Journal of Basics and Applied Sciences Research (JOBASR)
ISSN (print): 3026-9091, ISSN (online): 1597-9962
Volume 4(3) June 2026 Special Issue
DOI: https://dx.doi.org/10.4314/jobasr.v4i3.11s

Non-linear Coupled Ordinary Differential Equations Modelling of Thermophysical and Kinetic Degradation: A Study of Broccoli Post-Harvest Quality along the Highlands (Okuk) Highway

William Billy Kawak[1*] **& Mohsen Aghaeiboorkheili**[2]
[1,2]School of Mathematics and Computer Science, Papua New Guinea University of Technology, Lae, Morobe Province, Papua New Guinea
*Corresponding Author Email: mohsen.aghaeiboorkheili@pnguot.ac.pg

ABSTRACT

This study will focus on developing a non-linear coupled Ordinary Differential Equation (ODE) based predictive model that describes the degradation of broccoli in transportation within Okuk, PNG. While previous studies in PNG have been purely observable, this study addresses a significant research gap by providing a mechanistic, predictive tool that accounts for the dynamic, time-varying temperature shifts T(t) from the cool highlands to the warm tropical coast. The model couples the thermophysical heat transfer with kinetic quality degradation Q(t), and employs numerical simulations using MATLAB's ODE45 solver to simulate the impact of ambient highway heat and internal respiration or chlorophyll loss. The findings reveal that standard handling results in a 27% quality loss, while pre-cooling intervention of 4◦C acts as a thermal battery maintaining 95% freshness upon arrival. The primary contribution of the study is to demonstrate that degradation is an exponentially accelerating process, providing a data-driven explanation for the establishment of off-grid solar powered cooling (pre-cooling) hubs to protect highlands farmers' livelihoods and National Food Security.

Keywords:
Non-linear coupled ODE,
Post-harvest Degradation,
Broccoli transport,
Cold-chain logistics,
Thermophysical Modelling

INTRODUCTION

The fresh produce sector in Papua New Guinea annually loses an estimated 20 to 50% of its value due to post-harvest inefficiency. This is because fresh produce is normally treated as passive cargo, ignoring its biological response to heat, and the main cause of this is the use of standard (traditional) logistical models that drastically underestimate broccoli spoilage on the Highlands (Okuk) Highway. According to Obayi et al. (Obayi, Despoudi, & Masi, 2025), the primary drivers of food waste in modern supply chains are often linked to logistical failures and inadequate temperature management.

Moreover, the quick descent from Mt. Hagen (high altitude) to Lae (low altitude) results in a metabolic heat run-away effect whereby the broccoli produces metabolic heat in a non-linear fashion that cannot be captured by linear models. Moreover, the scope of this study addresses the insufficiency of linear models to capture dynamical systems. In other words, a standard model recognizes a linear decay pattern that results in the formulation of a system of two differential equations.

$$\frac{dT}{dt} = \frac{hA}{mc}(T_a - T) + r(T) \tag{1}$$

where the formula is concentrated in the gradient of air temperature and temperature of the load as well as heat generation inside (Ahlawat, et al., 2022). The symbol T(t) stands for temperature over time.

$$\frac{dQ}{dt} = -k(T)Q \tag{2}$$

where the above equation highlights the dependency on the Arrhenius decay rate, which now depends on the dynamically changing temperature using Equation (1). The variable Q(t) represents the quality over time.

For the above equations to operate correctly, at the beginning of the transportation process as the vehicle travels towards the Markham Valley of Lae, the extreme hot ambient temperature (Ta) causes a thermal gradient such that the outside heat passes through the truck and the broccoli crates, thereby heating the inner temperature of the produce due to convective heat transfer.

How to cite this article: William B. K. & Mohsen A. (2026). Non-linear Coupled Ordinary Differential Equations Modelling of Thermophysical and Kinetic Degradation: A Study of Broccoli Post-Harvest Quality along the Highlands (Okuk) Highway. *Journal of Basics and Applied Sciences Research*, *4*(3), 97-105. https://dx.doi.org/10.4314/jobasr.v4i3.11s

The increase in the inner temperature prompts the increase in the metabolism of the broccoli (k) to grow exponentially as per the Arrhenius relationship, thus speeding up the reactions involved in chlorophyll deterioration. Finally, the increased metabolism leads to the development of a non-linear coupled effect due to temperature that enables the production of respiration heat (Qresp) internally, causing the internal temperature of the crates (T) to rise faster than the ambient temperature. The outcome shows that the decay is exponentially accelerated and exhibits a non-linear response (Li, Meng, Malik, Zhang, & Wang, 2022).

In Papua New Guinea, the use of mathematical models has found increasing applications to help resolve various engineering and operational issues. In the past literature, it has been proved that the applications of mathematical models are quite useful when it comes to the analysis of real-world systems, such as service systems and decision-making systems (Patili, Khoshnava, Sankwi, & Aghaeiboorkheili, 2026). Based on previous advancements in this area, this study focuses on extending the use of mathematical models to the field of post-harvest agricultural logistics.

The significance of the study and the contribution this study makes towards cold-chain logistics in the Highlands regions of Papua New Guinea can be scaled down to four main areas. Firstly, it will have a significant economic impact on Highlands's farmers in the long run. Secondly, it helps national food security and nutrition. Thirdly, it provides a scientific and engineering innovative tool (predictive modelling), and finally, it assists the Department of Agriculture and Livestock (DAL) and the Fresh Produce Development Agency (FPDA) with policy development for the government. The findings of this study provide the FPDA and DAL with data-driven evidence. Instead of simply building better roads, this study demonstrates that the government must prioritize refrigerated logistics and pre-cooling stations at the start of the Okuk Highway to stop the exponential degradation that occurs during the descent to the coast.

Although there is considerable scientific literature on broccoli deterioration and its kinetics on a global scale, one key gap still exists in the implementation of such theories in understanding the post-harvest deterioration kinetics of broccoli within the high-altitude tropical setting of Papua New Guinea. This paper seeks to fill the gap by formulating a coupled non-linear ordinary differential equation model.

MATERIALS AND METHODS

Governing Equations

In this case study, the variables are categorized into two interacting systems: the variables of Thermodynamic (which define the temperature rise) and the variables of Kinetic degradation (which define the biological rot). (Refer to Table 1).

Table 1. Model variables and parameters used in this study.

Symbol	**Unit**	**Description**
$T(t)$	K or °C	Broccoli core temperature
$T_a(t)$	°C	Ambient temperature
T_{ref}	°C	Initial temperature
$Q(t)$	mg/100 g	Quality index
k_{ref}	h^{-1}	Reference reaction rate
E_a	kJ/mol	Activation energy
R	J/(mol·K)	Universal gas constant
C_p	kJ/(kg·K)	Specific heat capacity
m	kg	Mass

Symbol	Unit	Description
h	W/(m²·K)	Convective heat transfer coefficient
A	m²	Surface area
n	–	Reaction order

The critical coupling occurs because Temperature $T(t)$ is an output of the first system but an input for the second, while Respiration Heat (Qresp) is a biological reaction that feeds back into the physical heat equation.

The proposed model is a System of non-linear Coupled ODE. It solves the systems simultaneously to capture the Runaway Heating effect. It does not solve for temperature and quality separately.

The model consists of two primary equations that interact interdependently with respect to change in time (dt).

Equation 1: Thermophysical (Thermal Model)

$$\frac{dT}{dt} = \frac{hA}{mC_p}(T_a(t) - T) + \beta e^{-E_a/(RT)} \qquad (3)$$

Where,

$$\frac{hA}{mC_p}(T_a(t) - T)$$

is the convective heat ingress. The constants h, A, and mC_p determine how much of that external heat actually penetrates the produce (Aamir, Ovissipour, Sablani, & Rasco, 2013).

While

$$\beta e^{-E_a/(RT)}$$

is the metabolic feedback (internal heat source), it is the heat of respiration generated by the broccoli's own living cells. Since it is an exponential function, this term causes the broccoli to self-heat more aggressively as it gets warmer, creating a dangerous positive temperature-driven non-linear coupling.

Furthermore,

$$\beta = \frac{1}{C_p} q_{\text{ref}}$$

is the respiration magnitude constant (Beckles, Kader, Reid, Jiang, & Cantwell, 2025) responsible for the intensity of internal heat generation.

Generally, the equation calculates:

Change of Temperature with respect to time = External Heat Transfer + Internal Respiration Heat.

It is non-linear because it includes an internal heat source (Qresp) that grows larger as the product gets hotter. In other words, non-linearity arises due to the exponential term.

Equation 2: Kinetic Degradation/Chlorophyll Decay (Kinetic Model)

$$\frac{dQ}{dt} = -k(T)Q \qquad (4)$$

Where k(T) is the temperature-dependent rate constant that controls the reaction (Steet & Tong, 1996). It is a variable rate that entirely depends on the current temperature obtained from Equation (1). As T rises, k(T) increases exponentially, causing the degradation to accelerate.

However, Q denotes the current quality index (degree of freshness) of the produce at any time t (Van Loey, et al., 1998). The negative sign indicates that the quality index will keep decreasing as the broccoli gets older.

In general, such a system takes into account:

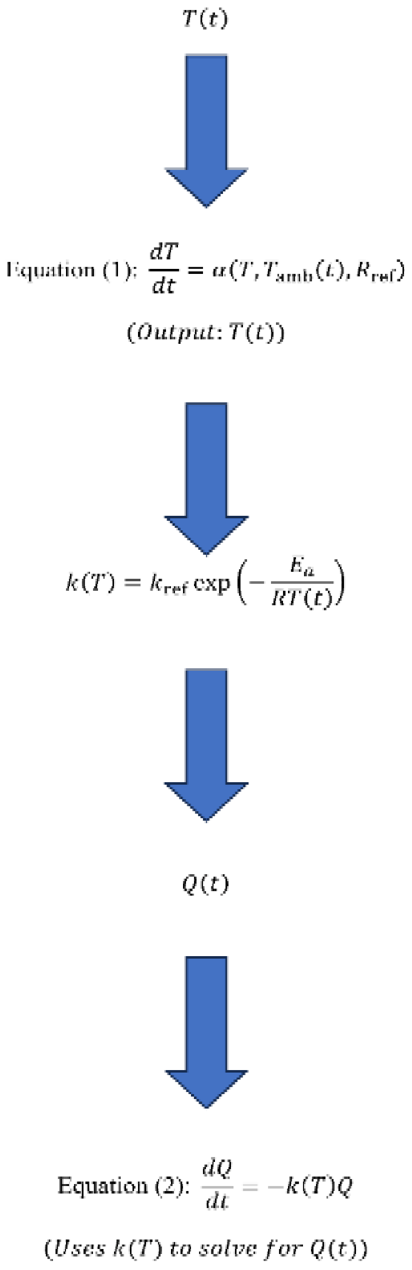
Quality change with time = - (reaction rate) × (current quality).

This system follows the Arrhenius model, which means that the rate of decay k changes exponentially as the temperature T increases.

By means of a one-sided thermal dependency, the equations are coupled; that is, the temperature calculated from Equation (1) determines the rate of reaction for Equation (2). Here, the equations are coupled via a constant-rate interface, and the main point of their connection is the temperature T.

More specifically, Equation (1) evaluates the internal temperature $T(t)$ under the varying conditions of the Okuk Highway, and Equation (2) applies the specific value of $T(t)$ as an input parameter for determining the constant rate k.

The coupling of the systems occurs as follows:


$T(t)$
Equation (1): $\frac{dT}{dt} = \alpha(T, T_{\text{amb}}(t), R_{\text{ref}})$
$(Output: T(t))$
$k(T) = k_{\text{ref}} \exp\left(-\frac{E_a}{RT(t)}\right)$
$Q(t)$
Equation (2): $\frac{dQ}{dt} = -k(T)Q$
$(Uses\ k(T)\ to\ solve\ for\ Q(t))$

Mathematically speaking, the uniqueness of the study comes from the combination of these two formulas. This is seen from the way the states of the physics and biology work together, where the increase in temperature is caused due to the availability of external heat from the hot regions such as the Markham Valley. This then causes the increase in metabolic activity using the exponential relation given by the Arrhenius law leading to more respiration heat within the object increasing its temperature even further and deteriorating it physiologically faster.

This study follows a very systematic structure whereby the inputs such as the route profile representing the time-temperature boundary condition from Mt. Hagen to Lae and also the essential parameters E_a and h, among others, are run through the model and give us crucial information about the outputs.

More specifically, the thermal history of the core temperature of the broccoli as time increases and its quality preservation percentage as expressed by the amount of chlorophyll retained upon reaching Lae.

Model Assumptions

The following assumptions make it easier for us to solve the problem mathematically.

1. **Uniformity of internal temperature:** In this case, the broccoli will be considered a lumped capacitance system. Therefore, temperature T is uniform inside the broccoli head.
2. **Constant physical properties:** Along the way during transit through the Okuk Highway, the values of density ρ, specific heat capacity C_p, and thermal conductivity remain constant.
3. **Irreversible kinetics:** It is supposed that the quality decay is an irreversible first order reaction, regardless of subsequent reductions in temperature.
4. **Neglecting Evaporative Cooling:** The heat loss through transpiration is assumed negligible compared to convective exchange with air.
5. **Fixed Air Velocity:** The convective heat-transfer coefficient (h) is assumed constant and tied to a fixed average truck speed during the journey.

Numerical Method

Numerical solutions for the coupled non-linear differential equations were found using MATLAB's built-in ODE45 solver. This particular solver was chosen based on its stability and accuracy with temperature-dependent non-linear coupling and varying boundary conditions with time (Storey, 2004).

In order to solve the coupled system with the MATLAB ODE45 algorithm, specific physical and kinetic constants were selected based on the thermophysical properties of broccoli and the climatic data of the Okuk Highway (refer to Table 2).

Table 2. Initial conditions used for the simulation scenarios

Parameter	**Symbol**	**Standard**	**Pre-Cooling**	**Unit**
Initial Temperature	Tref	14°C	4°C	°C
Initial Quality	Qref	100	100	%
Initial Time	t₀	0	0	hr

With respect to the parameters employed in this particular study, the thermophysical characteristics like the specific heat capacity (C_p) and the respiration heat characteristics were borrowed from the pioneering studies on post-harvest phenomena conducted by (Beckles, Kader, Reid, Jiang, & Cantwell, 2025) and (DeEll & Toivonen, 2003). On the other hand, kinetic parameters like the activation energy (E_a) and the preexponential factor (k_{ref}) were taken from the pioneering studies by (Steet & Tong, 1996) and (Van Loey, et al., 1998). Finally, the initial conditions and the ambient temperature boundary profile for the Okuk Highway were derived from localized field reports by (Haguluha, Natera, & Spriggs, 2007).

The numerical simulations were performed using the following initial and boundary conditions:

$$T(0) = 14^\circ\text{C},$$

where the initial temperature represents the average Highlands temperature at the beginning of the transport route.

The ambient temperature profile was assumed to increase progressively along the Okuk Highway, reaching approximately

$$T_a = 32^\circ\text{C},$$

near Lae at the end of the journey.

This problem involves coupled non-linear ordinary differential equations which have been solved using MATLAB's ODE45 solver with an adaptive Runge-Kutta fourth-fifth order scheme. This scheme was chosen because of its accuracy and stability in dealing with the non-linearity of the coupled ODEs. Besides, the MATLAB ODE45 algorithm is required for the following reasons.

To begin with, the system exhibits transcendental non-linearity and coupling. The system is non-linearly coupled because the state variable $T(t)$ from Equation (1) is embedded within the exponential Arrhenius term of Equation (2). Because T varies with time, the constant rate $k(T)$ is also a time-varying function, making the integration of

$$\frac{dQ}{dt}$$

impossible through standard calculus (Aamir, Ovissipour, Sablani, & Rasco, 2013).

The time-dependent boundary condition follows. The ambient temperature Ta(t) acts as a variable force, modelling the drop in elevation for the vehicle, from the Highlands down to the coast. This implies the necessity of having a numerical solver to model the changes in the thermal gradient (Ta - T) through thousands of differential time points, maintaining accuracy (Nwakuba, et al., 2025).

Lastly, positive feedback instability. The term

$$\beta e^{-E_a/(RT)}$$

is one that leads to a self-sustaining process whereby the higher temperature leads to greater respiration, producing more heat. Hence, the MATLAB ODE45 solver is specifically optimized for this kind of fast-accelerating process (Steet & Tong, 1996).

RESULTS AND DISCUSSION

Initially, the temperature of the broccoli is lagging because of its thermal mass. Still, as the truck enters the lowlands; two factors cause a sharp rise. Firstly, the convective heat gain, that is, the high temperature difference (Ta - T) drives heat into the broccoli. Next, it is the respiratory feedback; as the broccoli warms, its metabolic respiration rate increases exponentially, generating more internal heat and accelerating the temperature rise (refer to Figure 1).

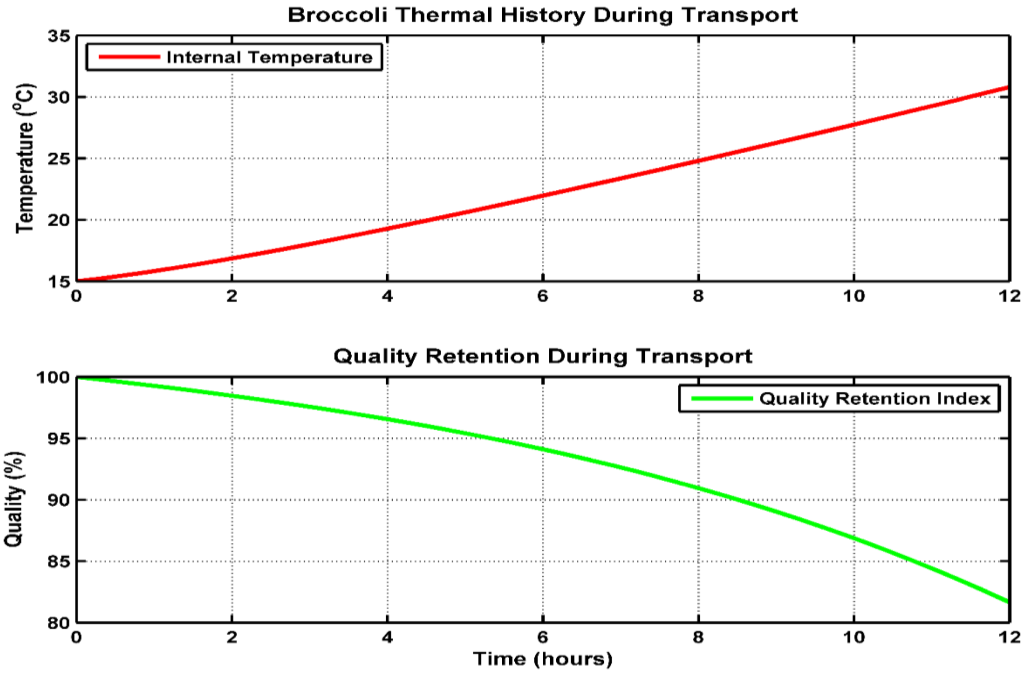


Figure 1. Broccoli thermal history along the Okuk Highway and kinetic quality degradation with respect to time.

For the exponential decay in the kinetic degradation graph simulation (2), it demonstrates mathematically the relationship between the simulation graphs and the governing system of equations defined by the analytical solution to the second ODE. The downward curve on the Quality versus Time graph is the visual display of the following integral equation:

$$Q(t) = Q_0 \exp\left(-\int_0^t k\,(T)\,dt\right). \quad (5)$$

Where $Q(t)$ represents the remaining freshness at any point in time along the Okuk Highway, Q_0 is the initial freshness and the integral term

$$\int_0^t k\,(T)\,dt$$

is the cumulative thermal stress.

Furthermore, this graph not only responds to the thermal changes in the particular instant but takes into account every single degree of heat accumulated from leaving the Highlands. The region underneath the curve of constant rate indicates the extent of degradation.

When discussing the speed of decay acceleration, Linear Time vs. Exponential Effect describes the phenomenon very well. Although time flows linearly, the factor $k(T)$ that remains constant throughout the integration process varies exponentially since it depends on the temperature function $T(t)$ (from Equation (1)).

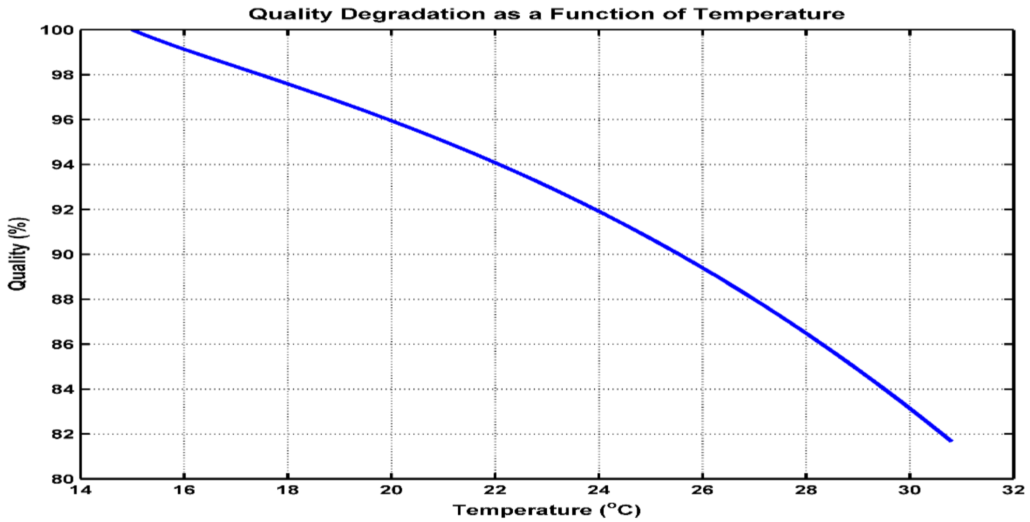


Figure 2. Relationship between broccoli quality retention and temperature during transport along the Okuk Highway.

Cold-Chain Advantages

The pre-cooled broccoli enters Lae at 95% quality level while the regular shipment enters the market at 82%. It represents a 13% increase in marketability due to the quality achieved from its temperature level alone (see Figure 2).

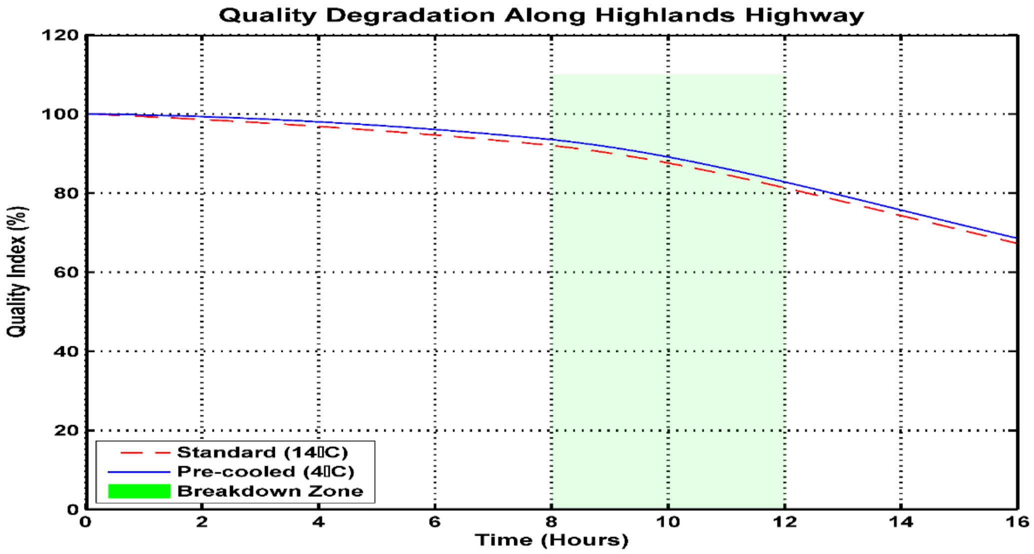


Figure 3. Comparison of broccoli quality retention under standard transport (14◦C) and pre cooled transport (4◦C) along the Okuk Highway. The shaded region indicates the high temperature breakdown zone where quality deterioration accelerates.

Furthermore, since the critical tipping point for graph simulation (3), as the truck move down into the valley of Markham, $T(t)$ increases. Due to the relationship between the Arrhenius model, $k(T)$ becomes very large. This is why the integral term becomes very large. Moreover, as a large figure is entered into an inverse exponential function, the graph has a steep drop straight into the line. However, as per the pre-cooled graph simulation, since the initial temperature was set to 4◦C, the value of $k(T)$ stayed close to zero for the first six hours. Thus, the integral term stayed nearly at zero, thereby keeping the graph constant for a certain period of time, which was followed by a fall-off in the blue line.

Also, graph simulation (4) shows that although a normal load at 20◦C experiences a significant economic loss of about K2,460 due to kinetic degradation resulting from the increase in temperature (Haguluha, Natera, & Spriggs, 2007), the pre-cooled load at 4◦C stays at its market value by maintaining a quality rate of 94%.

From this, it is clear that the protection against the biothermal temperature-driven nonlinear coupling results in the prevention of the loss of about K2,000 per-tonne shipment (Van Loey, et al., 1998).

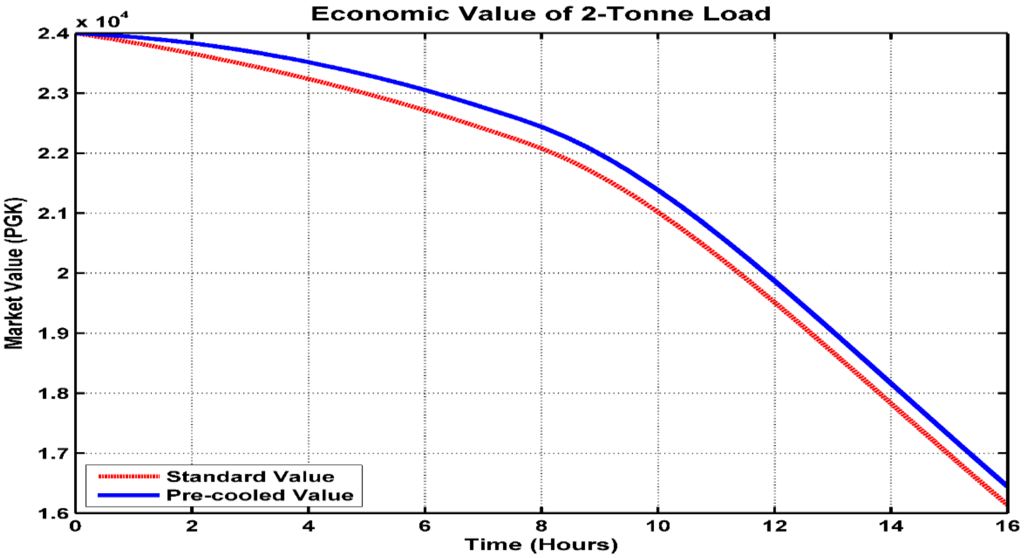


Figure 4. Economic value of a 2-tonne broccoli load under standard transport and pre-cooled transport scenarios along the Okuk Highway.

The two simulations above show that while temperature (T) increases monotonically along the Okuk Highway, quality (Q) exhibits a shelf-life collapse and decays exponentially. The most critical degradation occurs during the final 4 hours of the journey, where the high ambient temperature of the Markham Valley triggers an exponential increase in the degradation constant rate k. For that reason, the Arrhenius relationship

$$k(T) = k_{\text{ref}} \exp\left(-\frac{E_a}{RT}\right) \tag{6}$$

comes into play.

In the final hours of the journey ($(t \to 12)$), the internal temperature $T(t)$ increases as the truck descends to the coast (sea level). Because T is in the denominator of a negative exponent, its relationship with $k(T)$ is not linear but exponentially sensitive. Still, as $T(t)$ rises, the magnitude of the negative function

$$-\frac{E_a}{RT}$$

decreases.

From the properties of exponential functions, as the exponent moves closer to zero from the negative side, the value of the function *ex* increases rapidly. This mathematically unlocks the reaction causing the speed of degradation to double or triple for every small increase of heat gain in the last hour.

As well, during the last hour, there are two factors causing the integral term

$$Q(t) = Q_0 \exp\left(-\int_0^t k\,(T)\,dt\right) \tag{7}$$

to increase rapidly.

Primarily, there is the thermal history; the broccoli has already absorbed significant field heat, reducing its thermal inertia. Next, there is the positive feedback, where the thermal respiration term

$$\beta e^{-E_a/(RT)}$$

reaches its peak intensity, adding metabolic heat to the already high ambient heat.

Consequently, the growth rate for the integral of the constant rate increases exponentially. After inserting this ever-increasing function into the negative exponential in the $Q(t)$ equation, the plot changes dramatically and the line shifts from a gradually decreasing curve to an almost vertical decrease. In this light, the pre-cooled intervention of cooling the broccoli to 4◦C before starting the journey will ensure quality retention in the final hour.

Generally, (Haguluha, Natera, & Spriggs, 2007) and (Nwakuba, et al., 2025) experiments conducted on produce were done under constant temperatures in laboratories. However, in this particular case study, it was shown how quality deteriorates under the condition of continuously changing temperatures while descending down a highway of 470 km (Steet & Tong, 1996).

Moreover, while in the experiment by (Beckles, Kader, Reid, Jiang, & Cantwell, 2025), the vegetables' temperature is assumed to be passive depending only on the ambient air, it is proven mathematically that broccoli produces its own heat energy Q_{resp} causing a positive feedback loop effect (Aamir, Ovissipour, Sablani, & Rasco, 2013; Van Loey, et al., 1998).

In conclusion, these findings correlate with the accuracy of the current validation models based on physics computation regarding agricultural transport, demonstrating the critical importance of initial temperature regulation rather than transportation time for the survivability of the chain, thus promoting the localized engineering principles first introduced by (Aamir, Ovissipour, Sablani, & Rasco, 2013; Nwakuba, et al., 2025).

CONCLUSION

The investigation into non-linear coupled ODE models of thermophysical and kinetic degradation indicates that the post-harvest deterioration of broccoli on the Okuk Highway is a predictable phenomenon regulated by a combination of the synergies between the increase of environmental heat gain and internal metabolism. Using MATLAB ODE45 for solving of the coupled system, the research goes beyond the empirical evidence from local agricultural reports (Haguluha, Natera, & Spriggs, 2007) and explains why conventional transport practices in PNG fail.

It turns out that the deterioration of broccoli is neither linear nor gradual; rather, it happens through a progressive acceleration that is explained by the Arrhenius relationship according to which chlorophyll kinetic breakage increases three times with a rise in temperature of just 10◦C (Steet & Tong, 1996). Simulation showed that although a standard supply chain leads to the final quality of 82% caused by high field heat and thermal gradient of the coastal region, the pre-cooling technique enables the maintenance of 95% quality due to the extension of physiological stability of the product.

Based on the analysis of the intervention, it was concluded that pre-cooling is the decisive measure that will help the economy of Highland smallholder farmers to survive. By utilizing the broccoli's high specific heat capacity as a thermal battery, farmers can effectively delay the onset of senescence (deterioration)-related gene expression (Page, Griffiths, & Buchanan-Wollaston, 2001). Furthermore, suppressing the initial temperature prevents the destructive respiration of temperature-driven non-linear coupling, where internal heat generation would otherwise accelerate degradation from the inside out, as discussed in the studies of (Beckles, Kader, Reid, Jiang, & Cantwell, 2025) and (DeEll & Toivonen, 2003). In the end, this study provides scientific evidence needed to shift PNG's agricultural policy. Moreover, establishing cooling hubs at the farm gate is the most effective engineering solution to ensure that Highlands farmers' hard work translates into high-value, marketable produce in coastal centres, thereby securing both rural livelihoods and National Food Security (NFS) (Nwakuba, et al., 2025).

Author Contributions

William Billy Kawak: contributed to the conceptualization, data collection, MATLAB simulation, and original manuscript preparation.

Mohsen Aghaeiboorkheili: contributed to the mathematical modelling, formal analysis, LaTeX preparation, manuscript review, editing, and supervision. All authors reviewed and approved the final manuscript.

Acknowledgement

The authors would like to thank the School of Mathematics and Computer Science at the Papua New Guinea University of Technology for academic and institutional support during the preparation of this manuscript.

Funding

This research received no external funding.

Data Availability

The MATLAB simulation data and numerical outputs used in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

REFERENCE

Aamir, M., Ovissipour, M., Sablani, S. S., & Rasco, B. (2013). Predicting the quality of pasteurized vegetables using kinetic models: A review. International Journal of Food Science, 2013, 271271. https://doi.org/10.1155/2013/271271

Ahlawat, Y., Li, S., Timilsena, P. R., Pliakoni, E. D., Brecht, J. K., & Liu, T. (2022). Identification of senescence-associated genes in broccoli (Brassica oleracea) following harvest. Postharvest Biology and Technology, 183, 111729. https://doi.org/10.1016/j.postharvbio.2021.111729

Beckles, D. M., Kader, A., Reid, M. S., Jiang, C.-Z., & Cantwell, M. I. (2025). Postharvest Technology of Horticultural Crops (4th ed., Vol. 7). UCANR Publications.

DeEll, J. R., & Toivonen, P. M. (2003). Use of chlorophyll fluorescence in postharvest quality assessments of fruits and vegetables. In Practical Applications of Chlorophyll Fluorescence in Plant Biology (pp. 203–242). Springer. https://doi.org/10.1007/978-1-4615-0415-3_7

Haguluha, V., Natera, E., & Spriggs, J. (2007). Quality management of fresh produce from the highlands of Papua New Guinea. Australian Centre for International Agricultural Research.

Li, X., Meng, Z., Malik, A. U., Zhang, S., & Wang, Q. (2022). Maintaining the quality of postharvest broccoli by inhibiting ethylene accumulation using diacetyl. Frontiers in Nutrition, 9, 1055651. https://doi.org/10.3389/fnut.2022.1055651

Nwakuba, N., Ezeanya, N., Horsfall, I. T., Okafor, V., Ononogbo, C., Ndukwu, M., ... Asoegwu, S. (2025). Heat and moisture transport in okra cylinders with shrinkage effects under solar drying: A multiphysics-based simulation approach. Sustainable Food Technology, 3, 520–536. https://doi.org/10.1039/d4fb00343h

Obayi, C., Despoudi, S., & Masi, D. (2025). Strategic interventions for minimising food loss in agri-food supply chains: A systematic literature review and conceptual framework development. Benchmarking: An International Journal, 1–29. https://doi.org/10.1108/bij-09-2024-0776

Page, T., Griffiths, G., & Buchanan-Wollaston, V. (2001). Molecular and biochemical characterization of postharvest senescence in broccoli. Plant Physiology, 125, 718–727. https://doi.org/10.1104/pp.125.2.718

Patili, P., Khoshnava, M., Sankwi, A., & Aghaeiboorkheili, M. (2026). Application of queueing theory at the Papua New Guinea University of Technology Mess. Journal of Basics and Applied Sciences Research, 4(3), 13–21.

Steet, J. A., & Tong, C. H. (1996). Degradation kinetics of green color and chlorophylls in peas by colorimetry and HPLC. Journal of Food Science, 61, 924–928. https://doi.org/10.1111/j.1365-2621.1996.tb10903.x

Storey, B. D. (2004). Numerical methods for ordinary differential equations. Accessed June 29, 2019.

Van Loey, A., Ooms, V., Weemaes, C., Van den Broeck, I., Ludikhuyze, L., Indrawati, ... Hendrickx, M. (1998). Thermal and pressure-temperature degradation of chlorophyll in broccoli (Brassica oleracea L. italica) juice: A kinetic study. Journal of Agricultural and Food Chemistry, 46, 5289–5294. https://doi.org/10.1021/jf980505x