Review Article
Food Science and Technology

ISSN 0101-2061 (Print)
ISSN 1678-457X (Online)

DOI: https://doi.org/10.1590/fst.32722

CC BY

# The time-temperature tolerance theory behind thermal kinetic models for shelf-life prediction of common foods

Ying XU[1], Lu LU[1*]

**Abstract**

Time-Temperature Tolerance (TTT) is an efficient and intuitive method of shelf-life prediction or logistics stability evaluation, but specific for frozen foods, while other thermal kinetic models for chemical reactions and microbial growth are complicated for users and widely used in common foods. In this paper, one common law deduced from TTT theory is that the equivalent conversion ratio (*ECR*) of the elapsed times for one isothermal interval between different temperatures is only related to the temperatures and equal to the ratio of corresponding shelf-lives. The law was demonstrated by 1-order chemical kinetic model and Gompertz model for chemical reaction and microbial growth. Besides, Crimson seedless fresh grape and Mackerel also proved the constancy of the *ECRs* between fixed temperatures. With the corresponding *ECRs* of key quality indicator among relevant temperatures, effect of any time-temperature history can be accumulated into one isothermal one equivalently and the remaining shelf life would be easily predicted, which is the theory of TTT. As a results, the quality following the chemical reaction and microbial growth obey the TTT theory, and the TTT theory can be used to predict the shelf-lives of most foods with developed time-temperature monitoring technologies.

**Keywords:** time-temperature tolerance; chemical kinetic model; microbial growth model; shelf-life prediction; equivalent conversion ratio.

**Practical Application:** Time-Temperature Tolerance (TTT) for the shelf-life prediction of common foods.

## 1 Introduction

Along with the growing public concern over the food quality, production performance, human health, etc., prediction of food shelf-life and evaluation of logistics stability have become the hot points of researchers, consumers, and producers for a very long time. This could display the food spoilage process during the logistics and benefit to the quality control of foods. Logistics stability and shelf life are similar critical indicators for the food and logistics, respectively. Take shelf-life for example, it is the time period during which food remains safe for consumption while maintaining the desired quality characteristics (Galvão et al., 2022). It is a dynamic value dependent on many factors (Oliveira et al., 2022b), including temperature, water activity, light, air, pH, packaging materials etc. (Torres et al., 2016; Moschopoulou et al., 2019; Šimat et al., 2021; Rasul et al., 2022). Among these, temperature is one key factor not for its closely relationship with growth of microorganisms, reaction of enzymes and transformation of ingredients in foods (Oliveira et al., 2022a), but also for its synergistic effect with some other factors, like vacuum, modified atmosphere packaging (Šimat et al., 2021), etc. Until now, many models have been established for predicting the effect of temperature on food quality for the shelf-life prediction and corresponding stability evaluation.

TTT is one relatively simple theory original from empirical study for the shelf-life of frozen food by Van Arsdel in 1957 (Scott & Heldman, 1990; Ross & Olley, 1997; Fu & Labuza, 1997). According to related literatures, this theory is one effective prediction method specific for many frozen foods, such as red hake (Licciardello et al., 1982), sprouts (Lyon et al., 1988), tuna (Tanaka et al., 2012) as well as some processes of normal foods (Tano-Debrah et al., 2019; Dattatreya et al., 2007; Shukla et al., 2020). But recently, less research was on it. Instead, many kinetic models, such as chemical kinetic models, microbial growth models were adopted for the prediction of food shelf-life frequently and efficiently (Kwolek & Bookwalter, 1971; Labuza & Riboh, 1982; Phimolsiripol & Suppakul, 2016). For example, the models are succeeding in prediction of sensory quality, texture, nutrition, active compounds, wasters or microbials of fruits (Zhang et al., 2021; Zapata et al., 2022), vegetables (Zhou et al., 2022; Zhao et al., 2022), meat (Yimenu et al., 2019), edible fungus (Song et al., 2018; Niu et al., 2020), processed foods (Yang et al., 2021; Secer et al., 2020; Giannoglou et al., 2019), etc.

Though this, TTT theory is still impressive for its simplicity and effectiveness on the frozen food. For frozen food, the time-temperature history is usually divided into many different isothermal episodes, and according to TTT theory, the percentages of each elapsed isothermal intervals in the view of whole shelf-life can be accumulated together for predicting the remaining shelf-life, without the effect of prior sequence of these during the whole history. Though many scholars tried to extend its application scope to the non-frozen foods, there are no theoretic basis so far

*Received 22 Feb., 2022*
*Accepted 26 Apr., 2022*
[1] *College of Humanities & Social Development, Nanjing Agricultural University, Nanjing, Jiangsu, China*
*Corresponding author: gushiliangshi1111@163.com

and the application effect is relatively low. Along with the further development of time-temperature monitoring technologies, this work become necessary and feasible.

Many chemical kinetic and microbial growth models were established and adopted for the shelf-life non-frozen foods. For example, according to literatures, many quality indicators of food follow the 0-, 1-, or 2- order reaction as well as the bacterial models (Labuza & Riboh, 1982; Van Boekel, 2008) which can reveal the changing process of given food quality and the remaining shelf-life. These methods have their own advantages and limitations. The TTT is too general to expose more information about the quality change (and only effect in frozen foods by now), while chemical kinetic model and bacterial model are too complicated to be applied and understand easily. For this reason, Ma et al. (2016) derived contour diagram theory from the research of Kwolek & Bookwalter (1971) for the storage stability evaluation from 0-order or 1-order kinetic models which is similar with the theory of TTT, but the rules in their research cannot been broadened to the growth of bacteria at ambient temperature, such as Baranyi and Roberts model, Gompertz model etc. Therefore, in this paper, one common theorical basis for the of relationship between TTT with other models would be established and interpretated, for widening the use scope of TTT in non-frozen foods. In contrast to the frequently used kinetic models, with the TTT, it will be more convenient for food producer or supplier to monitor the quality of most foods, which could support the following strategies to keep their quality and prolong their shelf-lives as well as the application of time-temperature indicator (TTI).

In the section 2, the theoretical assumption original from TTT were interpreted, and validation of chemical kinetic model and microbial growth model for the TTT theory were derived in Section 3. Section 4 displayed 2 cases carried out for demonstrating the common rules intuitively before the Discussion in Section 5.

## 2 Theoretical assumption for contour diagram

### *2.1 TTT theory*

TTT is invited as one prediction method specific for frozen food. The TTT theory is shown in Equations 1 and 2 and Equation 3 is deducted from the theory.

$$P_{CSL} = \Sigma(\Delta t_{Ti} / SL_{Ti}) \tag{1}$$

$$RSL_{Ti} = (1 - P_{CSL}) \times SL_{Ti} \tag{2}$$

$$\begin{aligned} CSL_{Tj} &= P_{CSL} \times SL_{Ti} = \Sigma(\Delta t_{Ti} / SL_{Ti}) \times SL_{Tj} = \left(SL_{Tj} / SL_{T1}\right) \times \Delta t_{T1} + \left(SL_{Tj} / SL_{T2}\right) \times \Delta t_{T2} + \\ &\ldots + \left(SL_{Tj} / SL_{Ti}\right) \times \Delta t_{Ti} + = \left(ECR_{T1-Tj}\right) \times \Delta t_{T1} + \left(ECR_{T2-Tj}\right) \times \Delta t_{T2} + \left(ECR_{Ti-Tj}\right) \times \\ &\Delta t_{Ti} + = \Delta t_{T1-Tj} + \Delta t_{T2-Tj} + \Delta t_{Ti-Tj} \end{aligned} \tag{3}$$

In these equations, $T_i$ and $T_j$ are temperature at *i-th* and *j-th* isothermal process intervals, respctively and *i*, *j* are sequence number of each isothermal process divided from one natural logistics. $SL_{Ti}$ and $SL_{Tj}$ is the shelf-life at $T_i$ and $T_j$, respectively. $\Delta t_{Ti}$ is the time of *i-th* isothermal process interval, $P_{CSL}$ is the consumed proportion of shelf-life, $RSL_{Ti}$ and $CSL_{Tj}$ are the remaining and consumed shelf-life at the temperature of $T_i$, respectively. $ECR_{T1-Tj}$ *is* equivalent conversion ratio of one interval from $T_i$ to $T_j$., and $\Delta t_{Ti-Tj}$ is the equivalent time at $T_j$ of the *i-th* isothermal process interval at $T_i$.

As TTT theory shown, the rates of each isothermal process intervals time ($\Delta t_{Ti}$) to the full shelf-lives ($SL_{Ti}$) under corresponding temperatures can be summed up to be the consumed proportion of shelf-life ($P_{CSL}$) as Equation 1. Therefore, the remaining shelf-life ($RSL_{Ti}$) at certain temperature shown in Equation 2 can be obtained by multiplying the remaining proportion of shelf-life with the shelf-life ($SL_{Ti}$) at that temperature Meanwhile, the consumed shelf-life ($CSL_{Tj}$) at certain temperature ($T_j$) can be calculated by accumulating the product of each isothermal process interval time ($\Delta t_{Ti}$) with one corresponding parameter ($SL_{Tj}/SL_{Ti}$) which is defined as Equivalent Conversion Ratio (*ECR*) in this paper, as shown in Equation 3.

Based on the TTT theory, both $SL_{Tj}$ and $SL_{Ti}$ are fixed at given temperature $T_j$ and $T_i$. Also, the corresponding *ECR* is fixed. But for most shelf-life prediction models, whether the *ECRs* for the conversion from $\Delta t_{T1}$ to $\Delta t_{T1-Tj}$ are constant or easily calculated for many models which is necessary for the application of TTT theory.

According to Ma et al.'s (2016) research, *ECRs* of chemical kinetic models is stable which leads to the establishment of contour diagram method for shelf-life prediction. But there is no evidence for the constancy of *ECRs* for the microbial growth. Hence, the constancy of *ECRs* between any given temperatures in most thermal kinetic models would benefit to the application extension of TTT theory to unfrozen foods.

### *2.2 Theory foundation for Assumption*

For exploring the basic laws of TTT theory, reaction extent of quality spoilage with some modification is adopted from the research of Zhang et al. (2017). Generally, one variable temperature process (like dotted line in Figure 1) can be approximate to one process combined with many isothermal intervals (n) (like full line in Figure 1) with the equivalent quality spoilage. In this paper, the division of each interval is based on the equal quality instead of time as Zhang et al. (2017) did. Along time,

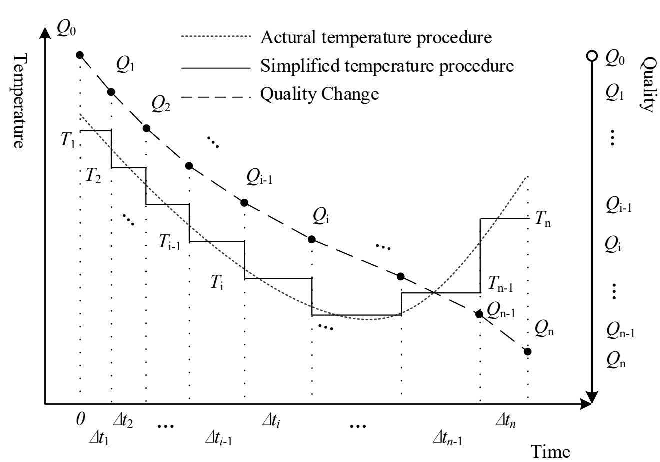


**Figure 1**. The diagram of one anisothermal process and corresponding phased process with isothermal intervals.

the temperature is fluctuant (like dotted line or full line), and the quality continuously falls like break line in Figure 1.

In this figure, $Q_0$ and $Q_n$ is the initial quality and final quality at the end of shelf-life, respectively. $T_i$, $\Delta t_{Ti}$ and $Q_i$ are the temperature, interval time, end quality of *i-th* isothermal interval, and *i* is the sequence value of each interval ranging from 1 to n. The conversion from a variable temperature process like Figure 1 into one isothermal process would help us to understand the TTT theory easily.

In order to distinguish the parameters at each interval of the initial process and equivalent converted process, all of them (Initial process and Converted process) are organized and marked in Figure 2. $T_i$, $\Delta t_{Ti}$ and $Q_i$ are the parameters of initial process as mentioned before, while $\Delta t'_{Ti}$, $Q'_i$ are the corresponding parameters of converted process at temperature *T'*.

As deduction from Part 2.1, the constancy examination of *ECRs* between given temperatures is the key step for the application of TTT theory. For the fixed start quality status and end status at each interval, the ratio of spoilage speeds of the concerned quality indicator between the given temperatures should be constant too. The constancy verification of the *ECRs* is the problem ready to be solved in this paper.

## 3 The TTT theory behind chemical reaction and microbial growth

There are many methods for the stimulation of food spoilage, generally based on chemical reaction and microbial growth. For the enzyme or chemical reaction, there are more initial reaction substrate promoting the reaction process at first, and the reaction speed would slow down along with consumption of substrate and accumulation of products; In the aspect of microorganisms, one adaptation period is necessary for them before growth fast. Then, more and more microbials as well as damage to the food quality would promote the increasing speed of microorganisms. But at the same time, more and more ingredients of foods are consumed impeding the continuous growth of microorganisms and leading the number of microorganisms to a top value slowly.

Based on this, 2 classic models: chemical kinetic model (1- order kinetic model with Arrhenius equation) and microbial growth model (Gompertz model with Belehradek equation) which were frequently taken for describing the food spoilage and predicting shelf-life, were adopted in this section, to verify the applicability of TTT theory.

### *3.1 The equation deduction based on 1-order chemical kinetic model*

1-order kinetic model has been widely used in the prediction of the sensory quality, enzyme reaction, chemical reactions, etc. successfully. The start quality and end quality of *i-th* interval ($Q_i \rightarrow Q_{i+1}$) at *T* and *T'* are listed as Equation 4 and Equation 5, while the elapse times of the intervals at *T* and *T'* are Equations 6 and 7, respectively. The ratio ($ECR_{T\rightarrow T',Qi\rightarrow Qi+1}$) for the *i-th* isothermal interval from *T'* to *T* can be deduced as Equation 8.

$$ln(Q_i) = ln(Q_0) + k_0 \times exp\left[-Ea/(R\times T)\right]\times t_{iT};\ ln(Q_{i+1}) = ln(Q_0) + k_0 \times exp\left[-Ea/(R\times T)\right]\times (t_{iT} + \Delta t_{iT}) \quad (4)$$

$$ln(Q_i) = ln(Q_0) + k_0 \times exp\left[-Ea/(R\times T)\right]\times t_{iT'};\ ln(Q_{i+1}) = ln(Q_0) + k_0 \times exp\left[-Ea/(R\times T')\right]\times (t_{iT'} + \Delta t_{iT'}) \quad (5)$$

$$\Delta t_{iT} = \left\{\left[ln(Q_{i+1})/\ ln(Q_0)\right] - ln\left[ln(Q_i)/\ ln(Q_0)\right]\right\} / \left\{k_0 \times exp\left[-Ea/(R\times T)\right]\right\} \quad (6)$$

$$\Delta t_{iT'} = \left\{\left[ln(Q_{i+1})/\ ln(Q_0)\right] - ln\left[ln(Q_i)/\ ln(Q_0)\right]\right\} / \left\{k_0 \times exp\left[-Ea/(R\times T')\right]\right\} \quad (7)$$

$$ECR_{T\rightarrow T',Qi\rightarrow Qi+1} = \Delta t_{iT'} / \Delta t_{iT} = exp\left[-Ea/(R\times T)\right] / exp\left[-Ea/(R\times T')\right] = ECR_{T\rightarrow T'} \quad (8)$$

In these equations, $t_{iT}$ and $t_{iT'}$ are the start time of i-th interval at *T* and *T'*, while $\Delta t_{iT}$ and $\Delta t_{iT'}$ are the corresponding elapse time. *Ea*, *R* and *k* are reaction activation energy, gas law constant and coefficient of the function, respectively, and they are constant for one given subject. Based on this, it is obviously that the *ECR* of the interval between any two given temperatures is one constant and equal to the ratio of corresponding shelf-life ($ECR_{T\rightarrow T'}$), which is following the supposed law of section 2.1 original from TTT theory. The other chemical kinetic models also follow the TTT theory analogously.

### *3.2 The equation deduction based on Gompertz model*

The equation of Gompertz model and Belehradek function for the microbial growth at *T* is like Equations 9 and 10.

$$lgN_i = lgN_0 + lg(N_{max}/N_0)\times exp\left\{-exp\left[(\lambda - t_{iT})\times e\times \mu_{max}/lg(N_{max}/N_0)+1\right]\right\} \quad (9)$$

$$lgN_{i+1} = lgN_0 + lg(N_{max}/N_0)\times exp\left\{-exp\left[\begin{matrix}(\lambda - t_{iT} - \Delta t_{iT})\times e\times \\ \mu_{max}/lg(N_{max}/N_0)+1\end{matrix}\right]\right\} \quad (10)$$

In the above equations, $N_0$ is the initial microbial quantity, while $N_i$, $N_{i+1}$ and are the amount of microbials at start and end of the *i-th* interval. $N_{max}$ is the maximum number of the microbial under the concerned situation. *e* is the natural logarithm

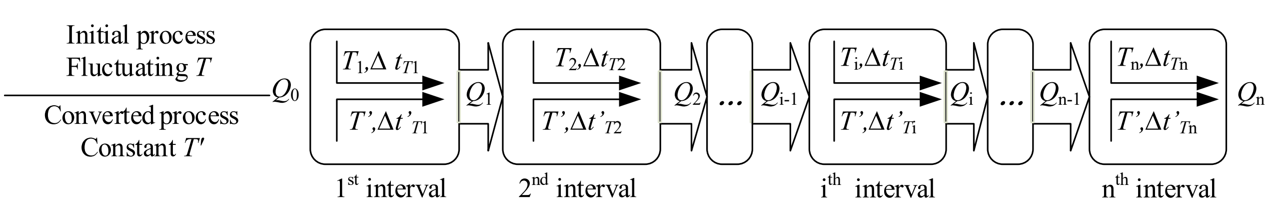


**Figure 2**. Corresponding parameters of time temperature history in each interval of initial process and converted process.

(2.718). λ and $\mu_{max}$ are the latency time and maximum rate of the microorganism which is closely related with temperature as that:

$$\mu_{max} = b_{\mu}^{2} \times \left(T - T_{min\mu}\right)^{2};\ 1/\lambda = b_{\lambda}^{2} \times \left(T - T_{min\lambda}\right)^{2} \quad (11)$$

$b_{\mu}$, $b_{\lambda}$, $T_{min\mu}$, $T_{min\lambda}$ are parameters of λ and $\mu_{max}$. The corresponding parameters and equations at *T'* are like that at *T*. After the deduction from Equation 9 and Equation 10, the ratio $ECR_{T\rightarrow T',Ni\rightarrow Ni+1}$ from *T* to *T'* at *i-th* interval is obtained as:

$$ECR_{T\rightarrow T',Ni\rightarrow Ni+1} = \Delta t_{iT'} / \Delta t_{iT} = \mu_{max} / \mu'_{max} = ECR_{T\rightarrow T'} \quad (12)$$

For the equation of $\mu_{max}$ as Equation 11, temperature is the only variable for the $\mu_{max}$ and $\mu'_{max}$. when the corresponding temperatures are fixed, $ECR_{T\rightarrow T',Ni\rightarrow Ni+1}$ is one constant and equal to the ratio of corresponding shelf-life ($ECR_{T\rightarrow T'}$), which is following the supposed law of section 2.1 original from TTT theory.

### *3.3 The ECRs for the TTT theory*

For the variable temperature process in Figure 2, shelf-life ($SL_{T'}$) and each elapse time of the equivalent converted isothermal process can be calculated as Equation 13 with corresponding $ECR_{Ti\rightarrow T'}$ from $T_1$, $T_2$, … $T_i$,… $T_n$ to *T'*, respectively.

$$SL_{T'} = \Delta t_{T'1} + \Delta t_{T'2} + \ldots \Delta t_{T'i} + \Delta t_{T'n} = \Delta t_{T1} \times ECR_{T1\rightarrow T'} + \Delta t_{T2} \times ECR_{T2\rightarrow T'} + \Delta t_{Ti} \times ECR_{Ti\rightarrow T'} + \Delta t_{Tn} \times ECR_{Tn\rightarrow T'} \quad (13)$$

In this equation, $\Delta t_{T'i}$ are the equivalent elapsed time of $\Delta t_{Ti}$ at *i-th* interval, and i is the natural number from *1* to *n*.

In this section, only two classic kinetic models are used to verify relationship between the chemical reaction, microbial growth with TTT theory, while many other models including Linear model, Monod model, Logistic model, Baranyi & Roberts model, etc. are also can achieve the similar results through analogous deduction. From the deductions above, it reveals that most chemical reaction and microbial growth are following the TTT theory, and TTT theory can be adopted to replace the corresponding models for shelf-life prediction or logistics stability evaluation. But it should be noted that the effect of cold injury or high temperature sterilizing on food were excluded in this rule.

## 4 Cases verification for the ECRs constancy

### *4.1 The case by 1-order chemical kinetic model for TTT theory*

In this part, one case was set based on some previous research results (Phimolsiripol & Suppakul, 2016; Song et al., 2018; Secer et al., 2020; Zhang et al., 2021; Zhou et al., 2022; Zhao et al., 2022) for the verification of ECRs' constancy. The shelf-life prediction of Crimson seedless fresh grape based on the grape firmness was adopted from Ma's research (2016) in this section. The initial firmness of grape is 2.20 kg/cm$^2$, while the edge of the appropriate quality is 1.44 kg/cm$^2$. $K_0$, *Ea* and *R* are -exp(12.211) kg/cm$^2$/hour, 44.5 kJ/mol and 8.314 J/mol/K, respectively. 4 isothermal processes at -4 °C, 0 °C, 10 °C and 20 °C, respectively, was set to reflect the effect of the frozen, ice, cold, and normal temperature on fresh grape. According to the 1- order kinetic model with Arrhenius equation, the degrade process at the 4 temperatures are like Figure 3a with the shelf-life of 913.16, 682.46, 341.61 and 179.26 hours, respectively. The degradation speeds of the indicator are like Figure 3b. Along with time, the quality degradation become slow, and the more quality is consumed, the slower the degradation speed is.

For examining the constancy of *ECRs* for each interval, 0.01 kg/cm$^2$ which is about 0.45% of the initial quality value is adopted for the length of each interval. The elapsed time of each interval can be calculated and plotted in Figure 3c. At the same time, the average spoilage speed of each interval is also drawn in Figure 3d. According to the Figure 3c and 3d, the duration of each interval at different temperature and corresponding average speeds are proportional in each quality point. The *ECRs* between every two temperatures are listed as constants in Table 1, no matter the length of these interval.

Similarly, the *ECRs* between the other two temperatures also can be calculated by Equation 13. The *ECR* table apply to all the conversion between the isothermal intervals between corresponding temperatures. The constant *ECR* value between any two reasonable temperatures confirmed the work of the assumption in Section 2.2 and the applicability of TTT theory in the reaction following the chemical kinetic models.

### *4.2 The case by Gompertz model and Belehradek function for TTT theory*

For the microbial growth, according to previous research as reference (Niu et al., 2020; Fan 2011; Ding et al., 2015; Shen 2015), one case about the microbials growth of Mackerel (Liu et al., 2015) based on Gompertz model and Belehradek function is referred as that: $\lg N_0$=4.03, $\lg N_{max}$=8.93, $b_{\mu}$=0.0137, $T_{min\mu}$=-6.62 °C, $b_{\lambda}$=0.0105, $T_{min\lambda}$=-6.61 °C. Since that, the number of microbial grows at the temperature of -4 °C, 0 °C, 10 °C, 20 °C like the full line in Figure 4a. According to the recommended microbial spoilage threshold of 7 log CFU/g (International Commission on Microbiological Specifications for Foods, 1986), their shelf-lives are 927.14, 145.22, 23.04 and 8.98 hours, respectively. Along with time, the grow speed increases at first and declines after reaching the top (Figure 4b). But the top speeds of the microorganism vary at different temperatures.

For the examination of *ECRs*' constancy, $\Delta N$=10$^5$ cfu/g, 0.1% of $N_{max}$, was adopted as the length of each interval. The elapsed time of each interval at different temperatures along with quality degradation are drawn in Figure 4c and the average speed of each interval is in the Figure 4d. The elapsed time and average speed of each interval at different temperatures are proportional in each quality point, no matter the quality condition. Since that, the *ECRs* of interval times (and average growth speeds) at different given temperatures is constant as listed in Table 2.

When the amount of microbials is usually described in the lg form, corresponding *ECRs* achieve the same result as Table 2. The constant *ECR* value of microbial growth also confirm the applicability of TTT theory to the microbial growth models. Besides, the other related microbial growth models would achieve the same result.

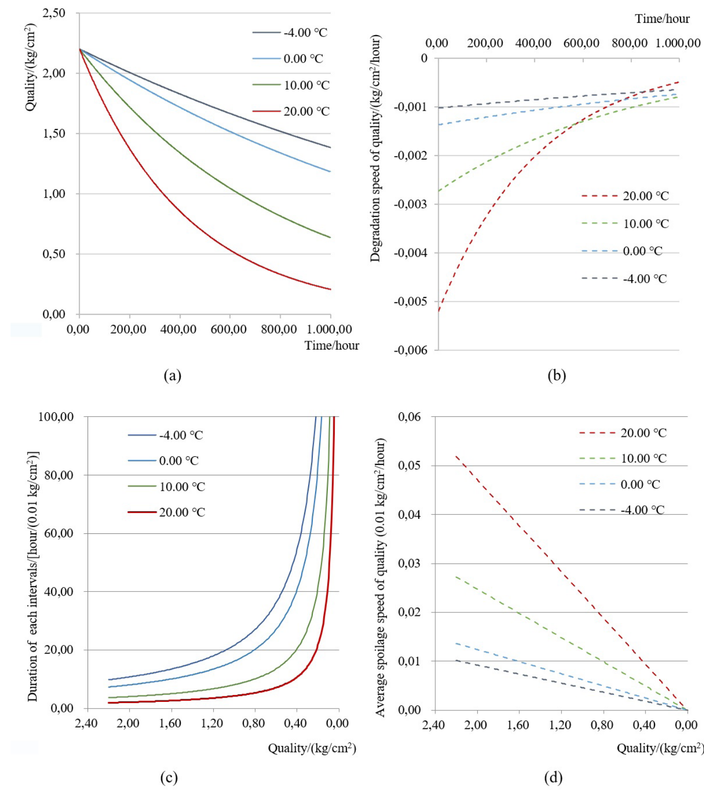


**Figure 3**. the kinetic characteristics during the quality change based on chemical kinetic model. (a) the quality change along with time; (b) the degradation speed of quality along with time; (c) duration of each interval ($\Delta Q$=0.01 kg/cm²) along with quality change; (d) average degradation speed of each interval along with quality.

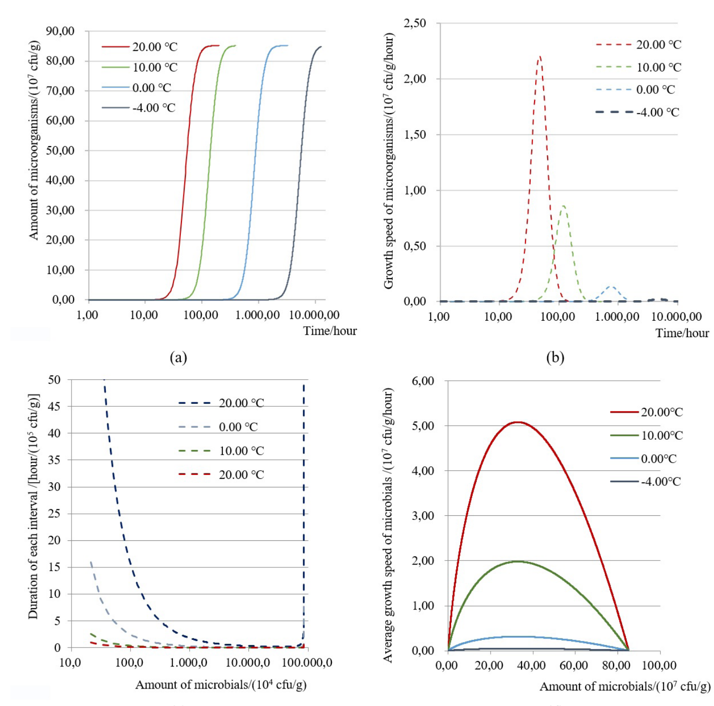


**Figure 4**. The growth characteristics during microbial growth based on Gompertz model. (a) the growth of microorganism along with time; (b) the growth speed of microorganism along with time; (c) duration of each interval ($\Delta\ N_0$ =$10^5$ cfu/g) along with microbial growth; (d) average growth speed of each interval along with microbial growth.

**Table 1**. The *ECR** based on 1-order kinetic models for the given case.

| Temperature | -4.00 °C | 0.00 °C | 10.00 °C | 20.00 °C |
|---|---|---|---|---|
| -4.00 °C | 1.0000 | 0.7439 | 0.3724 | 0.1954 |
| 0.00 °C | 1.3442 | 1.0000 | 0.5006 | 0.2627 |
| 10.00 °C | 2.6855 | 1.9978 | 1.0000 | 0.5248 |
| 20.00 °C | 5.1177 | 3.8071 | 1.9057 | 1.0000 |

*Each *ECR* value is the conversion multiple of elapse time from corresponding row temperature to column temperature.

**Table 2**. The *ECR** based on microbial growth models for the given case.

| *ECR** | -4.00 °C | 0.00 °C | 10.00 °C | 20.00 °C |
|---|---|---|---|---|
| -4.00 °C | 1.0000 | 0.1566 | 0.0249 | 0.0097 |
| 0.00 °C | 6.3843 | 1.0000 | 0.1587 | 0.0618 |
| 10.00 °C | 40.2401 | 6.3030 | 1.0000 | 0.3898 |
| 20.00 °C | 103.2318 | 16.1696 | 2.5654 | 1.0000 |

*Each *ECR* value is the conversion multiple of interval duration from corresponding row temperature to column temperature.

## 5 Discussion

Based on the interpretation of TTT theory by chemical kinetic model and microbial growth model, for one quality indicator, the *ECR* (ratio of elapsed times for one same interval between every two different temperature) is only affected by the corresponding temperatures, and equal to the ratio of corresponding shelf-lives. With the information of *ECRs* or shelf lives at different temperatures, any variable temperature process can be transferred into one isothermal process with corresponding *ECRs* after dividing it into enough isothermals equivalently.

However, in most previous research, TTT theory is known as one shelf-life prediction specific for frozen foods rather than the unfrozen foods at ambient temperature (Torres et al., 2016; Fu & Labuza, 1997). According to comparison of the temperature control efficiency between frozen foods and unfrozen foods, it can be found that frozen foods have a longer shelf-life and are usually stored under stable frozen temperatures. So temperature fluctuation (Wang et al., 2007) cause relatively less effect on the frozen foods than that on the other foods. But now, the accurate temperature record and control technologies have made a substantial progress reducing the effect of temperature changing efficiently (Ndraha et al., 2018), so TTT theory would be widely used in shelf-life prediction and logistics stability evaluation for both frozen foods and unfrozen foods in nowadays. This can be confirmed by the application of TTT in the successful match of time-temperature indicator (Gu et al., 2007).

In another sides, TTT theory is a general method with fair compatibility. For example, the degradation of nutrition maybe caused by many enzymes and microbial. Though the kinetic models for the enzyme and microorganism are different in many aspects, but they are all following the TTT theory as interpreted in this paper. Moreover, when one quality index is caused by the additive effect of more than one factors independently, the ratio of its average degradation speeds during one isothermal interval between different temperatures are also constant, which would also keep the stability of *ECRs* and lead it follow the TTT theory. Maybe that is why TTT is still valid for comprehensively predicting food quality affected by many microbial, enzymes separately or together in previous research (Tano-Debrah et al., 2019; Dattatreya et al., 2007; Shukla et al., 2020).

According to the TTT theory, one variable temperarure process can be converted into one isothermal with the corresponding *ECRs* and the parameters are stable for one quality indicator between two temperatures. Since that, the sequence would not affect the accumulation of intervals of TTT theory, which is the same as many scholars' results previously (Fu & Labuza, 1997).

Finally, as the application in the research of Kwolek & Bookwalter (1971) and Ma et al. (2016) shown, TTT would become one intuitive and convenience method for the remaining shelf-life prediction and stability of storage evaluation.

## 6 Conclusion

In this paper, TTT theory was expanded to the foods whose quality spoilage process follows the chemical kinetic model and microbial growth model by using equation deduction and case validation, including unfrozen foods. During this, one basic law originated from TTT theory about the *ECR*, was proved to be applicable to the classic thermal kinetic models and the *ECR* is equal to the ratio of corresponding shelf-lives. With the finding of this paper, the TTT theory would be effective and efficient in quality management of many types of foods, with the accurate temperature controlling and monitoring technologies nowadays.

## Conflict of interest

The authors declare no conflict of interest.

## Availability of data and material

The data presented in this study are openly available in [https://github.com/gushiliangshi1111/data-for-TTT/blob/e07624f7643a8935e8dbeab77c0b3d1027877817/TTT%20database.xlsx] at [doi]

## Acknowledgements

I would like to thank all the participants of this study.

## References

Dattatreya, A., Etzel, M. R., & Rankin, S. A. (2007). Kinetics of browning during accelerated storage of sweet whey powder and prediction of its shelf life. *International Dairy Journal*, 17(2), 177-182. http://dx.doi.org/10.1016/j.idairyj.2006.02.004.

Ding, T., Li, T., Li, J., Zou, Z., & Zhou, K. (2015). Applicability analysis of microbial growth dynamics models and establishment of shelf-life model for salmon slices during the cold storage. *Journal of Chinese Institute of Food Science and Technology*, 15(5), 63-73. http://dx.chinadoi.cn/10.16429/j.1009-7848.2015.05.009.

Fan, J. (2011). *Study of the shelf life prediction for chicken products*. Zhengzhou: Henan Agricultural University.

Fu, B., & Labuza, T. P. (1997). Shelf life testing: procedures and prediction methods for frozen foods. In M. C. Erickson & Y. C. Hung (Eds.), *Quality in frozen foods* (pp. 377-415). Boston: Springer. http://dx.doi.org/10.1007/978-1-4615-5975-7_19.

Galvão, L. M. V., Sousa, M. D., Nascimento, A. M. D. B., Souza, B. V. C., & Nunes, L. C. C. (2022). Evaluation of shelf life of isotonic beverage enriched with cajuina. *Food Science and Technology*, 42, e25520. http://dx.doi.org/10.1590/fst.25520.

Giannoglou, M., Evangelopoulou, A. M., Perikleous, N., Baclori, C., Tsironi, T., & Taoukis, P. (2019). Time temperature integrators for monitoring the shelf life of ready-to-eat chilled smoked fish products. *Food Packaging Shelf*, 22, 100403. http://dx.doi.org/10.1016/j.fpsl.2019.100403.

Gu, X., Liu, Y., Liu, B., Hua, Z., & Wang, X. (2007). Experimental definition on TTT of cap-packaged Dmilk. *Shipin Kexue*, 28(12), 316-319. http://dx.chinadoi.cn/10.3321/j.issn:1002-6630.2007.12.075.

International Commission on Microbiological Specifications for Foods – ICMSF. (1986). *Microorganisms in foods: sampling for microbiological analysis: principles and specific application* (2nd ed., Vol. 2, pp. 127-278). Hoboken: Blackwell Scientific Publication. https://doi.org/10.2307/1268642.

Kwolek, W. F., & Bookwalter, G. N. (1971). Predicting storage stability from time temperature data. *Food Technology*, 25(10), 51-63. Retrieved from https://pubag.nal.usda.gov/download/31530/pdf

Labuza, T. P., & Riboh, D. (1982). Theory and application of arrhenius kinetics to the predication of nutrient losses in foods. *Food Technology*, 36(10), 66-74. Retrieved from http://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=PASCAL83X0064691

Licciardello, J. J., Ravesi, E. M., Lundstrom, R. C., Wilhelm, K. A., Correia, F. F., & Allsup, M. G. (1982). Time-temperature tolerance and physical-chemical quality tests for frozen red hake. *Journal of Food Quality*, 5(3), 215-234. http://dx.doi.org/10.1111/j.1745-4557.1982.tb00745.x.

Liu, L., Xing, S., Zhang, J., Gu, J., & Zou, Q. (2015). Microbial growth kinetics model of mackerel based on baranyi model at fluctuating temperatures. *Shipin Kexue*, 36(5), 89-92. https://doi.org/10.7506/spkx1002-6630-201505017.

Lyon, D. H., McEwan, J. A., Taylor, J. M., & Reynolds, M. A. (1988). Sensory quality of frozen Brussels sprouts in a time-temperature tolerance study. *Food Quality and Preference*, 1(1), 37-41. http://dx.doi.org/10.1016/0950-3293(88)90007-9.

Ma, C., Xiao, X., Zhu, Z., Vlad, L. B., & Zhang, X. (2016). Contour diagram based evaluation on logistics stability of table grapes under variable temperature. *Journal of Food Process Engineering*, 39(4), 391-399. http://dx.doi.org/10.1111/jfpe.12231.

Moschopoulou, E., Moatsou, G., Syrokou, M. K., Paramithiotis, S., & Drosinos, E. H. (2019). Food quality changes during shelf life. In C. M. Galanakis (Ed.), *Food quality and shelf life* (pp. 1-13). Oxford: Academic Press. http://dx.doi.org/10.1016/B978-0-12-817190-5.00001-X.

Ndraha, N., Hsiao, H. I., Vlajic, J., Yang, M. F., & Lin, H. T. V. (2018). Time-temperature abuse in the food cold chain: review of issues, challenges, and recommendations. *Food Control*, 89, 12-21. http://dx.doi.org/10.1016/j.foodcont.2018.01.027.

Niu, Y., Yun, J., Bi, Y., Wang, T., Zhang, Y., Liu, H., & Zhao, F. (2020). Predicting the shelf life of postharvest Flammulina velutipes at various temperatures based on mushroom quality and specific spoilage organisms. *Postharvest Biology and Technology*, 167, 111235. http://dx.doi.org/10.1016/j.postharvbio.2020.111235.

Oliveira, C. C. M., Oliveira, D. R. B., & Silveira, V. Jr. (2022a). Variability in the shelf life of table grapes from same batch when exposed under different ambient air conditions. *Food Science and Technology*, 41(Suppl. 1), 290-300. http://dx.doi.org/10.1590/fst.14220.

Oliveira, C. C. M., Oliveira, D. R. B., Spagnol, W. A., Tavares, L. R., & Silveira, V. Jr. (2022b). Heterogeneity of the remaining lifespan of table grapes in refrigerated transportation. *Food Science and Technology*, 42, e05821. http://dx.doi.org/10.1590/fst.05821.

Phimolsiripol, Y., & Suppakul, P. (2016). Techniques in shelf life evaluation of food products. In G. W. Smithers (Ed.), *Reference module in food science* (pp. 1-8). Amsterdam: Elsevier. http://dx.doi.org/10.1016/B978-0-08-100596-5.03293-5.

Rasul, S. F., Noori, R. J., Ali, K. M., Khdhir, R. B., Ahmed, S. R., & Qadir, A. M. (2022). Roles of different packaging materials on the quality and shelf life of yogurt. *Food Science and Technology*, 42, e70821. http://dx.doi.org/10.1590/fst.70821.

Ross, T., & Olley, J. (1997). Problems and solutions in the application of predictive microbiology. In F. Shahidi, Y. Jones & D.D. Kitts (Eds.), *Seafood safety, processing, and biotechnology* (pp. 101-118). Boca Raton: CRC Press. https://doi.org/10.1201/9781003075899.

Scott, E. P., & Heldman, D. R. (1990). Simulation of temperature dependent quality deterioration in frozen foods. *Journal of Food Engineering*, 11(1), 43-65. http://dx.doi.org/10.1016/0260-8774(90)90038-A.

Secer, O. M., Guneser, B. A., & Guneser, O. (2020). Prediction of shelf-life and kinetics of quality changes in canned stuffed grape leaves. *Lebensmittel-Wissenschaft + Technologie*, 132, 109850. http://dx.doi.org/10.1016/j.lwt.2020.109850.

Shen, P. (2015). *The growth kinetics of spoilage organisms and shelf life prediction for the north pacific squid*. Shanghai: Shanghai Ocean University.

Shukla, A., Das, C., & Goud, V. V. (2020). Infusion of gingerols into candied mango enhances shelf-life by inhibiting browning and associated quality parameters during storage. *Food Chemistry*, 316, 126354. http://dx.doi.org/10.1016/j.foodchem.2020.126354. PMid:32058195.

Šimat, V., Čagalj, M., Skroza, D., Gardini, F., Tabanelli, G., Montanari, C., Hassoun, A., & Ozogul, F. (2021). Sustainable sources for antioxidant and antimicrobial compounds used in meat and seafood products. *Advances in Food and Nutrition Research*, 97, 55-118. http://dx.doi.org/10.1016/bs.afnr.2021.03.001. PMid:34311904.

Song, Y., Hu, Q., Wu, Y., Pei, F., Kimatu, B. M., Su, A., & Yang, W. (2018). Storage time assessment and shelf-life prediction models for postharvest *Agaricus bisporus*. *Lebensmittel-Wissenschaft + Technologie*, 101, 360-365. http://dx.doi.org/10.1016/j.lwt.2018.11.020.

Tanaka, T., Kenji, T., & Koji, N. (2012). Time-temperature-tolerance (T.T.T.) of on-board frozen tuna during subsequent on-land frozen storage with particular reference to commercial scale Trial-I. *Transactions of the Japan Society of Refrigerating and Air Conditioning Engineers*, 1(1), 99-107. https://doi.org/10.11322/tjsrae.1.99.

Tano-Debrah, K., Saalia, F. K., Ghosh, S., & Hara, M. (2019). Development and sensory shelf-life testing of KOKO plus: a food supplement for improving the nutritional profiles of traditional complementary foods. *Food and Nutrition Bulletin*, 40(3), 340-356. http://dx.doi.org/10.1177/0379572119848290. PMid:31242762.

Torres, E. F., Rodrigo, D., & Martínez, A. (2016). Preservation of foods. In B. Caballero, P. Finglas & F. Toldrá (Eds.), *Encyclopedia of food and health* (pp. 491-496). Oxford: Academic Press. http://dx.doi.org/10.1016/B978-0-12-384947-2.00566-3.

Van Boekel, M. A. J. S. (2008). Kinetic modeling of food quality: a critical review. *Comprehensive Reviews in Food Science and Food Safety*, 7(1), 144-158. http://dx.doi.org/10.1111/j.1541-4337.2007.00036.x.

Wang, X., Liu, B., Gu, X., Qin, R., & Qiu, J. (2007). Effect of temperature fluctuation on the chemical, microbiological and sensory quality of frozen meat dumplings. In *Academic Annual Conference of Shanghai Refrigeration Association*. Shanghai, China.

Yang, S., Zhang, M. N., Shan, C. S., & Chen, Z. G. (2021). Evaluation of cooking performance, structural properties, storage stability and shelf life prediction of high-moisture wet starch noodles. *Food Chemistry*, 357, 129744. http://dx.doi.org/10.1016/j.foodchem.2021.129744. PMid:33878579.

Yimenu, S. M., Koo, J., Kim, B. S., Kim, J. H., & Kim, J. Y. (2019). Freshness-based real-time shelf-life estimation of packaged chicken meat under dynamic storage conditions. *Poultry Science*, 98(12), 6921-6930. http://dx.doi.org/10.3382/ps/pez461. PMid:31504907.

Zapata, J. E., Sepulveda, C. T., & Alvarez, A. C. (2022). Kinetics of the thermal degradation of phenolic compounds from achiote leaves (*Bixa orellana* L.) and its effect on the antioxidant activity. *Food Science and Technology*, 42, e30920. http://dx.doi.org/10.1590/fst.30920.

Zhang, H., Zhang, X., Sun, G., Fu, Z., & Ma, C. (2017). Dynamic calibration method for time temperature indicator towards quality of agricultural produce under cold chain. *Nongye Jixie Xuebao*, 48(2), 314-321.

Zhang, W., Luo, Z., Wang, A., Gu, X., & Lv, Z. (2021). Kinetic models applied to quality change and shelf life prediction of kiwifruits. *Lebensmittel-Wissenschaft + Technologie*, 138, 110610. http://dx.doi.org/10.1016/j.lwt.2020.110610.

Zhao, S., Han, X., Liu, B., Wang, S., Guan, W., Wu, Z., & Theodorakis, P. E. (2022). Shelf-life prediction model of fresh-cut potato at different storage temperatures. *Journal of Food Engineering*, 317, 110867. http://dx.doi.org/10.1016/j.jfoodeng.2021.110867.

Zhou, B., Luo, Y., Huang, L., Fonseca, J. M., Yan, H., & Huang, J. (2022). Determining effects of temperature abuse timing on shelf life of RTE baby spinach through microbial growth models and its association with sensory quality. *Food Control*, 133, 108639. http://dx.doi.org/10.1016/j.foodcont.2021.108639.