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Predicting Quality Attributes and Waste of Strawberry Packed Under Modified Atmosphere Throughout the Cold Chain

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Predicting quality attributes and waste of strawberry packed under modified atmosphere throughout the cold chain

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Abstract

Modified Atmosphere Packaging (MAP) is used commercially to extend the shelf life of strawberries. The attainment of desired gas (O_2, CO_2) concentrations inside MAP relies on the product respiration and the mass transfer through packaging and will affect the quality. The objective of this work is to build a mathematical model for strawberries to assess the effect of the uncertainties on headspace gas concentration and quality: 1) cold chain related temperature and relative humidity variations and 2) variability associated to product respiration and quality based on literature. Weight loss was more influenced by the cold chain storage conditions (temperature and RH) whereas spoilage had similar influence of cold chain conditions and product parameters. Waste generated in the cold chain was estimated from industrial standard weight loss and spoilage thresholds. A sensitivity analysis of the stochastic MAP model showed the influence of input parameters on the quality pointing to interventions associated to a reduction of the respiration rate (e.g. modification of packaging) and reduction of water transfer (e.g. coating) may prove more successful than other interventions to which the waste generation of this product is not so sensitive to. As a conclusion this work presents a

toolbox to interpret cold chain data: 1) develop mathematical models to predict fate of quality 2) simulate cold chain conditions allowing for uncertainty 3) estimate the waste generation kinetics based in quality criteria and thresholds 4) perform a sensitivity analysis to identify most sensitive technological parameters 5) identify interventions that will affect those technological parameters.

Keywords: mathematical modelling; coating, variability; sensitivity analysis; strawberry

1. Introduction

Strawberries are highly perishable in nature with high metabolic rate and thus have short shelf life. The major limiting factor of the quality of strawberries is spoilage due to *Botrytis* infection. The tissue of strawberry deteriorates through natural senescence during the food distribution chain and *Botrytis* develops due to tissue softening because of over ripening (Hertog et al., 1999). The most effective intervention to extend the shelf life is to use low temperature storage (Sanz et al., 2000). Packaging is another important technique to extend the shelf life of perishable fruit to facilitate longer transportation distribution (Caner et al., 2008). The storage quality can be further improved by using Modified atmosphere packaging (MAP) and altering the concentration of gases surrounding the fresh strawberry (Geysen et al., 2005; Zhang et al., 2003).

MAP has been used to increase and preserve the shelf-life of produce, while also responding to the emerging consumer demand for convenience and quality (Oliveira *et al.*, 2012b). Design of optimal Modified Atmosphere Packaging for specific produce depends on the characteristics of produce, permeability of packaging film and dependence on external factors such as temperature and relative humidity (Zagory e Kader, 1988). Apart from extending the shelf life of strawberries it maintain the quality characteristics firmness, prevents weight loss and microbial spoilage (Caner et al., 2008; Larsen and Watkins, 1995; Pelayo et al., 2003).

Sources of uncertainty in postharvest distribution of strawberries

Managing uniform quality of produce is a tedious task because of many sources of variability, inherent biological variation and fluctuation in storage conditions (Duret et al., 2015). Postharvest management aims at controlling the variation as much as possible by sorting and grading product at different stages of postharvest chain (Hertog et al., 2009a). Identifying and quantifying different sources of variance in the experimental data and assigning them to uncertainties in parameter value and error provides better interpretation of postharvest behaviour (Aguirre, 2008; Hertog et al., 2007a). Biological variation has been previously studied by including this variation in the quality change model, estimating the initial variation ("harvest age") and using it to assess the effect throughout the postharvest chain (Hertog et al., 2009b). Over the last decade models explaining biological variation in fresh produce have been developed (Duret et al., 2015; Gwanpua et al., 2014; Hertog et al., 2007b, 2004).

In a MAP gas exchange kinetic model the uncertainty can also be estimated at the respiration models of the strawberries. Michaelis-Menten inhibition constants for O_2 consumption (Km_{O_2}) and constant for fermentative CO_2 production ($Kmc_{O_{2(f)}}$), the reference rate constant of maximum oxygen consumption (Vm_{O_2}) and maximum carbon dioxide production ($Vm_{CO_{2(f)}}$) and the activation energy rate that have been experimentally assessed will have uncertainty, conventionally in the form of a standard error, associated to it (Hertog et al., 1999).

When describing the kinetics of weight loss in a packaged produce, the fruit skin mass transfer coefficient (K_s) is one of the main source of product variation due to structural variation in skin of individual fresh produce along with the initial spoilage of batch (N_0) (Hertog et al., 1999). The statistical values of these parameters are presented in Table 2. The objective of this study is to predict the quality of strawberry in supply cold chain. To study the effect of cold chain variability and product variability on the quality of strawberry which will help estimate the waste generated. Sensitivity analysis is then performed to account for the effect of different parameters and design an intervention that will reduce losses in supply chain.

2. Materials and method

2.1. Model hypothesis

1. CO_2 production is a combination of oxidative and fermentative production, the oxidative consumption is proportional to the O_2 evolution and the fermentative production follows the Michaelis-Menten equations.
2. The temperature of the surface of commodity (T_s) is equal to the temperature of air surrounding the commodity (T_i).
3. The surface of the commodity is assumed to be perfectly saturated condition.
4. The metabolic energy released by produce, large part of it (80-100 %) is dissipated as heat.
5. Condensation of water may occur in the product or the package when the free volume air relative humidity reaches 100% using a saturated surface model.
6. The quality of strawberry is described as weight loss due to transpiration and by *Botrytis* spoilage as modelled by (Hertog et al., 1999).

2.2. Mathematical Model development

The mathematical model takes into account the heat and mass transfer balances due to the metabolic behaviour of strawberry and the transport phenomenon across package. The assumptions used in the mathematical model and sub model to describe respiration-transpiration of strawberry and gas transport across package (Table 1). The influence of these on the quality of strawberry during distribution chain is estimated.

2.2.1. Transpiration

Transpiration is caused due to vapour pressure deficit VPD (Pa) between the produce surface and the surrounding atmosphere (Xanthopoulos et al., 2012). VPD is the function of difference in the amount of moisture in air and the amount of moisture air can hold when it is saturated (Becker et al., 1996).

$$VPD = (a_w - RH)p_s \tag{11}$$

It is assumed that water activity of strawberry is ($a_w \sim 0.99$).

Saturated water vapour pressure at the surface of commodity can be calculated using following equation (Rennie and Tavoularis, 2009) based on saturated water vapour pressure data from ASHRAE (1997).

$$p_s = 0.041081186{T_s}^3 - 32.43188{T_s}^2 + 8567.5269T_s - 757070.1 \tag{12}$$

Transpiration occurs when water vapour pressure at the surface of commodity exceeds the water vapour pressure of the headspace of package (Becker et al., 1996; Xanthopoulos et al., 2012).

$$m_w = VPD \times K_t \tag{13}$$

Transpiration rate (kg $m^{-2}h^{-1}$) is product of water vapour flux (m_w) and the surface area of the commodity(A_c)

$$t_r = m_w A_c \tag{14}$$

$$K_t = \frac{1}{\left(\frac{1}{K_s} + \frac{1}{K_a}\right)} \tag{15}$$

Here, K_t is transpiration coefficient (kg $m^{-2}s^{-1}Pa^{-1}$) which is constant for the same commodity, K_s (kg $m^{-2}s^{-1}Pa^{-1}$) is skin mass transfer coefficient obtained from literature,

K_a (kg m^{-2}s^{-1}Pa^{-1}) is air film mass transfer coefficient calculated using the Sherwood-Reynolds-Schmidt correlations (Becker et al., 1996) .

$$Sh = \frac{K_a d_c}{D_{H_2O,air}} \tag{16}$$

For convective mass transfer from commodity spherical in shape, (Becker et al., 1996) recommended Sherwood-Reynolds-Schmidt correlation of the following form to be used.

$$Sh = 2.0 + 0.552\, Re^{0.53} Sc^{0.33} = \frac{K_a'\, d_c\, R\, T_s}{D_{H_2O,air}\, M_{H_2O}} \tag{17}$$

It is assumed, there is negligible flow around the commodity ($Re \approx 0$). Therefore, air film mass transfer coefficient can be calculated as:

$$K_a = 2 \times \frac{D_{H_2O-air}\, M_{H_2O}}{d_c\, R\, T_s} \tag{18}$$

Transpiration Heat

The process of transpiration requires energy for evaporation of moisture from surface of produce, this process cools down the commodity. Evaporative heat transfer rate (Q_{tr}) is a product of latent heat of vaporization (λ) and transpiration rate (t_r).

$$Q_{tr} = \lambda\, t_r \tag{19}$$

2.2.2. Relative humidity in headspace

The concentration of water vapour inside the package is dependent on the rate of water vapour transfer from the moisture sources to moisture sinks within the package. The main moisture sources in the package is water transpired from the surface of fresh produce (t_r) and the main source of moisture sink is permeation of water vapour through the film (m_{pr}) (Becker et al., 1996).

The amount of water vapour in the headspace is calculated using humidity ratio which is the ratio of mass of water vapour in headspace to mass of dry air in the headspace of package (kg/kg).

$$\frac{dHR}{dt} = \frac{t_r - m_{pr}}{W_a} \tag{20}$$

Relative humidity is calculated as ratio of humidity ratio inside the package (*HR*) to the humidity ratio of saturated water vapour (HR_{sat}) (Becker et al., 1996; Jalali et al., 2017; Song et al., 2002).

$$HR_{sat} = \frac{0.62198 P_s}{(P_{atm} - P_s)} \tag{21}$$

$$RH = \frac{HR}{HR_{sat}} \tag{22}$$

2.2.3. Condensation

In perforation mediated packaging condensation rate is seldom modelled in MAP, due to near saturation conditions and non-uniform or fluctuating temperature within the package, condensation can occur on the commodity surface or inside of package film and walls. It is assumed that the water vapour condensed on the surface of commodity does not penetrate the skin of fresh produce. For condensation to take place the partial pressure of water vapour should be greater than the saturated water vapour pressure (Jalali et al., 2017; Joshi et al., 2018; Rennie and Tavoularis, 2009).

$$M_{con} = \begin{cases} K_a\left(P_{H_2O} - P_c\right)\delta A_c\,, & if\,(P_{H_2O} > P_s) \\ 0 & otherwise \end{cases} \tag{23}$$

The corresponding rate of release of heat due to condensation on the surface of commodity is Q_{con} calculated as:

$$Q_{con} = \lambda\, M_{con} \tag{24}$$

The rate of condensation on package wall (M_{wcon}) is calculated similarly using air film mass transfer coefficient (K_a).

$$M_{wcon} = \begin{cases} K_a\left(P_{H_2O} - P_s\right)\delta A_w, & if\,(P_{H_2O} > P_s) \\ 0 & otherwise \end{cases} \quad (25)$$

The heat released during condensation (Q_{wcon}) heats up gases in atmosphere near wall.

$$Q_{wcon} = \frac{\lambda M_{wcon}}{A_w} \quad (26)$$

2.2.4. Quality

The quality of fresh produce is determined by the overall characteristics (appearance, texture, flavour and nutritive value) of fresh produce (ElMasry et al., 2007). The perception of quality is highly subjective and depends on consumer and number of qualitative factors. Quality of fresh produce in general is often described using a chemical kinetic model (Merts, 1996). The main attributes of quality in strawberries is weight loss and spoilage.

2.2.4.1. Weight loss

The amount of water vapour transpired from the surface of fruit (t_r) and carbon loss due to respiration accounts for the weight loss.

$$\frac{dW_l}{dt} = t_r + M_c r_{CO_2} W_s \quad (27)$$

2.2.4.2. Spoilage

The inhibition of spoilage in strawberry in modified atmosphere is assumed to be the result from inhibitory effect of gas composition on gas exchange in strawberry. When the gas exchange is inhibited the overall metabolic rate and the ripening rate will be inhibited resulting in a slower spoilage rate (Hertog et al., 1999). (Tijskens and Polderdijk, 1996) used relative metabolic rate (equation 28), which represents a ratio of the actual respiration rate under any gas conditions to the respiration rate under normal air conditions (21% O_2, 0.03% CO_2) at the same temperature. In the case of strawberries fermentative activities are taken into account in the respiration model therefore the gas exchange is expressed in terms of CO_2 production.

$$Rel_{MR} = \frac{r_{CO_{2(f)}}([O_2],[CO_2],[H_2O],T_s)}{r_{CO_2}(21\%\, O_2, 0.03\% CO_2, T_s)} \quad (28)$$

The spoilage of strawberry due to *Botrytis*, in terms of percentage of strawberry affected can be described by the following ordinary differential.

$$\frac{dN}{dt} = Rel_{MR} \times k_s \times N \times \left(\frac{N_{max} - N}{N_{max}}\right), initiate\ at\ N_0 \quad (29)$$

Where N_{max} is maximum spoilage (100%), k_s is the spoilage rate constant which depends on the temperature according to Arrhenius equation. The value of activation energy associated with the spoilage rate constant is mentioned in table 2.

3. Numerical Simulations of the ODE system

The mathematical model developed in the section above is used to estimate the effect of input parameter uncertainty on the prediction of concentration of gases and effect on waste generation during cold chain distribution. Stochastic simulations were performed using three simulation scenarios to analyse the results of variability on strawberry cold chain distribution.

1) A distribution scenario where temperature and relative humidity are varying accordingly with the cold chain data described in (Joshi et al., 2018).

2) A distribution scenario with an ideal cold storage temperature (40 C). and relative humidity (80%) and with variable product properties as specified in table 2.

3) A distribution scenario considering the joint uncertainties of 1) and 2).

The value of product parameters used in the model are in table 2. The ordinary differential model was solved using the deSolve library (Soetaert et al., 2010) using the *lsoda* solver on R 3.4.3 (R Development Core Team, 2008). All the plots were produced using the ggplot2 library (Wickham, 2009). Sensitivity analysis using a main and first order interactive effects model excluding time were analysed using a Lowry plot (McNally et al., 2011).

3.2. Uncertainty assessment

3.2.1. Assessment of cold chain on waste production

The uncertainty in cold chain was expressed in changes temperature and relative humidity. Figure 3.3 shows the temperature and relative humidity export cold chain profile used for the study (Joshi et al. 2018). Figure 3.4 shows the retail cold chain profile for temperature and relative humidity used for the study. The mathematical model was simulated against these cold chain profiles to study the effect of cold chain uncertainty on the quality of strawberry results are presented in section 5.3.1.

3.2.2. Assessment of product variability on waste production

The product parameters responsible for variability are presented in table 2 are simulated at fixed cold chain profile of ideal storage temperature of 4^0C and relative humidity 80%. The results in following section show the uncertainty due to the product parameter uncertainty on the quality parameters of strawberry causing waste in supply chain.

To further investigate the effect of individual product parameter, a sensitivity analysis was performed using a main and first order interactive effects model excluding time. The results are presented using a Lowry plot (McNally et al., 2011)

3.2.3. Combined assessment of product and cold chain uncertainty effect on waste

The combined assessment of cold chin uncertainty and product uncertainty was done to understand which parameter is more influenced by which uncertainty and the interventions that can be designed to maintain the quality and reduce waste in supply chain. For further analysis, sensitivity analysis is done to access the effect of individual parameter on quality explained in next section.

3.3. Validation

Strawberry (150g, 3-5 cm diameter) were purchased from local wholesale fruit market Dublin, Ireland and packaged in an industry standard perforated polypropylene LDPE film (4 perforations) and were stored in either ideal conditions (4^0 C) or abuse condition (1/2 day in packaging facility at 8 ºC followed by transportation at 4 ºC up to 2 days, followed by retail storage including 4h at 20 ºC, followed by 2 days at 8 ºC, and finalised by retail shop 4h at 20ºC 2 days at 8 ºC) for a period of 10 days.

A chitosan solution (1.5 %) was prepared by dissolving chitosan (Sigma-Aldrich Ltd., UK,medium molecular weight, 75-85% deacetylated) in distilled water containing 1% glacial acetic acid using a magnetic stirrer. After complete dissolution 0.2% Tween 80 (Sigma-Aldrich Ltd., UK) was added to the solution. The pH of the solution was adjusted to 5.2 with 1N NaOH (Sigma-Aldrich Ltd., UK) (Petriccione et al., 2015). A second sample of the same batch of strawberries was immersed in chitosan solution for 60s then allowed to dry for 1 hour in air dryer at room temperature and stored in the same conditions as above.

Strawberries were visually examined on regular intervals during storage period. The fruits showed surface mycelia growth or bacterial lesions were considered decay. Results were expressed as percentage of spoiled fruits. Weight loss was expressed as percentage loss of initial weight (Han et al., 2004).34.

Results and discussions

4.1. Cold chain variability assessment

The mathematical model in section 2 was used to simulate the effect of cold chain variation to predict the changes in the concentration of gases in the headspace and quality of strawberry against the export cold chain profile. The governing ODE equations (5 and 6) were used to obtain the concentration of carbon dioxide and oxygen in the headspace of package. The results presented in Fig 1 were simulated along with the export cold chain. It can be seen how the creation and maintenance of optimal atmosphere inside modified atmosphere package depends on the respiration rate of the product and on the permeability of the films both of which are dependent on temperature. At very low oxygen concentration (<2%) anaerobic respiration is initiated in the tissue which shortens the shelf life. The results obtained from the simulations showed there was no anaerobic condition observed in the package.

Temperature fluctuation and their effect on the atmosphere inside the package have a major effect on the quality of strawberry. The spoilage of strawberry increases with increase in temperature, however the effect of MA was evident on the package. A linear effect of concentration of CO_2 is observed on the spoilage. At 0% CO_2, 1.72 % spoilage is observed to 0.87% spoilage at 18 % CO_2 (Kader, 1986). At higher concentration of CO_2 (20-80%) clear inhibition was observed. At these extremely high level of CO_2 fungal growth is inhibited in strawberries (Ke et al., 1991). The amount of water vapour in the headspace of the package is estimated using Fick's diffusion and psychometric equations, this was used to calculate relative humidity inside the package. The results obtained showed the package water vapour pressure was saturated (RH=100%) during storage. (Fishman et al., 1996) obtained similar results for MAP of mango, and (Song et al., 2002) obtained similar experimental and predicted results of relative humidity saturating rapidly during storage.

Weight loss as a result of transpiration and carbon loss due to respiration was directly dependent on the temperature (Fig 1 (c)). Sanz et al., (2000) reported weight loss of 3.53% in control packages and 0.9% in micro-perforated packages towards the end of storage (7 days). The barrier in the movement of water vapour through the film and perforations leads to less weight loss. The spoilage of strawberry increases with increase in temperature Fig 1. However the effect of MA was evident on the package. The spike in spoilage (>5%) after 2 days of storage was due to the result of abusive temperature profile. A linear effect of concentration of CO_2 was observed on the spoilage, at 0% CO_2 1.72 % spoilage was observed to 0.87% spoilage at 18 % CO_2 (Kader, 1986). At higher concentration of CO_2 (20-80%) clear inhibition of spoilage was observed. At these extremely high level of CO_2 fungal growth was inhibited in strawberries (Ke et al., 1991).

4.2. Product variability assessment

Knowledge of biological variation in quality within batch is important in managing uniform quality within cold chain. It could help predict the factors responsible for deterioration of quality during storage. The model developed in this scenario study can help find the effect of product variability on the fate of quality and waste generation (Hertog et al., 1999). The results obtained are the estimates of the values expected due to variability in product parameters. Fig 2 shows the propagation of product parameters on the quality characteristics of strawberry at different storage temperature (4, 20 and 8^0 C). It is evident from the figure the variation was directly dependant on the temperature, higher the temperature higher is the variation associated with it.

$Vm_{O_2,ref}$ and $Vm_{CO_2(f)ref}$ are the respiration rate parameters which are directly dependant on temperature. The increase in temperature resulted in increase in the respiration rate. (Geysen et al., 2005) mentioned the effect of temperature on the activation energy of maximum O2 consumption. Weight loss of strawberry constantly increased with time, with a higher weight loss being observed at higher temperature. Strawberries have no protective skin their skin mass transfer coefficient (Ks) is significantly higher than other commodities, which leads to higher weight loss due to transpiration. There is less uncertainty seen in weight loss due to the product parameters. As the storage temperature increased the variability also increased as evident in figure 2(c). At 40C the weight loss was less than 0.5% in 10 days whereas at 200C the 2.7% weight loss was observed. Spoilage increased with increases of storage temperature as evident from figure 5.3(d). At 40C the spoilage observed was less than 15% in 10 days storage, at 80C the spoilage of around 37% was observed and at 200C 100% spoilage was seen in 6 storage days. The effect of CO2 on spoilage could be explained by the effect of CO2 on the respiration rate. Hertog showed that *Botrytis* inoculated strawberry displayed an inhibitory effect of CO_2 on spoilage levels below 20%, which was strongly batch dependant (Hertog et al., 1999).

4.3. Comparing the effect of variability on quality of strawberry

The uncertainty associated with cold chain variability (temperature and relative humidity) and the variation associated with biological product parameters was compared by plotting kernel density plots for each food chain distribution day and for each of the scenarios. Fig 3 (a) and (b) show how the concentration of gases in the headspace of package was dependent both on cold chain and product variability. The second peak observed in the figure is the result of abusive storage temperature (>10^0C). Variation at the 4^{th} day of distribution in CO_2 and O_2 seems to be largely cold chain dependent, however by day 6 the cold chain variation has reduced below the variation of the product.

Weight loss in strawberry showed dependence on the cold chain factors, temperature and relative humidity of storage. Strawberry stored at 10 C showed less than 1% weight loss in 8 days whereas at 200 C 8% weight loss was observed in 4 days which is above the acceptable limit (Nunes et al., 1998). The spoilage of strawberry (Fig 3(d)) showed more influence by the cold chain factors at the beginning of the cold distribution but product uncertainty had more prominent influence later during storage. Strawberries have been found to be colonised by the fungus *B. cinerea* before packaging, with the fungal infection increasing with storage time and inadequate storage conditions (Almenar et al., 2007). The initial spoilage (N_0) is a value representing initial ripening stage or sensitivity of strawberry to botrytis infection (Hertog et al., 1999). From fig 3(c) and (d) it is evident that to control weight loss variation the cold chain conditions (temperature and relative humidity) needed to be controlled whereas in case of spoilage product parameters are the main cause of variability and need to be controlled to maintain the shelf life.

4.4. Sensitivity Analysis

Sensitivity analysis was performed to study the results of variation and how it could be apportioned qualitatively and quantitatively to different sources of variation in the model input (Kader, 1984) The result of the sensitivity analysis (SA) on the weight loss of packed strawberry is presented in Fig 4 (a). The most important parameters contributing to the 90% of the variability were a combination of respiration rate parameters ($RQ_{ox,}$ $Vm_{O_2,ref}$, K_{mO_2}), skin mass transfer coefficient (K_s) and the activation energies associated with (E_{aVmO_2}, $E_{aVm_{CO_2(f)}}$). It was also a combination of main effect of the product parameters and their interactive effects. This suggests that controlling the respiration rate of fresh produce and reducing the mass transfer through skin will help reduce losses during supply chain.

Identification of an effective intervention

The result of sensitivity analysis of spoilage of strawberry shows that the most important parameters contributing to 90% of variability were the initial spoilage and spoilage rate constant ($k_{s,ref}$) (Fig 4(b)). Thus, the waste due to spoilage could be reduced by controlling the initial quality of strawberry and the spoilage rate. The product parameters contributing to the concentration of CO_2 in the headspace of packaging were $Vm_{O_2,ref}, RQox\ and\ E_{Vm_{O_2,ref}}$. Those contributed to the 90% of the variability thus controlling respiration would aid to reduce the waste produced in the supply chain.

4.5. Validation experiment

The input model parameters from table 2 and 3 are used to compare the experimental and predicted results presented in the fig. 5. The experiments were performed to simulate real life abusive supply chain conditions for 10 days. Weight loss, colour, firmness and spoilage were measured at 1, 3, 5, 7 and 10th day. The grey ribbon represents the uncertainty margins of 5% and 95% percentiles due to variability in the simulations of these conditions.

The results for weight loss showed that the variability associated with the product parameter was not high (fig 2(c)). Cold chain parameters were responsible for the variability caused for weight loss during the distribution chain of strawberry.

Spoilage showed high product variability which increased with increases in storage temperature (fig. 2(d)). The experimental results fell within the grey ribbon pertaining to the variability associated with it (Fig 5(d)).

4.6. Waste estimation during supply chain

Fig 6 show the total waste estimation throughout the supply chain, as a combination of waste due to weight loss and the spoilage for coated and uncoated strawberries. Threshold values were used to calculate the waste (weight loss of 5% or above which it starts shrivelling and becomes unmarketable) and 5% for strawberry spoilage. It can be seen how significant amounts of out-of-specification product yielding finally to waste start appearing in day 2 of distribution and that by the end of day 3 there was approximately 10% of all product potentially on a course of not being suitable for consumption and yielding to waste due to variability in the product and cold chain conditions reflecting on the weight loss and spoilage..

5. Conclusions

A mathematical model was developed to predict the changes in quality of packed strawberry during distribution. It took into account the heat and mass transfer processes taking place in MAP like respiration, transpiration condensation and transport of these gases through permeable film. The kinetic behaviour of fresh produce was modelled with respect to the cold chain condition and product parameter. The effect of cold chain variability and product variability on the quality of fresh produce was assessed. Weight loss was influenced by the cold chain factors whereas spoilage has initial influence from cold chain factors but product variability becomes prominent towards end of storage. The results of sensitivity analysis showed that controlling respiration rate and skin mass transfer would help reduce the waste produced during supply chain. This mathematical model contributed to assessing the factors responsible for spoilage and designing strategies to reduce waste produced in cold supply chain.

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7. Bibliography

Aguirre, L., 2008. Combination of natural variability estimation with real time measurement for mushroom shelf life assessment. Dublin Dublin Inst. Technol.

Almenar, E., Del Valle, V., Hernández-Muñoz, P., Lagarón, J.M., Catalá, R., Gavara, R., 2007. Equilibrium modified atmosphere packaging of wild strawberries. J. Sci. Food Agric. 87, 1931–1939.

ASHRAE, R.H., 2006. SI ed. Am. Soc. Heating, Refrig. Air-Conditioning Eng. Atlanta, GA.

Becker, B.R., Misra, A., Fricke, B.A., 1996. Bulk Refrigeration of Fruits and Vegetables Part I: Theoretical Considerations of Heat and Mass Transfer. HVAC&R Res. 2, 122–134. https://doi.org/10.1080/10789669.1996.10391338

Bird, R.B., 2002. Transport phenomena. Appl. Mech. Rev. 55, R1–R4.

Burton, W.G., 1982. Post-harvest physiology of food crops. Longman Group Ltd.

Caner, C., Aday, M.S., Demir, M., 2008. Extending the quality of fresh strawberries by equilibrium modified atmosphere packaging. Eur. Food Res. Technol. 227, 1575–1583.

Duret, S., Gwanpua, S.G., Hoang, H.-M., Guillier, L., Flick, D., Laguerre, O., Verlinden, B.E., De Roeck, A., Nicolai, B.M., Geeraerd, A., 2015. Identification of the significant factors in food quality using global sensitivity analysis and the accept-and-reject algorithm. Part III: Application to the apple cold chain. J. Food Eng. 148, 66–73. https://doi.org/http://dx.doi.org/10.1016/j.jfoodeng.2014.09.039

ElMasry, G., Wang, N., ElSayed, A., Ngadi, M., 2007. Hyperspectral imaging for nondestructive determination of some quality attributes for strawberry. J. Food Eng. 81, 98–107. https://doi.org/10.1016/j.jfoodeng.2006.10.016

Fishman, S., Rodov, V., Ben-Yehoshua, S., 1996. M Effect on Oxygen and Water Vapor Dynamics in Modified-Atmosphere Packages J. Food Sci. 61, 956–961.

Geysen, S., Verlinden, B.E., Conesa, A., Nicolai, B.M., 2005. Modelling respiration of strawberry (cv. Elsanta) as a function of temperature, carbon dioxide, low and superatmospheric oxygen concentration. Frutic 5, 12–16.

Gwanpua, S.G., Vicent, V., Verlinden, B.E., Hertog, M., Nicolai, B.M., Geeraerd, A.H., 2014. Managing biological variation in skin background colour along the postharvest chain of ‘Jonagold’apples. Postharvest Biol. Technol. 93, 61–71.

Han, C., Zhao, Y., Leonard, S.W., Traber, M.G., 2004. Edible coatings to improve storability and enhance nutritional value of fresh and frozen strawberries (Fragaria× ananassa) and raspberries (Rubus ideaus). Postharvest Biol. Technol. 33, 67–78.

Hertog, M., Boerrigter, H.A.M., Van den Boogaard, G., Tijskens, L.M.M., Van Schaik, A.C.R., 1999. Predicting keeping quality of strawberries (cv.Elsanta’) packed under modified atmospheres: an integrated model approach. Postharvest Biol. Technol. 15, 1–12.

Hertog, M., Lammertyn, J., De Ketelaere, B., Scheerlinck, N., Nicolaï, B.M., 2007a. Managing quality variance in the postharvest food chain. Trends food Sci. Technol. 18, 320–332.

Hertog, M., Lammertyn, J., Desmet, M., Scheerlinck, N., Nicolaï, B.M., 2004. The impact of biological variation on postharvest behaviour of tomato fruit. Postharvest Biol. Technol. 34, 271–284.

Hertog, M., Scheerlinck, N., Lammertyn, J., Nicolaï, B.M., 2007b. The impact of biological variation on postharvest behaviour of Belgian endive: The case of multiple stochastic variables. Postharvest Biol. Technol. 43, 78–88.

Hertog, M., Scheerlinck, N., Nicolaï, B.M., 2009a. Monte Carlo evaluation of biological variation: Random generation of correlated non-Gaussian model parameters. J. Comput. Appl. Math. 223, 1–14.

Hertog, M., Scheerlinck, N., Nicolaï, B.M., 2009b. Monte Carlo evaluation of biological variation: Random generation of correlated non-Gaussian model parameters. J. Comput. Appl. Math. 223, 1–14.

Jalali, A., Seiiedlou, S., Linke, M., Mahajan, P., 2017. A comprehensive simulation program for modified atmosphere and humidity packaging (MAHP) of fresh fruits and vegetables. J. Food Eng. 206, 88–97. https://doi.org/https://doi.org/10.1016/j.jfoodeng.2017.03.007

Joshi, K., Warby, J., Valverde, J., Tiwari, B., Cullen, P.J., Frias, J.M., 2018. Impact of cold chain and product variability on quality attributes of modified atmosphere packed mushrooms (Agaricus bisporus) throughout distribution. J. Food Eng. 232, 44–55.

Kader, A.A., 1991. Quality and its maintenance in relation to the postharvest physiology of strawberry. Qual. its Maint. Relat. to post-harvest Physiol. strawberry. Timber Press. Portl. 145–152.

Kader, A.A., 1986. Biochemical and physiological basis for effects of controlled and modified atmospheres on fruits and vegetables. Food Technol.

Kader, A.A., 1984. Effects of postharvest handling procedures on tomato quality, in: Symposium on Tomato Production on Arid Land 190. pp. 209–222.

Ke, D., Goldstein, L., O'MAHONY, M., Kader, A.A., 1991. Effects of Short -term Exposure to Low O2 and High CO2 Atmospheres on Quality Attributes of Strawberries. J. Food Sci. 56, 50–54.

Larsen, M., Watkins, C.B., 1995. Firmness and concentrations of acetaldehyde, ethyl acetate and ethanol in strawberries stored in controlled and modified atmospheres. Postharvest Biol. Technol. 5, 39–50.

Lee, D.S., Song, Y., Yam, K.L., 1996. Application of an enzyme kinetics based respiration model to permeable system experiment of fresh produce. J. Food Eng. 27, 297–310.

McNally, K., Cotton, R., Loizou, G.D., 2011. A Workflow for Global Sensitivity Analysis of PBPK Models. Front. Pharmacol. 2, 31. https://doi.org/10.3389/fphar.2011.00031

Merts, I., 1996. Mathematical Modelling of Modified Atmosphere Packaging Systems for Apples. Dep. Process Environ. Technol. Massey University, New Zealand.

Nunes, M.C.N., Brecht, J.K., Morais, A., Sargent, S.A., 1998. Controlling temperature and water loss to maintain ascorbic acid levels in strawberries during postharvest handling. J. Food Sci. 63, 1033–1036.

Pelayo, C., Ebeler, S.E., Kader, A.A., 2003. Postharvest life and flavor quality of three strawberry cultivars kept at 5 C in air or air+ 20 kPa CO 2. Postharvest Biol. Technol. 27, 171–183.

Petriccione, M., Mastrobuoni, F., Pasquariello, M.S., Zampella, L., Nobis, E., Capriolo, G., Scortichini, M., 2015. Effect of chitosan coating on the postharvest quality and antioxidant enzyme system response of strawberry fruit during cold storage. Foods 4, 501–523.

R Development Core Team, 2008. R: A Language and Environment for Statistical Computing. https://doi.org/{ISBN} 3-900051-07-0

Rennie, T.J., Tavoularis, S., 2009. Perforation-mediated modified atmosphere packaging: Part I. Development of a mathematical model. Postharvest Biol. Technol. 51, 1–9. https://doi.org/http://dx.doi.org/10.1016/j.postharvbio.2008.06.007

Sanz, C., Perez, A.G., Olias, R., Olias, J.M., 2000. Modified atmosphere packaging of strawberry fruit: Effect of package perforation on oxygen and carbon dioxide/Envasado de fresas en atmósfera modificada: Efecto de la perforación del envase en el contenido de oxígeno y dióxido de carbono. Food Sci. Technol. Int. 6, 33–38.

Siracusa, V., 2012. Food packaging permeability behaviour: a report. Int. J. Polym. Sci. 2012.

Soetaert, K., Petzoldt, T., Setzer, R.W., 2010. Solving differential equations in R: package deSolve. J. Stat. Softw. 33, 1–25.

Song, Y., Vorsa, N., Yam, K.L., 2002. Modeling respiration–transpiration in a modified atmosphere packaging system containing blueberry. J. Food Eng. 53, 103–109. https://doi.org/http://dx.doi.org/10.1016/S0260-8774(01)00146-7

Tijskens, L.M.M., Polderdijk, J.J., 1996. A generic model for keeping quality of vegetable produce during storage and distribution. Agric. Syst. 51, 431–452.

Wickham, H., 2009. ggplot2: Elegant Graphics for Data Analysis. https://doi.org/978-0-387-98140-6

Xanthopoulos, G., Koronaki, E.D., Boudouvis, A.G., 2012. Mass transport analysis in perforation-mediated modified atmosphere packaging of strawberries. J. Food Eng. 111, 326–335. https://doi.org/http://dx.doi.org/10.1016/j.jfoodeng.2012.02.016

Zhang, M., Xiao, G., Peng, J., Salokhe, V.M., 2003. Effects of modified atmosphere package on preservation of strawberries. Zool. Stud. 42, 143–148.

Table 1 Equations used in the mathematical model

Process	Equation	Reference	Eq. no.
Respiration	$r_{O_2} = \frac{Vm_{O_2}.[O_2]}{Km_{O_2}.\left(1+\frac{[CO_2]}{Kmc_{CO_2}}\right)+[O_2].\left(1+\frac{[CO_2]}{Kmu_{CO_2}}\right)}$ $r_{CO_2(f)} = \frac{Vm_{CO_2(f)}}{\left(1+\frac{[O_2]}{Kmc_{O_2(f)}}+\frac{[CO_2]}{Kmc_{CO_2(f)}}\right).Km_{CO_2(f)}+1}$ $r_{CO_2} = RQ_{ox}.r_{O_2} + r_{CO_2(f)}$	Strawberry respiration rate follow uncompetitive type inhibition. The CO_2 production is a combination of oxidative and the fermentative process (Hertog et al., 1999; Song et al., 2002)	(1) (2) (3)
Respiration heat	$Q_s = \frac{2816}{6} \times \frac{r_{O_2} + r_{CO_2}}{2} \times \alpha \times W_p$	α is conversion factor of respiration energy dissipated as heat. The literature suggests the value of α has a range between 0.8-1.0 (Burton, 1982). For 100% conversion of respiration energy as heat α =1 (Song et al., 2002)	(4)
Mass Balance			
Gas exchange in package	$\frac{d[O_2]_i}{dt} = 100 \times \left(\frac{A_p P_{O_2} P_{atm}}{L_f}\left[\frac{[O_2]_o}{100} - \frac{[O_2]_i}{100}\right] - W_p r_{O_2}\right) \times \frac{1}{V_f}$ $\frac{d[CO_2]_i}{dt} = 100 \times (\frac{A_p P_{CO_2} P_{atm}}{L_f}\left[\frac{[CO_2]_o}{100} - \frac{[CO_2]_i}{100}\right] + W_s r_{CO_2}) \times \frac{1}{V_f}$	The mass balance of gas components in the package is represented by ordinary differential equations (Song et al., 2002). As the package initially contains air, initial conditions (t=0) becomes $[O_2]_i$=21.0%, $[CO_2]_i$=0.03%	(5) (6)
Permeability	$P_{O_2,CO_2,H_2O} = P_{O_2,CO_2,H_2O\ ref} + \frac{\pi R_h^2 \times D_{i,air}}{(L_f + R_h)} \times N_h$	Permeability is a function of permeability of film and the number and size of perforations.	(7)

Water permeation through film	$\frac{dm_{pr}}{dt} = \left[\frac{P_{H_2O} A_p (P_i - P_o)}{L_f}\right]\left[\frac{0.018 P_{atm}}{RT_s}\right]$	The driving force of permeation of water vapour from the headspace of package to surrounding is the water vapour pressure difference.	(8)
Heat Balance			
Temperature headspace of package	$Q_s W_s + Q_{con} + h_p A_p (T_i - T_o) = Q_{tr} + W_s C_s \frac{dT_s}{dt} + W_a C_a \frac{dT_s}{dt}$	The heat is generated by respiration and heat is transferred in headspace due to convection, transpiration and condensation. This ODE is used to estimate the temperature of the fresh produce (Lee et al., 1996)	(9)
	$\frac{dT_s}{dt} = \frac{Q_r + Q_{con} - h_p A_p (T_i - T_o) - Q_{tr}}{W_s C_s + W_a C_a}$		(10)

Table 2 Parameter estimate and their standard error for strawberry Source: (*Becker et al., 1996; Hertog et al., 1999)

Parameter	Value	Standard error (SE)
$Vm_{O_2,ref}$ (µmol kg^{-1}sec^{-1})	0.27	0.010
$E_{aVm_{O_2}}$(J mol^{-1})	74826	3451
$Vm_{CO_2(f)ref}$(µmol kg^{-1}sec^{-1})	0.50	0.22
$E_{aVm_{CO_2(f)}}$ (J mol^{-1})	57374	14400
Km_{O_2} (%)	2.63	0.274
Kmc_{CO_2}	+∞	-
Kmu_{CO_2}	+∞	-
$Kmc_{O_2(f)}$ (%)	0.056	0.041
$Kmc_{CO_2(f)}$	+∞	-
$Km_{CO_2(f)}$ (%)	1	-
K_s *(kg m^{-2} sec Pa)	13.6 x 10^{-9}	4.8
$k_{s,ref}$ (day^{-1})	0.60	0.045
Ea_s (J mol^{-1})	70108	7056
N_0 (%)	0.83	0.10

Table 3 Properties of packaging film, produce and other conditions used in the model

$P_{O_2\,ref}$ (m^{3}m h^{-1}m^{-2}Pa)	8.5 x 10^{-14}	(Xanthopoulos et al., 2012)
$P_{CO_2\,ref}$(m^{3}m h^{-1}m^{-2}Pa)	2.8 x 10^{-13}	(Xanthopoulos et al., 2012)
$P_{H_2O\,ref}$(m^{3}m h^{-1}m^{-2}Pa)	4.5 x 10^{-13}	(Xanthopoulos et al., 2012)
ρ_b (kg m^{-3})	600	(Xanthopoulos et al., 2012)
ϵ	0.27	(Xanthopoulos et al., 2012)
a_w	0.99	(Xanthopoulos et al., 2012)
C_s (kJ kg^{-1} K^{-1})	4	(ASHRAE, 2006)
$[CO_2]_i$ (%)	0.03	(Song et al., 2002)
$[O_2]_i$ (%)	21.0	(Song et al., 2002)
M_{O_2}(kg mol^{-1})	0.032	(Bird, 2002)
M_{CO_2}(kg mol^{-1})	0.044	(Bird, 2002)
M_{H_2O}(kg mol^{-1})	0.018	(Bird, 2002)
R (J K^{-1}mol^{-1})	8.314	(Bird, 2002)
P_{atm} (Pa)	101325	(Bird, 2002)
ρ_{O_2} (kg m^{-3})	1.43	(Siracusa, 2012)

ρ_{CO_2}(kg m^{-3})	1.98	(Siracusa, 2012)
T_{ref} (^{0} C)	10	(Hertog et al., 1999)
N_H	4	Experimental
d_c(m)	0.03	Experimental

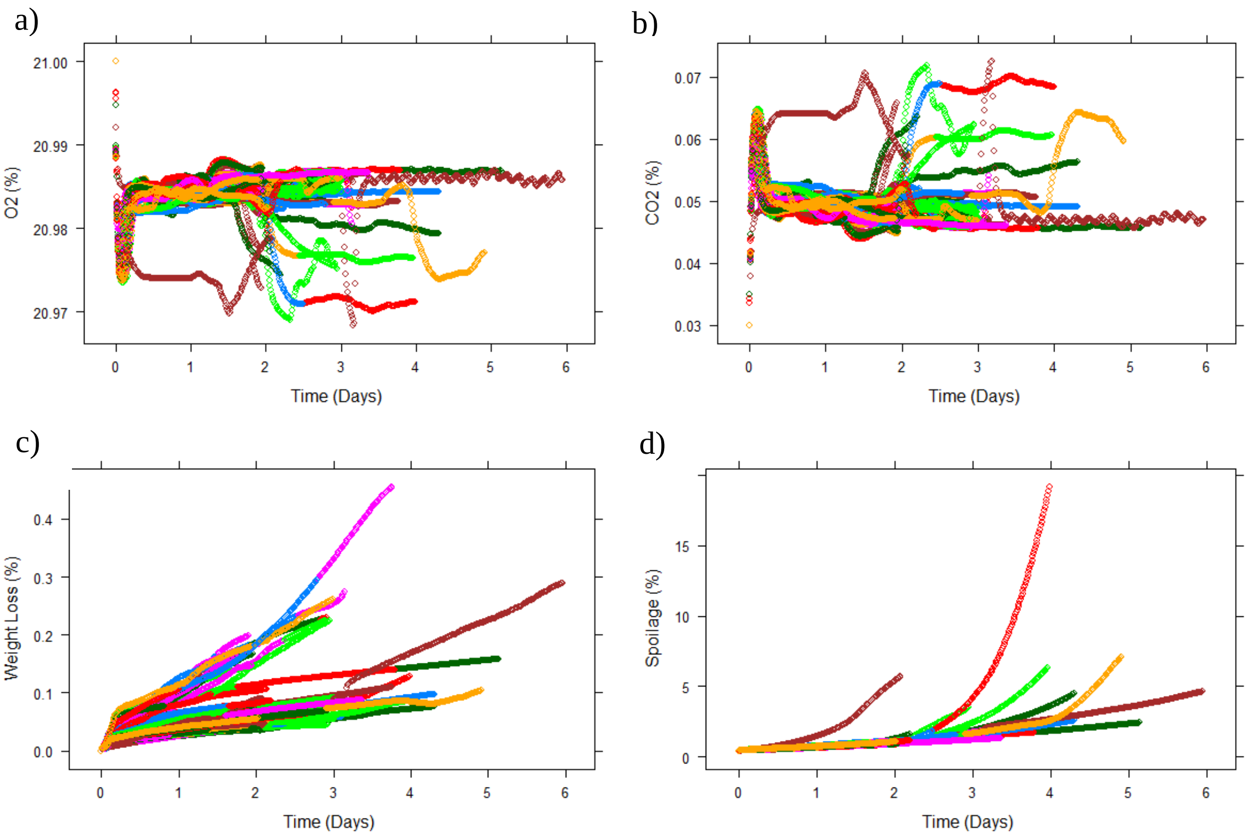
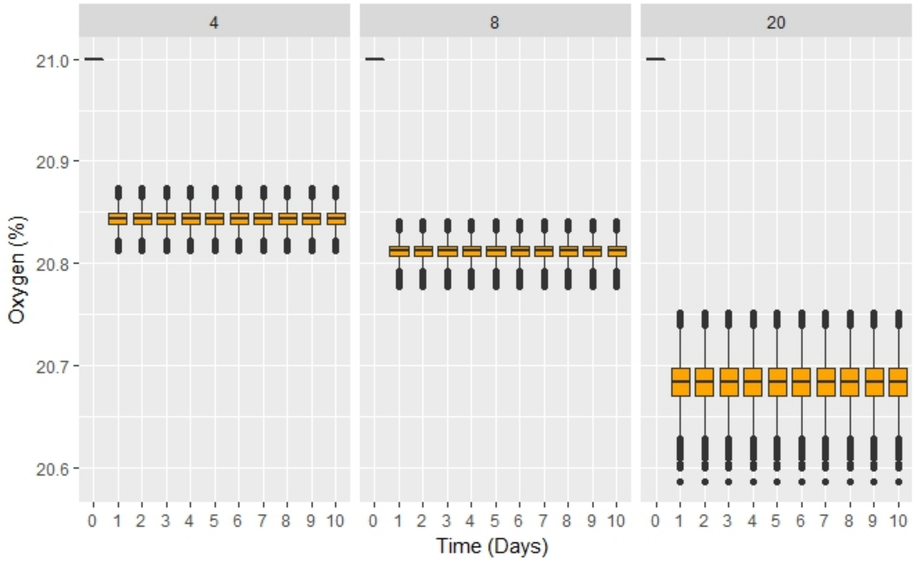
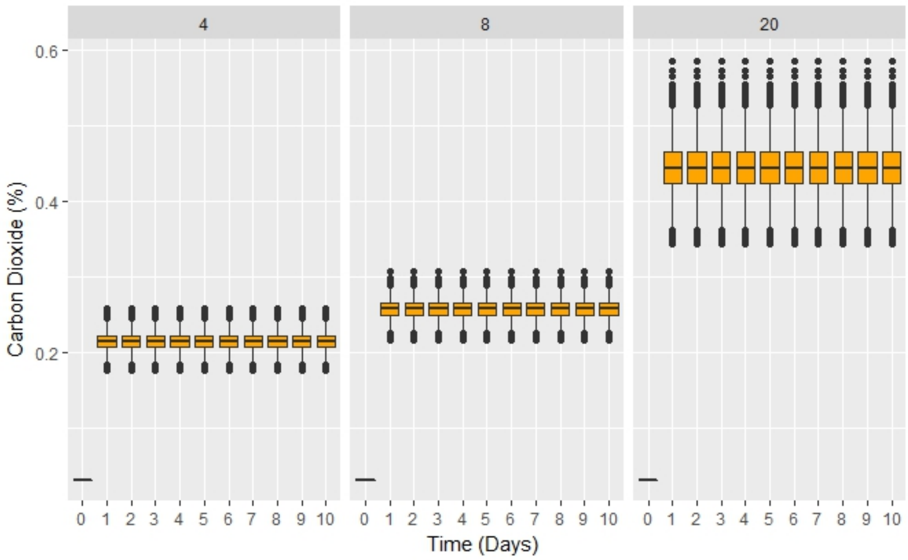


Fig 1. Simulation results of average (a) oxygen concentration and (b) carbon dioxide concentration in the headspace of packages (c) weight loss observed and (d) spoilage against the cold chain profile.

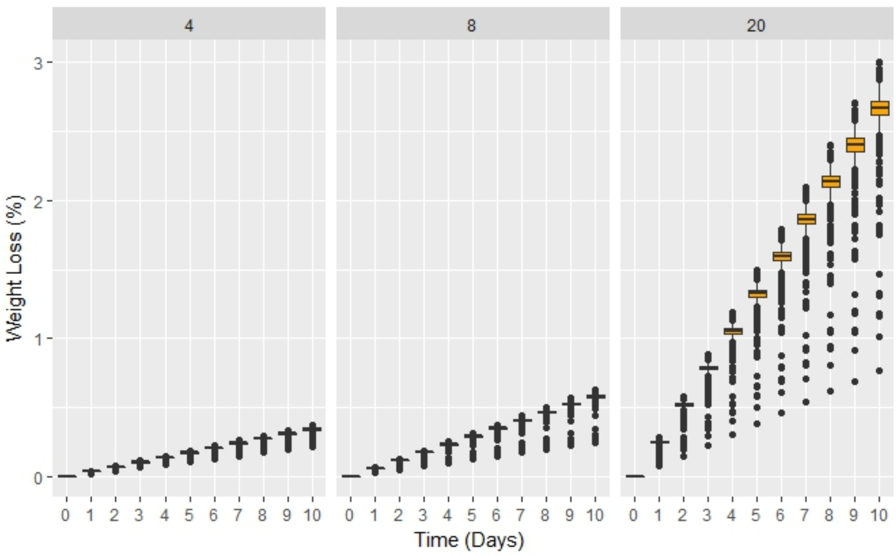
a)


4
8
20
Oxygen (%)
21.0
20.9
20.8
20.7
20.6
0 1 2 3 4 5 6 7 8 9 10
Time (Days)

b)


4
8
20
Carbon Dioxide (%)
0.6
0.4
0.2
0 1 2 3 4 5 6 7 8 9 10
Time (Days)

c)


4
8
20
Weight Loss (%)
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10
Time (Days)

d)

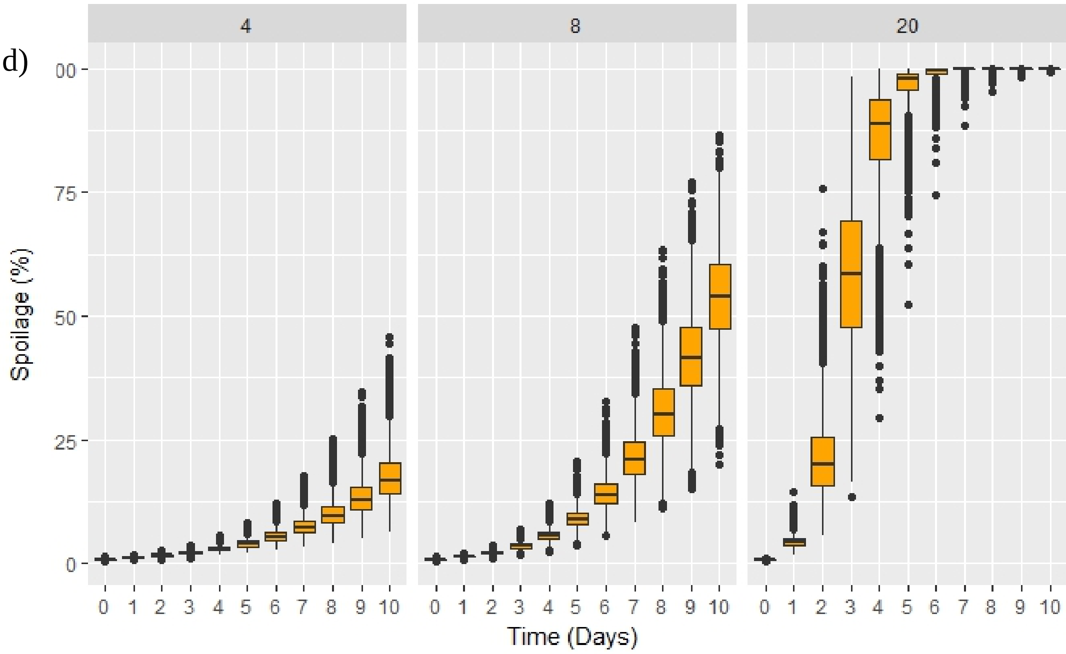
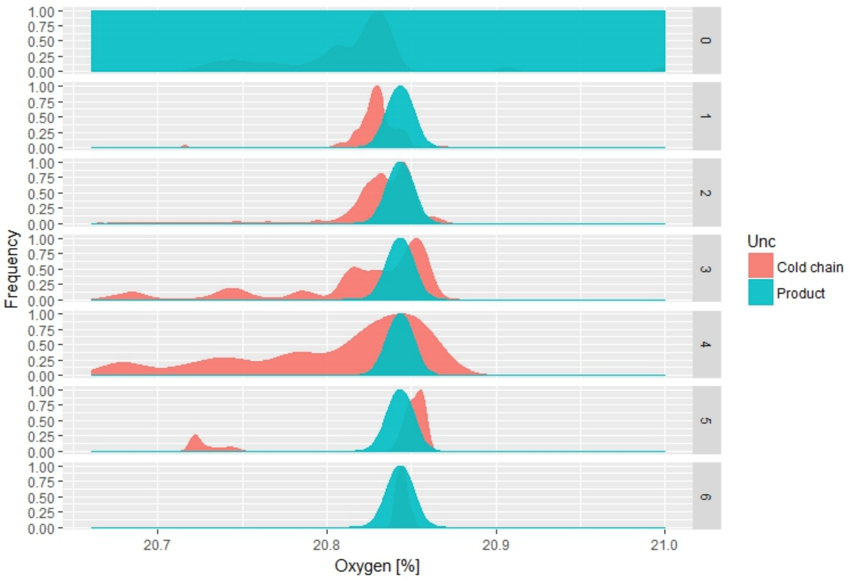
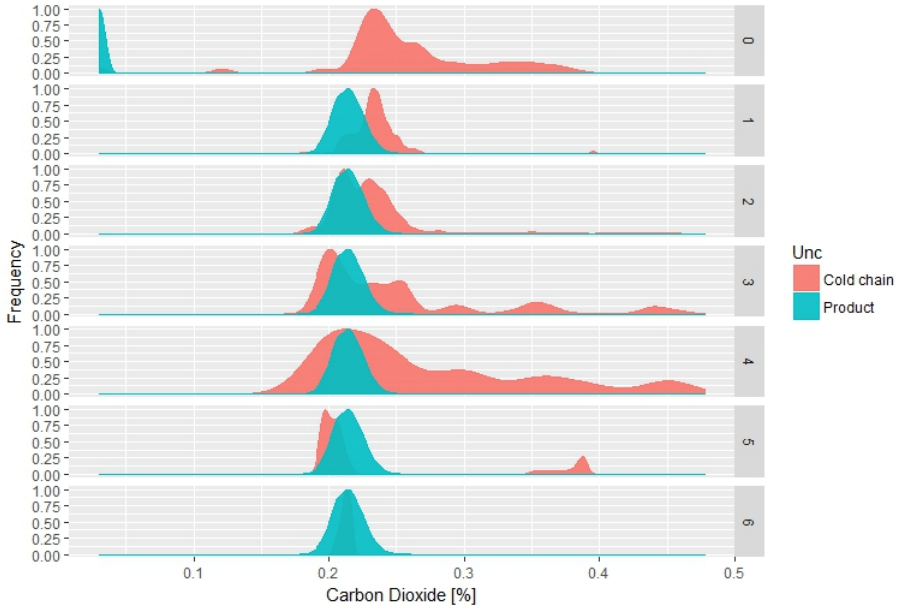


Fig 2 Propagation of product parameter variability observed in (a) concentration of oxygen (b) carbon dioxide in headspace (c) weight loss and (d) Spoilage observed in strawberry packed in modified atmosphere 15 days storage at 4^0 C and 80% RH.

a)

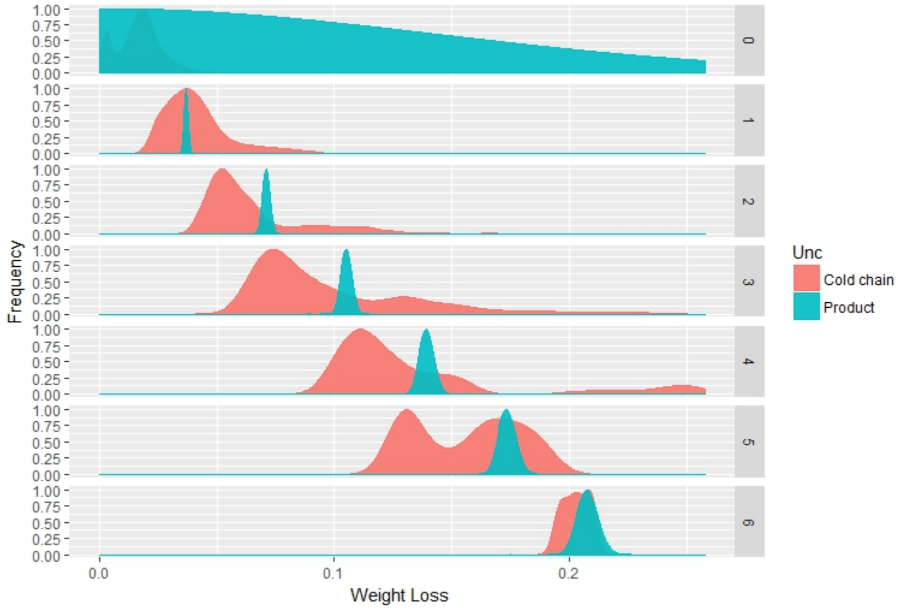


b)



Frequency
Carbon Dioxide [%]
0.1
0.2
0.3
0.4
0.5
0.00
0.25
0.50
0.75
1.00
0
1
2
3
4
5
6
Unc
Cold chain
Product

c)



Frequency
Weight Loss
0.0
0.1
0.2
0.00
0.25
0.50
0.75
1.00
0
1
2
3
4
5
6
Unc
Cold chain
Product

d)

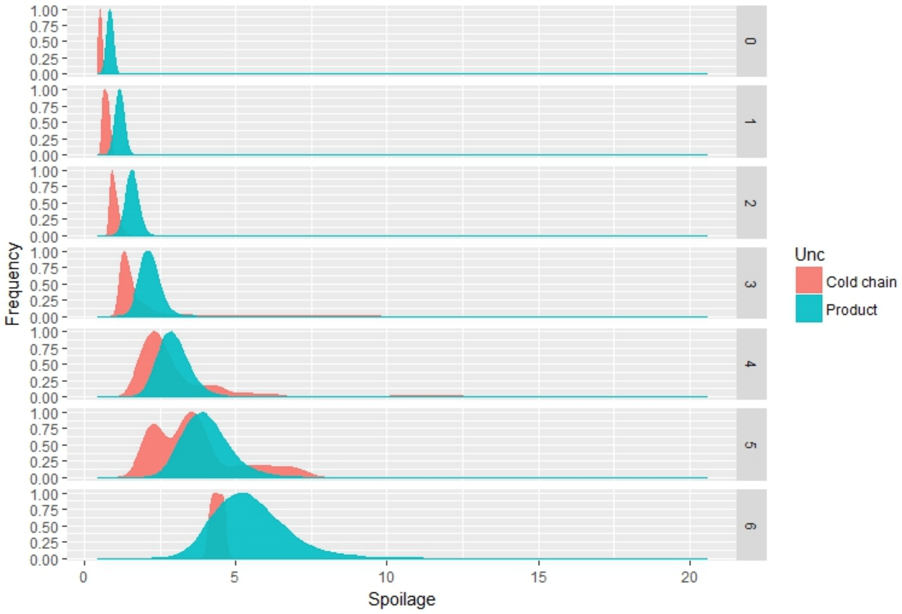
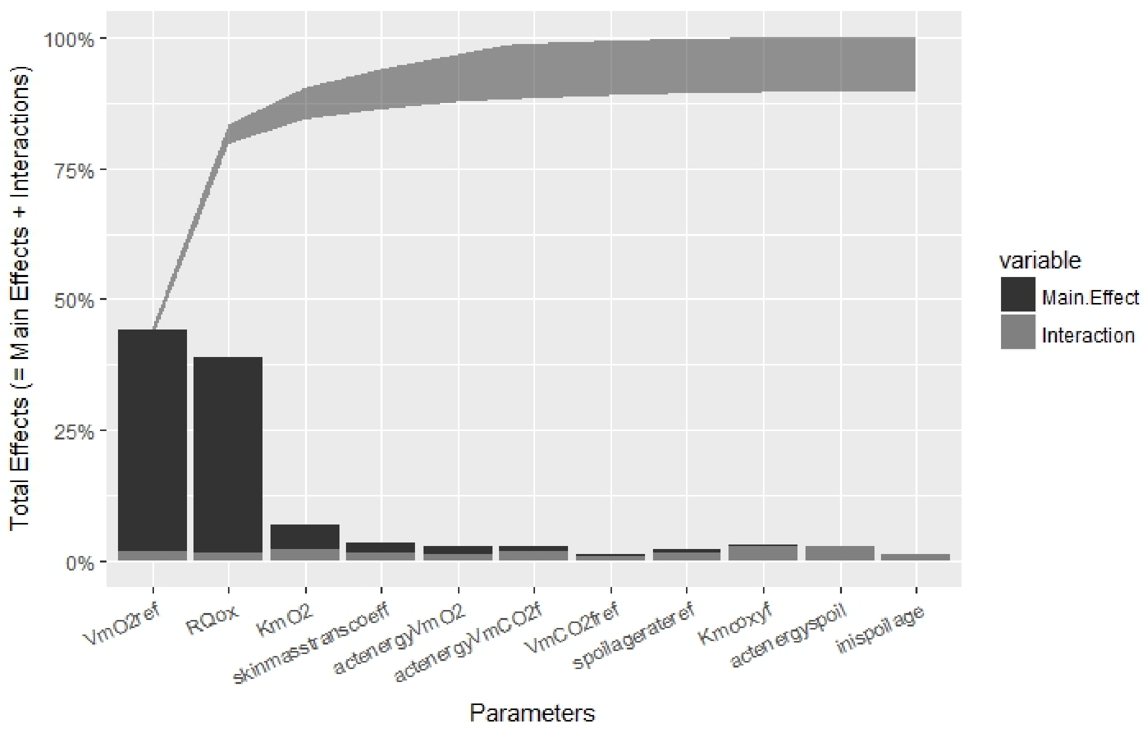
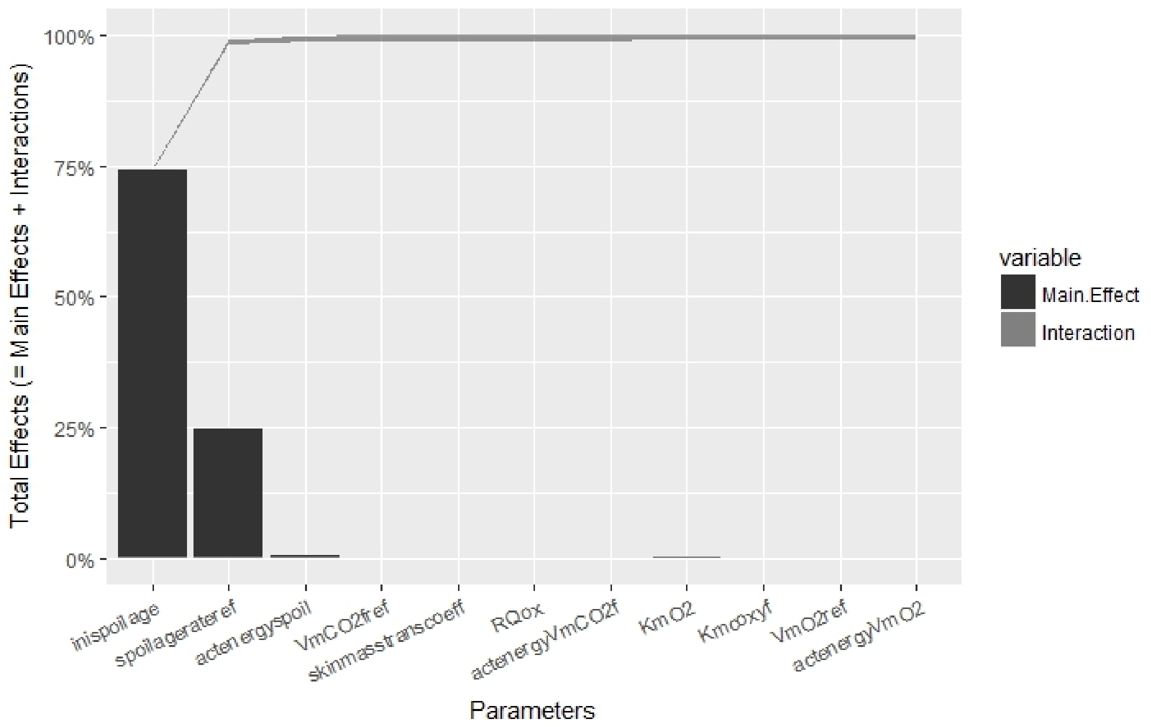


Fig 3 The effect of cold chain uncertainty (green) and product parameter uncertainty (orange) on the (a) oxygen concentration (b) carbon dioxide concentration in headspace (c) weight loss during storage (d) Spoilage of strawberry. Each subplot within (a), (b), (c) and (d) represents the simulated variation in a given distribution day

a)



b)



c)

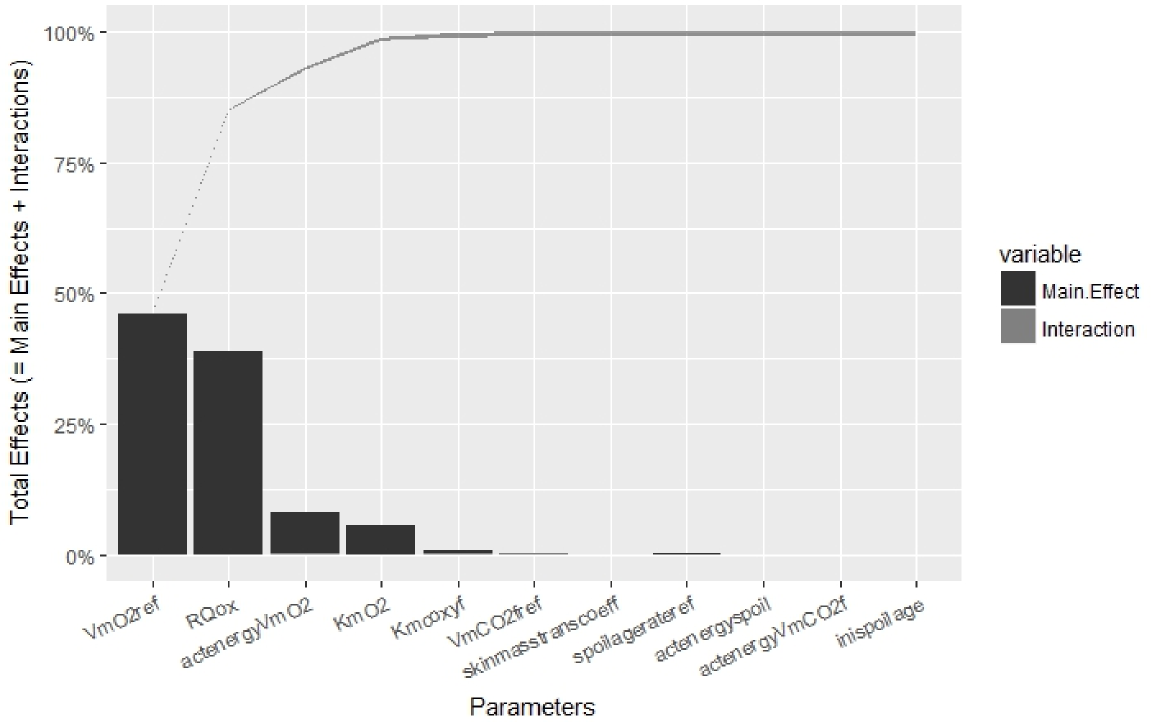


Fig. 4 Lowry plot for the effect of product parameters on the a) weight loss b) spoilage, c) CO_2

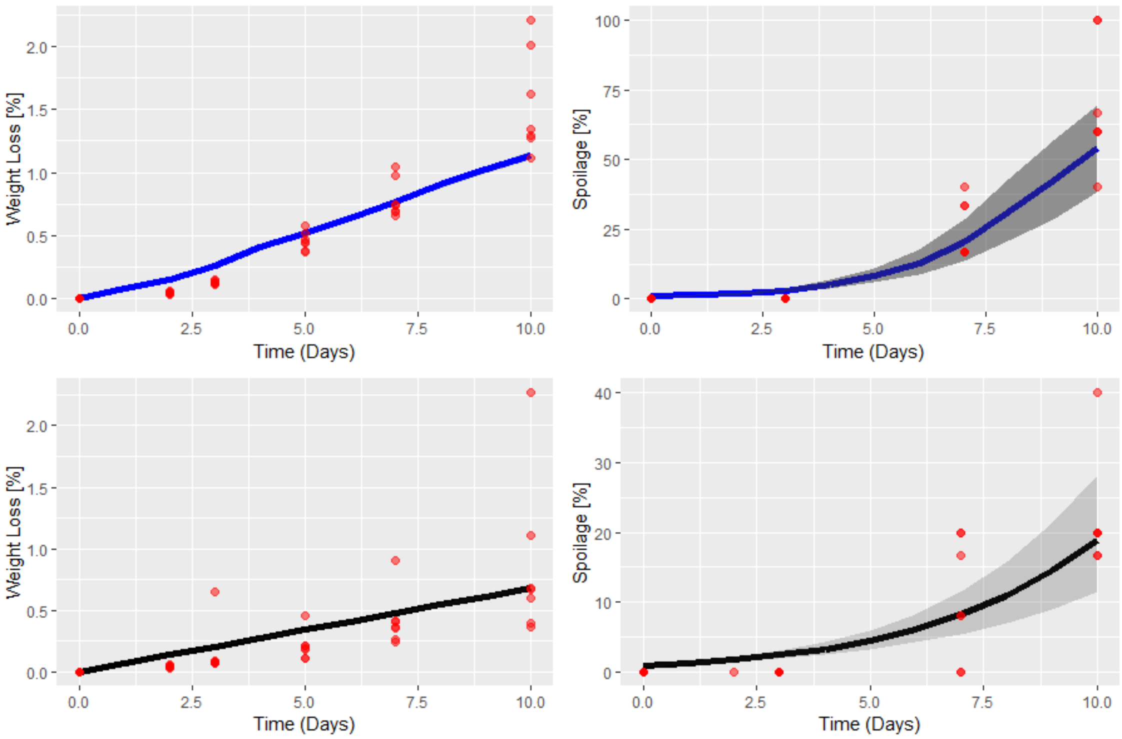


Fig. 5 Comparison of model predictions with the experimental data (points) at different storage conditions ((4, 8, 20^0 C) (a, b) and at ideal temperature (4^{0}C) (c,d) a) weight loss b) spoilage at (4, 8, 20^0 C) , c) weight loss and d) spoilage at (4^{0}C).

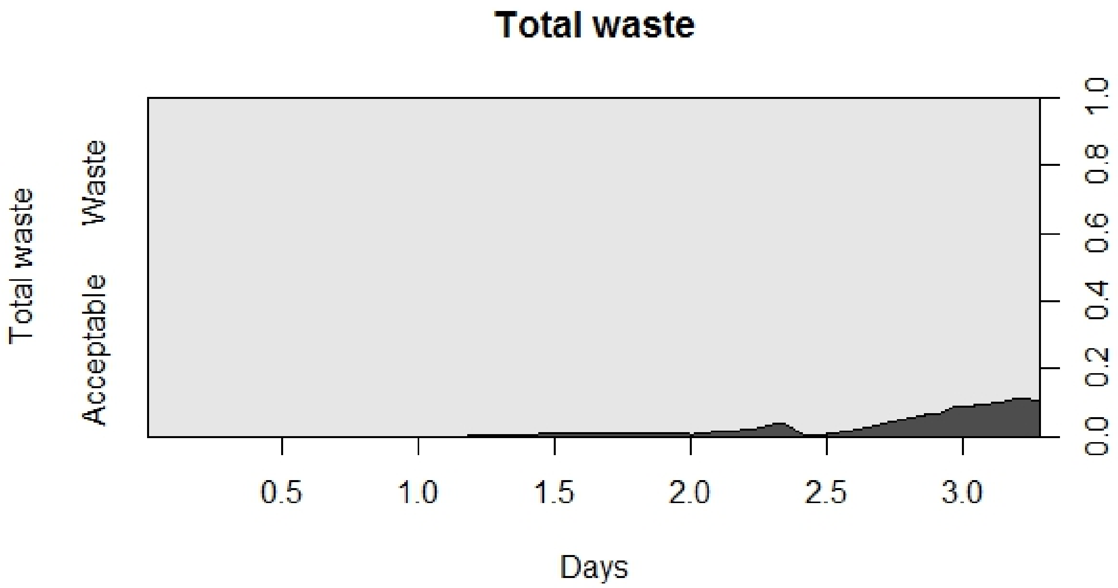


Fig. 6 Conditional density plot of total waste generated in the strawberry supply chain.