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Mathematical Modeling of Packaging Properties as Hurdles for Food Degradation: A Case Study on Olive Oil

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Abstract

Context and Objective: Food quality and shelf life are strongly influenced by the interaction between packaging properties and mass transport processes. This study explored how hurdle technology can be applied to food preservation, focusing on olive oil as a practical case due to its high sensitivity to oxidation and light. Methodology: An analogy was developed between transport phenomena in packaging and the fundamental laws of electricity, providing a simple physical basis for understanding preservation mechanisms. This was supported by parametric simulations and mathematical modeling, which were used to predict how different packaging materials and conditions influence product stability. Main Results: The application to olive oil showed that packaging properties such as resistance to oxygen and light permeation have a direct effect on preservation effectiveness. Model predictions highlighted clear differences in stability depending on the choice of packaging, demonstrating the critical role of material selection. Conclusions: The study presents an integrated framework that links packaging characteristics with food preservation outcomes. By combining physical analogies with modeling tools, it offers a practical basis for designing packaging solutions that extend shelf life and protect sensitive foods such as olive oil.

Keywords: hurdles; packaging materials; quality; modeling; shelf life

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1. Introduction

Consumer demand for more natural and fresh-like foods using only mild preservation techniques (e.g., refrigeration, modified-atmosphere packaging and bio-conservation) imposes a strong need for new or improved mild preservation methods that allow producing fresh-like, yet stable and safe foods, have emerged [1,2]. In this regard, hurdle technology has been used to describe the combined methods for preserving foods, so they remain stable and safe even without refrigeration [3,4].

According to [5], hurdle technology advocates the intelligent use of combinations of different preservation factors or techniques (hurdles) in order to achieve multi-target and mild but reliable preservation effects. The higher the hurdle, the greater the effort needed to overcome it. The linkage of hurdle technology to the hazard analysis critical control points (HACCP) concept and the relationship to predictive microbiology have also been studied. Fundamental phenomena within the microorganisms' structures, such as lipid oxidation in membranes and the homeostasis of microorganisms, have been also investigated in the light of hurdle technology [6]. Following this approach, several topics have been studied, including temperature, water activity (aw), pH, redox potential, preservatives hurdle effect, hurdle technology, shelf stable products, intermediate moisture foods, and perspectives of such an approach. In recent years an ever-increasing number of new techniques based on technological developments in the field of food preservation has been reported [7]. Various modern processes have been developed for food and food ingredient manufacturing based on membrane technology, supercritical fluid technology, as well as non-thermal preservation techniques such as high hydrostatic pressure, pulsed electric fields, ultrasound, pulsed light, and hurdle systems, along with new analytical techniques (food image analysis and biosensors) [8,9]. Having reviewed the non-thermal combined processing techniques for satisfying consumer demand for fresher, higher quality, and safer food, Ref. [10] pointed out that, in order to counter preservation deficiencies, they proposed the combination of traditional and emerging food preservation techniques as these present a number of potential benefits for food preservation.

Technological advancements in the area of packaging aimed to improve barrier properties, to promote active antimicrobial functionality, and to apply these materials in demanding high-pressure processing of packaged foodstuffs were discussed by [11], and nanotechnological perspectives were reviewed by [12] to maintain the constant supply of products over lengthened periods of time according to health and safety issues.

Recent reviews have emphasized the rise of intelligent and active packaging technologies [13], AI-driven shelf-life prediction [14], and the revalorization of byproducts for biodegradable films [15]. Additionally, comprehensive surveys on active packaging trends [16] and advances in modeling and predictive analytics for shelf-life estimation [17,18] illustrate the rapidly evolving landscape that motivates the current framework.

It has been broadly accepted that consumers are the main decision makers regarding the quality attributes of products. Hence, "quality" may be accordingly defined as the percentage of the satisfied consumers [19]. The specific level of satisfaction, type-group of consumers, particular market needs, consumer training and information, cost of quality, time efficiency, innovations in quality, and market field competition are among the major factors in defining the boundaries of the food product's quality, when food is pictured as a system existing within its physical as well as its surrounding human environment [20]. If that is the case of quality perception, then the corresponding satisfaction limits may be clearly and confidently defined [21].

Sequentially to the above, the shelf life of a product can be viewed as the descriptor that strongly links the consumers' satisfaction to the possibility of disclaiming this satisfaction within a certain time frame [22]. Shelf life then evidently defines the adequate time during which the food product is in the proper and adequate state to fulfill the satisfaction requirement. This later statement conclusively signifies that the shorter shelf life, the higher the possibility for disclaiming the consumers' satisfaction, or equally stated, shelf life is the risk of dissatisfaction which is getting higher with the closer to the end of the shelf life a product is getting at [23].

Then, since shelf life can be, to a certain extent, predicted or even quite accurately calculated, the risk of being disclaimed for a given food–pack–environment system should also be quite accurately calculated. Managing this calculated risk of dissatisfaction must consider the preservation engineering tools that support an advanced resistance to the reduction in the shelf life [24]. That leads us in fact to the definition of "preservation" as the risk management process within the limits of the given system, based on the calculated risk(s). The resistance to the shelf-life reduction requirements should also be recognized as the managerial means—also within in the present work named as the "hurdles"—placed against dissatisfaction. Hence, hurdles may be considered as efficient for a given system only when they reduce the possibility of disclaiming the satisfaction to an acceptable quality level, allowing for the realization of a pre-decided percentage level of satisfied consumers.

Following the above descriptive points, a straightforward consideration is emerging on how we may secure a knowledge-based quantifiable estimation of the hurdles' efficiency, for any food–pack–environment system. This consideration shall constitute the main objective of this work. In particular, we wish to investigate how to secure and justify the contextual base for estimating the hurdles' effect on the overall packaging efficiency. Having achieved that, we shall successively proceed to a reasonable association of the hurdles, in terms of their appropriate (justified), optimized (efficient), and applicable (effective) use, in support of their selection procedure. This is because our aim is to present a ready-to-use engineering tool rather than another predictive model regarding packaging and shelf life. Thus, for this work we aim to analyze the "hurdle technology" concept using simulations and predictive modeling for quality parameters, rather than safety/quality risk analysis, as commonly performed. Furthermore, this concept will be validated in the case of packaged olive oil, regarding the selection of the appropriate hurdles to ensure the maximum feasible shelf life. Packaged olive oil constitutes an appropriate model system for the application of the hurdle theory, as its quality deterioration is driven by concurrent and quantifiable mechanisms, including oxidative degradation, photo-oxidation, and interactions with packaging permeability. These processes act as distinct yet interdependent hurdles, allowing for systematic evaluation of their relative contributions to overall quality loss. Moreover, the product's commercial importance and high susceptibility to environmental stressors render it an exemplary case for validating preservation models based on the hurdle framework.

2. Materials and Methods

The following methodology was used to accomplish the above objectives. Initially, we established a packaging concept that works against food quality reduction, in support of a better description of the total system and an efficient design of the preservation process. The validation of the preservation efficiency relies upon those means and conditions affecting the relevant degradation phenomena for this system. Therefore, the defined borderlines of these phenomena, their outmost limits related to the preservation hypothesis (i.e., the objective of preserving food at a high quality for as long period as possible), the established quality threshold per quality factor, the calculated risk-level, the experimentation parameters and their values, the analytical devices capabilities and their deviations during monitoring, need to be known, too. Such an approach has a certain prerequisite, i.e., to clearly define both the system contributors of interest and the integrated preservation-related hazards and threats. Defining these prerequisites beforehand will allow for engineering-based parametric simulations and related mathematical model-based predictions for their inherent quality.

Following that step, we present the impact of the selected packaging—means and procedures—on the phenomena and properties' evolution for their influence on food preservation, i.e., for their contribution against the degradation of the food via the physicochemical processes that are taking place within this system. In brief, we wish to validate the resistance of the system against quality reduction. As we work on a holistic preservation cycle, i.e., a non-straightforward developmental process towards the improvement of the systemic degradation resistance and the consequent hurdles' efficiency, it is in the end our target to manage the system to obtain engineering-based decisions, hence, higher packaging selection accuracy and application efficiency.

Based on the idea that any hurdle imposed by the packaging material itself correlates a specific resistance to a specific food deteriorating factor, then, a methodological milestone in achieving our goals was to set the analogy between the packaging-integrated hurdles and the electrical resistors, as conceptualized in the following Figure 1.

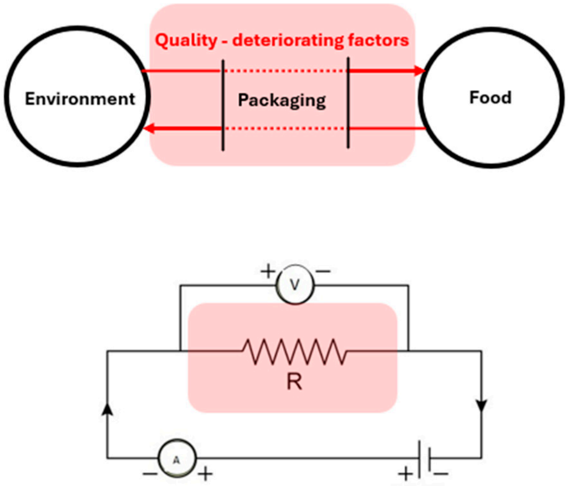


Figure 1. The concept of hurdles as resistors.

Markedly, the resistances as well as the topology of their connected circuit strongly depend on the type and the composition of the food as well as the packaging material, factors that significantly affect the shelf life of the food product. The aim here is the prolongation of the shelf life, i.e., the control of the parameters favoring food quality deterioration, against which the packaging has to function. For instance, the dark-colored and nearly non-transparent packaging material is quite well related to a higher resistance against the relevant light energy transfer to food. The disclaiming of the prolongation of product's shelf life (preservation hypothesis) recognizes one or more specific factors that affect food in terms of this hypothesis. An additional example concerns the temperature as the factor affecting the shelf life of oxidation sensitive products during processing, via the heat transferred through the packaging. For that particular case, the hurdle (i.e., the resistor) is the level of thermal insulation offered by the packaging material, design, geometry, etc.

The above-described analogies between hurdles and resistors are summarized and further clarified in the following Table 1.

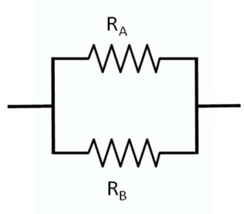
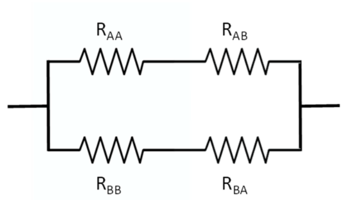
Table 1. Analogy between electrical resistances and packaging hurdles.

Electricity	Food/Packaging System
Current	Transport (regarding the factor that influences the product)
Potential	Concentration (of the above factor)
Resistance	Packaging (preventing the above transport)

In particular, analogous to Ohm's law, the linear relationship between the concentration difference (gradient) and the transport phenomena through the packaging material can be easily defined. In the case of pure diffusion, this linear relationship is directly described through Fick's law, where the flux corresponds to the current, the concentration difference corresponds to the potential difference, and consequently, the diffusivity corresponds to the resistance. When transport phenomena, other than diffusion, also take place (convection, chemical reactions, etc.), the flux is given by a more complicated expression, where terms additional to the diffusivity must also be included. In this case, a new magnitude representing the effective resistance must be defined so that it produces equivalent results, as if the process was a linear behavior (i.e., pure diffusivity).

According to this present proposed approach, packaging may be considered as a series of resistors, rather than a single one, depending on the type of packaging material(s) and the hazardous factors that need to be restricted. As in the case of electricity, such resistors might be connected either in series or in parallel. For example, if two independent factors of interest are considered, two resistors exist (one per factor) and are considered to be connected in parallel. If these two factors are dependent on each other, then more resistors exist, which are connected in series (see Table 2).

Table 2. Resistors' connection rules.

Case	Factors	Dependency	Resistors	Description	Connected
1	A, B	Independent	R_A	Resistance to transport due to factor A under the presence of factor A	In parallel 
			R_B	Resistance to transport due to factor B under the presence of factor B	
2	A, B	Dependent	R_{AA}	Resistance to transport due to factor A under the presence of factor A	Combined 
			R_{AB}	Resistance to transport due to factor A under the presence of factor B	
			R_{BA}	Resistance to transport due to factor B under the presence of factor A	
			R_{BB}	Resistance to transport due to factor B under the presence of factor B	

The above discussion can be reasonably comprehensive for any finite number of factors and, consequently, for any relatively finite number of resistors. Yet, we will further support the methodological ability to define an overall resistor that may adequately describe the overall "hurdle" to the quality degradation, offered by the packaging, now to be actually viewed as a "tensor".

In mathematical terms, if an amount of N factors is considered, a tensor of N × N dimensions for the resistance to food quality deterioration can be determined, where its typical element R_{ij} describes the effect of the factor j on the transport of factor i. Obviously, the values of the resistors depend on the application (i.e., on the specific food packaging system and the storage conditions) and have to be calculated on that basis. The resistance matrix entries reported herein are deterministic model outputs and not experimental measurements; thus, conventional error bars are not applicable. Numerical accuracy was verified via time-step and grid-refinement analyses, with relative integration errors below 0.05%. To indicate robustness, we provide a brief sensitivity note: varying key kinetic and transport parameters within the literature-based ranges results in bounded changes in the tensor elements consistent with the dominance of light over temperature and oxygen permeability. These values should therefore be interpreted as context-dependent normalized indicators of relative influence rather than as point estimates with experimental variance. It is important to note here that this "Equivalent-Ohm's-Law" reflects the resistance to the shortening of the shelf life caused by the differences in critical variables rather than the values of variables themselves. This consideration liberates the use of this approach from the necessity of the estimation/calculation of the values of the critical variables/parameters, as far as their variation is adequate for the estimation of the hurdles' resistances.

In order to satisfy the objectives of this work and apply the previously mentioned framework, initial steps must include the proper description of the essential systemic parameters as now summarized in the properties, qualities, characteristics, and experiences groups. All of these four can be described through mathematical and natural laws through appropriate factors/contributors. The expression of each of the factors is mainly dependent on the conditions that actually permit their qualitative expressions and quantitative developments (outcomes) within the system. Such quality outcomes derived under various experimental conditions along with the, at the time, existing knowledge, will be used for calculating the hurdles' efficiency. That is possible considering that the quality-related outcomes will surpass or fall behind the pre-defined quality threshold. Needless to say, it is essential to include the quality parameters based on consumer satisfaction within the boundary values of the systemic descriptors. Then, the developed resistors' approach is applied to identify these thresholds in time.

Overall, the proposed procedure is described through a generalized expression of the form:

$$Quality\_related\_outcome = \bar{\bar{R}}\nabla\langle critical\_variable\rangle, \tag{1}$$

where the tensor $\bar{\bar{R}}$ represents the overall equivalent resistance to the possibility for-satisfaction or disclaiming of the hypothesis, i.e., for describing the quality deterioration with the time. The dimension of the tensor depends on the number of parameters determined as crucial for the specific application under question. More precisely, the above Equation (1) presumes a process for food quality control as follows: (a) define specific variables, which are considered to affect the quality of the packaged food and, consequently, its shelf life, (b) define a quality index that is supposed to describe the deterioration of food quality with the time, (c) describe the mass transport equations for the variables as well as the index above defined, and (d) aggregate these equations to produce the averaged result, which becomes Equation (1).

It should be emphasized that no new laboratory experiments were performed within the scope of this study. The olive-oil case study is based on previously published experimental work, which includes comprehensive details on packaging specifications, analytical protocols, and statistical treatment. In the present manuscript, these published datasets were integrated and reinterpreted through the proposed modeling framework, which is the focus of our contribution. In addition, the credibility of the proposed framework was examined through conceptual validation against established degradation trends reported in the recent literature. Specifically, the model consistently reproduced the dominant role of light exposure, the secondary influence of temperature, and the comparatively lower effect of oxygen permeability under typical packaging conditions. This alignment with broadly accepted findings supports the plausibility of the framework as a unifying tool for interpreting packaging-related degradation mechanisms.

3. Results: Application to Packaged Olive Oil

The validity of this approach was verified through its application to a food preservation case study regarding the oxidation process of edible oils. A typical case study is the oxidation of packaged olive oil, which is mainly influenced by the availability of oxygen air and the presence of light reaching the product through the packaging materials, while elevated temperatures may further stimulate the degradation phenomena. The oxidation reactions taking place in the oil phase can be summarized as follows [19]:

$$O_2 \xrightarrow[h\nu]{k_a} O_2^{\circ},$$
$$RH + O_2^{\circ} \xrightarrow{k_b} ROOH,$$
$$RH + O_2 \xrightarrow{k_c} ROOH, \tag{2}$$

where RH is any fatty acid serving as the oxidation substrate, $ROOH$ is the derived hydroperoxide, and k_a, k_b, and k_c are the Arrhenius-type reaction rate constants influenced by temperature, as estimate in detail elsewhere [25,26].

Although several hydroperoxides are involved in the above reactions, it is the concentration of hexanal in the oil mass that has been widely recognized as an adequate quality index during last five decades [27]. Besides chemistry, hexanal mass transport in the oil phase is diffusion-driven, while its concentration does depend on the presence of oxygen.

The oxidation of bottled olive oil has been mathematically described elsewhere [28,29], where a system of mass transport differential equations along with the appropriate boundary conditions were numerically solved to obtain the spatial distribution of hexanal concentration in the oil phase. More precisely, in the oil phase the equations are

$$\frac{\partial C_{O_2}}{\partial t} = D_{O_2,oil}\frac{\partial^2 C_{O_2}}{\partial x^2} - \xi k_a C_{O_2} - k_c C_{O_2} C_{RH}, \tag{2}$$

$$\frac{\partial C_{RH}}{\partial t} = -\xi k_a C_{O_2} - k_c C_{O_2} C_{RH}, \tag{3}$$

$$\frac{\partial C_{hexanal}}{\partial t} = D_{hexanal,oil}\frac{\partial^2 C_{hexanal}}{\partial x^2} + \xi k_a C_{O_2} + k_c C_{O_2} C_{RH}, \tag{4}$$

and the relative equations in the packaging material are

$$\frac{\partial C_{O_2}}{\partial t} = D_{O_2,packaging}\frac{\partial^2 C_{O_2}}{\partial x^2} + u\frac{\partial C_{O_2}}{\partial x}, \tag{5}$$

$$\frac{\partial C_{hexanal}}{\partial t} = D_{hexanal,packaging}\frac{\partial^2 C_{hexanal}}{\partial x^2}, \tag{6}$$

where C_i is the concentration of species i (namely: O_2, RH, and hexanal), $D_{i,oil}$ and $D_{i,packaging}$ denote the diffusion coefficients of species i in the oil phase and the packaging material, respectively, while ξ is the light indicator (ξ = 0 corresponds to dark, and ξ = 1 corresponds to light) and x, t are the spatial co-ordinate and time, respectively, as described elsewhere [28,29]. Finally, u denotes the oxygen velocity in the packaging material, defined through the permeability by the Darcy law.

The boundary conditions accompanying the above equations are as follows:

- Initial conditions ensure a constant initial spatial profile for the concentrations in the oil phase and in the packaging material.
- Axial symmetry is imposed at the central axis of the oil phase.
- On all the interfaces, the continuity of all the concentrations is guaranteed.
- A typical Langmuir-type adsorption is assumed for the oil on the oil–solid interface.
- Constant concentrations of oxygen and hexanal are assumed in the packaging outer boundary with the environment.

After a spatial averaging of this concentration over the volume of interests (*V*) through the expression

$$\left\langle C_{hexanal}(t) \right\rangle = \iiint_V C_{hexanal}(\underline{r}, t) dr \,, \tag{7}$$

it becomes possible to introduce the possibility of the product not reaching the end of its shelf life (P_{safe}) as

$$P_{safe}(t) = 1 - \frac{\int_{t_{critical}}^{t} \left\langle C_{hexanal} \right\rangle (t) dt}{\int_{0}^{t} \left\langle C_{hexanal} \right\rangle (t) dt}, \tag{8}$$

where $t_{critical}$ is the critical time when this possibility overcomes a pre-defined threshold. The above expression is used as the main quality index for olive oil oxidation status [30]. To obtain the appropriate values for the parameters used in the equations and the conditions, the above-described model has been also supported experimentally.

According to the aforementioned "hurdle" approach (see Table 1 and Figure 1), the current should be represented by the mass fluxes trough the packaging material and within the oil phase, and the potential corresponds to the hexanal and oxygen concentrations, thus allowing identifying the hurdles (=resistors). In this context, the factors affecting fluxes are the temperature and the light, considered as "dependent" (see second line of Table 2), since the presence of light may potentially also cause an increase in the oil's temperature. Consequently, four resistors might be defined: R_{TT}, which represents the resistance to transport due to temperature under the presence of temperature, R_{TL}, which represents the resistance to transport due to temperature under the presence of light, R_{LT}, which represents the resistance to transport due to light under the presence of temperature, and R_{LL}, which represents the resistance to transport due to light under the presence of light. Obviously, $R_{LT} = 0$ since the presence of elevated temperature does not generate light. The values of R_{TT}, R_{TL}, and R_{LL} depend on the storage conditions and must be calculated through specific experiments and simulations.

Considering the above approach, a rather obvious question may derive, as to its ultimate use and its benefits for predicting shelf life via the packaging hurdles. Such combined preservation approaches have also been shown to extend shelf life in protein-rich food systems, such as sausages with reduced fat content, through the use of antimicrobial agents and modified atmosphere packaging [31]. The skepticism may even be further extended when someone wishes to, potentially, compare the prediction of the shelf life via the hurdle concept to the existing conventional modeling techniques and approaches or even more to the well-established and accepted as more accurate lab tests. Such tests are mainly performed under quite specific, usually stable, set boundaries conditions [32]. Accordingly, the complete packed food system responds to these specific conditions. As with any physical system, it is the experience(s) we gain for that system that may allow us to approach, acknowledge, and describe in a descriptive way the phenomena that take place. Via the sensorial experience, we are establishing a unique in-time and in-space picture of the systemic contributors (elements) and evolution (physical laws). The important thing is that the only prediction that may derive from such an instantaneous view can be valid simply for the conditions existing at the time of observations [33]. This work is really an extrapolation of the first empirical experience of the system, feasible and applicable to any future conditions. In that sense, the properties of the packaging materials, when conceptualized as hurdles, rather than individual particularities of behavioral expressions at certain conditions, will allow for the classification of these parameters that will always be the hurdles, though at different levels. Furthermore, these levels of hurdles, which we call resistance, are interrelated to the system and also intra-related to the surrounding environment. The classification of the resistances that the packaging brings to the degradation of the packed system will further allow for the incorporation of the packaging materials' properties and a much better understanding of their role against the system's degradation [34].

Therefore, proceeding with an example in support of the hurdle concept would further contribute to providing a justified roadmap towards structuring and utilizing this concept from a practical point of view. In this work, we made use of initially empirically collected data to describe, via a systematic approach, the relevant packaging indicators expressed under both steady and un-steady environments, including temperature, light, and oxygen permeability of the packaging materials. The approach in un-steady environments could become further feasible via simulations, especially aiming in overcoming the difficulty of an appropriate experimental set-up, along with the complication of applying all the theoretically unlimited experimental set-ups related to the packed olive oil's supply chains.

The initial experimental set-up involved one year of storage under various combinations of conditions (temperature range between 15 and 40 °C; light or dark; packaging materials of different oxygen permeability). The simulations revealed that, overall, the most significant factor affecting the oil quality is the light, while the temperature is of moderate importance [30]. Finally, the permeability of the packaging material was found to be negligible [35]. Qualitatively speaking, the same trends also stand for alternating storage conditions, with particular slight differences.

The particular individual effect of light on the overall efficiency of packaging was estimated to be at the range of 70% to 85%, the effect of temperature, itself, was between 10% and 15%, while the significance of the oxygen permeability of the packaging materials was always nearly negligible. These values have been produced by dividing the P_{safe} value produced elsewhere [30], where specific discussion took place regarding the effect of each specific parameter.

Now, it is quite interesting to describe mathematically the representative analogous electrical circuit. Initially, we consider it an ideal device where some unknown phenomena occur towards the deterioration of shelf life of the product. Next, we define a macroscopic quantity (namely, P_{safe}) to describe the shelf life of the product. Finally, we identify the parameters that affect P_{safe} (namely, temperature and light). These steps allow for an expression, analogous to Equation (1), that is of the form:

$$P_{safe} = \bar{\bar{R}} \nabla \langle C_{hexanal} \rangle, \tag{9}$$

where the tensor $\bar{\bar{R}}$ represents the overall equivalent resistance as previously described. This tensor is of 2 × 2 dimension and has the form

$$\bar{\bar{R}} = \begin{bmatrix} R_{TT}(\Delta T) & R_{TL}(\Delta T, \Delta L) \\ R_{LT}(\Delta T, \Delta L) & R_{LL}(\Delta L) \end{bmatrix}, \tag{10}$$

where its elements are functions of the variables' differences, rather than the variables' values.

By applying the results of the simulations as mentioned above, the terms of the tensor for the case of stored packaged olive oil (Equation (10)) take specific values; therefore, the tensor becomes

$$\bar{\bar{R}} = \begin{bmatrix} \sim 0.1 & \sim 0.05 \\ 0 & \sim 0.8 \end{bmatrix}. \quad (11)$$

As far as P_{safe} is a possibility, i.e., it takes values between 0 and 1, the above resistors' values have been normalized to be representative of the occurring processes. It must be also stressed that these values are approximations that quantify the relative strengths of each process, since the tensor $\bar{\bar{R}}$ is a theoretical construction rather than a physical magnitude. In this context, the light is the most significant parameter affecting packaged olive oil's shelf life, while temperature is approx. 8 times less important than light. From a packaging engineering point of view, this result means that we have first to concentrate on the limitation of light effect in order to achieve a prolonged shelf life for the product.

In conclusion, the results emerging via this approach can provide sufficient guidance for the appropriate selection of the packaging materials. By considering packaging as the hurdle(s) that may apparently delay the inevitable quality degradation, the importance of the bottle transparency via the selection of dark colored materials is now becoming even more evident, along with various non-conventional and certain innovative direction packaging materials and applications. Although technically it has become quite feasible, it is still rather difficult to control the temperature through packaging (for instance, thermal insulation materials). Instead, it seems rather preferable to control the storage conditions by avoiding relatively high temperatures that could stimulate the quality degradation mechanisms. Finally, although oxygen penetration due to pressure difference is apparently of lower importance, it is still of moderate significance to select high to ultra-high barrier materials (such as glass bottles or multi-layer structures).

Finally, we may stress that the above engineering aspect constitutes only one of the factors that play an important role in the packaging process design. Other factors exist that deal with economics, marketing, sales and safety; however, all of these are considered to be outside the scope of this work that has been limited to the engineering point of view.

4. Discussion

The generalized use of the hurdle concept through an equivalent electrical circuit gains significant applicability when the Equivalent-Ohm's-Law is used [Equation (1)] along with the determination and calculation of the relative equivalent resistors' tensor, which obviously depends on the application (see, for instance Equations (10) and (11)). Further research questions emerge regarding the effectiveness of individual and combined preservation hurdles within—and across—the packed-food systemic framework, as initially explored in the scientific literature on hurdle technology (see, for instance [36,37]). Recognizing and investigating that system in depth shall allow the experimenter or developer to efficiently engineer the functionality of the food–pack–environment system, accordingly. Although olive oil was selected as a model system, the framework can also be readily applied to other food categories where oxidative degradation and packaging permeability play a major role, such as edible oils, nuts, dairy products, or ready-to-eat meals sensitive to light and oxygen. We have identified the following three questions, which we shall handle theoretically in the following sections:

4.1. Is There Persistence (Determination) of Inefficiency over Time? If So, How Could We Overcome (Alter) That?

The inefficiency of a hurdle can be correlated to potential inadequacies in properties and/or attributes, which, accordingly, may imply incompetence in the expression of the natural laws and, furthermore, wastefulness of the systemic descriptors' (matter, energy, relationships, and outcome) participants (experience, properties, qualities, and characteristics).

Hence, it seems essential to deal with the hurdles on an engineering base rather than on a descriptive approach, for the identification of those conditions that may affect the expression of the relevant phenomena within packaging, for packaging, and due to packaging. The justified engineering of a food-packaging system through the fine-tuning of the conditions under which the hurdles of this sensor are functioning—whose hurdles have a high possibility in satisfying the preservation of the system—is the ultimate goal.

To further structure a complete and justified approach, the above initial question can be further considered through the following emerging concerns:

1. How can the inefficiency of packaging hurdle(s) within a given system be perceived in correlation to other packaging hurdle(s) (inner-efficiency independence of a hurdle)?

The significance of answering this question relies upon the efficient design of a totally effective system.

2. How does the inefficiency of preservation evolve when any one of the packaging hurdles is combined with one or more systemic hurdles (intra-efficiency dependency of a hurdle)?

Within this answer lays the potential of interactive properties among packaging and food, all to be considered through the applicable basic mass transport laws, via the solubility and diffusivity of compounds, during sorption, migration, and permeation phenomena.

3. How persistent may such inefficiencies become during the total system's shelf life?

It is apparently important to know the impact of such interactions in time, as changes above a certain point may significantly alter the hurdles' efficiency.

4. What are the engineering implications/opportunities because of the above?

Eventually, we may decide on an engineering-based tool, which could indicate to the developers any potential modifications to the system.

4.2. Is There Heterogeneity of Inefficiency Persistence (Comparable Tenacity) Among Systems?

Similar to the previous question, we shall try to deal with the underlying considerations before concluding on a closing remark. Such considerations include the following:

1. May the packaging properties and/or attributes expressed within a specific system be applicable as such in another system according to the inefficiency persisting levels?
2. Can a preservation indicator for a specific system be used as an indicator of preservation for another system, and if so, what are the applicability borderlines for such a transition between two or more systems?
3. Does the existence of similar packaging indicators (criteria) for independent systems imply a similarity among these systems and, if so, according to which criteria?
4. Or, vice versa, does a systemic similarity also suffice to conclude on their preservation indicators' similarity?
5. If so, what about the efficiency of the hurdles impregnated with similar indicators?
6. What are the engineering implications/opportunities due to the above?

4.3. What Do All of the Above Descriptions of Hurdle Inefficiencies Mean for the Selection of Packaging-As-Indicator?

Reaching the final conclusive points, it is the opinion of this work that, before anything else, developers should ask for a proper set-up of the preservation indicators and of the system descriptors for their expressions in terms of the applied laws and the coherence of phenomena, under certain conditions during storage.

Overall, to answer the above questions regarding the complete approach to the preservation hurdles, a methodology that can define and predict the efficiency of the hurdles against the deterioration of food quality has now been developed.

5. Conclusions

This study introduces a theoretical framework that reinterprets packaging properties as interacting variables within a coupled transport system, rather than as independent factors. The approach establishes an analogy between transport phenomena governing mass transfer through food–packaging interfaces and the formalism of electrical circuits, where each process is represented as a distinct resistance element. By quantifying these resistances, the framework enables the decomposition of the overall shelf life into discrete measurable contributions, thereby permitting the rigorous evaluation of packaging efficiency as a system-level property. The model was applied to the case of edible oil, wherein the calculated resistance tensor effectively predicted the degree to which individual transport barriers—such as permeability, diffusivity, and partition coefficients—govern the food–pack–environment interactions. This allowed for the estimation of the normalized hurdles' tensor, thereby demonstrating how packaging-induced transport resistances can prevent the system from reaching the terminal condition of shelf-life depletion. The methodology provides a quantitative tool for decision-making in packaging design, particularly in optimizing the material selection and structural configuration to minimize critical transport fluxes and extend product longevity. The implications of this model extend beyond the specific case of olive oil. Its structure is sufficiently general to be applied across diverse food matrices, offering a pathway to optimize packaging at the design stage by simulating how variations in material parameters alter system resistances and preservation outcomes. Future research should focus on the following: (i) applying the framework to heterogeneous and multiphase food systems with more complex diffusional environments, (ii) integrating microbiological kinetics as additional resistance terms within the model, thereby coupling physicochemical and microbial deterioration pathways, and (iii) developing computational implementations capable of optimizing shelf-life prediction under varying environmental stressors. Such advancements would enhance the model's role as a predictive decision-support instrument in the design and engineering of high-performance food packaging systems.

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