=11) and MAP (n = 16) products at constant and simulated supply chains (*i.e.*, at fluctuating temperatures) are summarise in Table 4 and 5, respectively. These include bacterial numbers at the start of the trial (*Pseudomonas* for OW and TVC for MAP), average storage temperatures, and observed shelf lives. The data was then used to evaluate the performance of the developed models.

Table 4: Summary of the observed and predicted shelf-lives (based on colour score) of overwrapped beef and lamb products reprocessed from wet aged VP primals and stored at different temperatures.

Packaging format and meat type	Retail cut	Wet aging duration (days)[a]	Initial count ($\log_{10}$ CFU/cm^2 or g)[b]	Average temperature[c]	Observed Shelf-life (days)[d]	Predicted Shelf-life (days)[e]	Model bias factor[f]	Model accuracy factor[f]
OW Beef	Steak	19	3.85	5.76[g]	4	3	0.94	1.11
				3.89	4	4		
				-0.34	8	9		
		35	4.12	6.28	3	3		
				2.29	5	5		
	Mince	Fresh	3.15	4.03[h]	5	4		
OW Lamb	Steak	Fresh	2.39	1.94	7	6	0.93	1.08
				-0.71	10	10		
		14	3.93	5.23[g]	3	3		
				3.78	3	3		
	Mince	Fresh	3.26	4.62[h]	5	4		

a. Primals were aged in VP at 0-3°C for different durations before reprocessing into OW products.
b. Initial *Pseudomonas* counts (upon the commencement of the trials, i.e., within 30 mins after reprocessing and packaging).
c. Observed average temperature during trial.
d. The time taken for OW products to reach end of shelf-life based on colour score (*i.e.,* score of ≤4).
e. The predicted shelf-life generated by the developed Shelf-life Calculator.
f. Bias and accuracy factor indices of Ross (1996) to assess the performance of the model.
g. Dynamic temperature profile (based on scenario 2 in Table 1).
h. Dynamic temperature profile (based on scenario 3 in Table 1).

Table 5: Summary of the observed and predicted shelf-lives (based on colour score) of modified atmosphere packed beef and lamb mince reprocessed from wet aged VP primals and stored at different temperatures.

Meat type	Wet aging duration (days)[a]	Initial count ($\log_{10}$ CFU/g)[b]	Average temperature[c]	Observed Shelf-life (days)[d]	Predicted Shelf-life (days)[e]	Model bias factor[f]	Model accuracy factor[f]
Beef	Fresh	4.93	8.24	4	4	0.93	1.07
			2.3	10	9		
			-0.27	19	16		
	12	5.54	3.62[g]	7	7		
			-0.20	14	15		
	21	5.95	6.19	5	4		
			2.01	9	9		
Lamb	Fresh	4.42	4.20[g]	7	8	1.03	1.03
	Fresh	4.72	8.22	4	4		
			5.62	6	6		
			1.92	11	11		
			0.11	16	17		
	12	3.96	8.36	4	4		
			1.93	11	12		
			0.1	18	18		
	12	4.60	11.98	2	3		

a. Primals were aged in VP at 0-3°C for different durations before reprocessing into MAP products.
b. Initial counts (upon the commencement of the trials, *i.e.*, within 3.5 hours after reprocessing and packaging).
c. Observed average temperature during trial.
d. The time taken for MAP products to reach end of shelf-life based on colour score (*i.e.,* score of ≤4).
e. The predicted shelf-life generated by the developed Shelf-life Calculator.
f. Bias and accuracy factor indices of Ross (1996) to assess the performance of the model.
g. Dynamic temperature profile (based on scenario 2 in Table 1).

3.3 Performance of predictive models

The shelf-life predictive models for OW and MAP beef and lamb products were evaluated for their performance by comparison with independent data not used to generate the models. The MS 365 ®Excel tool as described above (Section 2.1.3) was then used to predict the shelf-life of different meat products based on their time:temperature history and initial microbial counts. The observed *vs.* predicted shelf lives (days) of each product are shown in Tables 4 and 5.

The bias and accuracy factor analyses of Ross (1996) were used to assess the performance of the predicted shelf-life generated by the model compared with the observed data. Ross (1996) reported that the bias factor serves as a measurement index for the average variation between the predicted and observed values, whereas the accuracy factor is used to estimate the accuracy of an established model. Bias and accuracy factor values of 1 indicate a perfect agreement between observed and predicted values. In this study, the models were found to have a bias factor of 0.94 and 0.93, and an accuracy factor of 1.11 and 1.08 when used for predicting the shelf-life of beef and lamb steak and mince in OW trays, respectively. Similar results were found for models used for predicting the shelf-life of beef and lamb mince in MAP which were found to have bias factor of 0.93 and 1.03, and an accuracy factor of 1.07 and 1.03, respectively. These indices showed a good agreement between the observed and predicted shelf lives of OW and MAP beef and lamb products. The models generally underpredict the shelf-life of products with approximately ≤ 10% deviation, providing 'fail-safe' predictions. These results are also in accordance with previous models developed for shelf-life prediction of beef and lamb in VP in which the bias factor of 1.02 and 0.90, and an accuracy factor of 1.10 and 1.11, respectively, indicating a 'fail-safe' predictions with approximately 10% deviation (Huynh et al., 2016). It should also be noted that an over-prediction of time to spoilage was also observed by Albrecht et al., (2019), Bruckner et al., (2013) and Tang et al., (2013) for their shelf-life predictive models for poultry and pork meat.

From the above, the developed models were successfully validated to provide an accurate and reliable prediction of the shelf-life of beef and lamb products stored under common retail ready packaging formats, such as OW and MAP. Such models, along with existing models for shelf-life prediction of VP red meat can be readily adopted as a reliable decision-making tool in commercial supply chains. This tool will offer a cost-effective approach for meat processors to optimise and better understand their supply chains. Disposition of product affected by adverse events, such as unexpected temperature fluctuations or extended delivery times can be resolved speedily by using this tool.

4. Conclusion

This study describes the development of 'ready-to-use' shelf-life predictive models for OW and MAP beef and lamb products. The models were validated by independent data from commercially available products in simulated supply chains and were found to generally underpredict the shelf-life with approximately ≤ 10% deviation, providing 'fail-safe' predictions. The new models together with the existing models for shelf-life prediction of VP red meat can be incorporated into a 'ready-to-use' decision-making tool for the Australian red meat industry to optimise and monitor meat quality in diverse supply chains.

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