Pre- and Post-harvest Application of Ethylene in Bulb Onion (Allium Cepa l.) Hybrid 'Burguesa' Using Plithogenic n-SuperHyperGraphs

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Abstract. Preserving the physical characteristics of onion bulbs has posed a challenge in post-harvest storage and conservation for the agricultural industry. This study analyzed factors influencing the preservation of these characteristics throughout the production cycle, with a focus on the impact of ethylene treatments during various storage and conservation stages. SuperHyperEdge relationships among the involved vertices were evaluated using plithogenic n-SuperHyperGraphs as the basis for statistical analysis. Results indicated that ethylene treatment applied during harvesting, with stems and roots intact, at a dose of 1.0 mL•L^{-1} improved bulb preservation by reducing weight and pH variations while maintaining higher moisture content. It was concluded that ethylene use is an effective tool for onion preservation, encouraging further research into its combination with other treatments.

Keywords: Agricultural product preservation, treatments, pests, sprouting, plithogenic n-SuperHyperGraphs.

1 Introduction

The quality of food results from the interaction between various intrinsic and extrinsic attributes, reflecting both the inherent characteristics of the product and the expectations and experiences of the consumer [1]. Among the intrinsic attributes, texture, sweetness, acidity, aroma, flavor, nutritional value, and the absence of hazardous compounds stand out. Extrinsic factors, on the other hand, include aspects related to production and distribution systems, such as the use of agricultural chemicals, packaging materials, and sustainability in harvest and post-harvest management practices [2].

It is essential to note that the quality of horticultural products cannot be improved after harvest but can only be preserved through the control of critical factors during handling [3]. Pre-harvest conditions, such as agronomic practices, climate, and genetic material, are decisive in developing crops with high-quality standards. Additionally, factors such as mineral nutrition, chemical treatments, pest management, and environmental control directly influence the internal and external attributes of the products, as well as their storage capacity [4]. Therefore, nutrients like nitrogen, phosphorus, potassium, calcium, and magnesium serve as key indicators for evaluating storage potential.

The application of growth regulators and chemical treatments allows the modification of horticultural product attributes by influencing their susceptibility to specific disorders during storage [5]. These strategies are crucial for extending the shelf life of food and minimizing its deterioration. In the case of onions, a non-climacteric crop, the low endogenous production of ethylene during storage necessitates specific conditions [6], such as low temperature and relative humidity, to reduce sprouting, rooting, and microbial growth.

Ethylene, an essential phytohormone in the plant life cycle, plays a key role in various physiological processes, from germination to development and maturation. Although traditionally studied in climacteric fruits, its relevance in crops such as onions has gained increasing interest [7]. The controlled application of ethylene at specific doses has proven to be an effective strategy for prolonging storage [8], reducing sprouting, and maintaining post-harvest quality [9] [10].

Onions, as a crop of historical and culinary significance, are characterized by their chemical composition, rich in water, carbohydrates, and sulfur compounds that determine their flavor and properties [11]. Proper management during production and post-harvest stages is essential to ensure quality [12], meet market demands, and contribute to the sustainability of their cultivation [13]. For this reason, the development of advanced and sustainable preservation techniques is a priority in horticultural research.

Consequently, the present study aims to analyze the factors influencing the preservation of the physical characteristics of onion bulbs throughout their production cycle, with an emphasis on the impact of ethylene treatments at different stages of storage and conservation. For this study, the use of plithogenic n-SuperHyperGraphs is proposed for evaluating and modeling the relationships among the elements involved, as well as conducting statistical analysis of each SuperHyperEdge to assess research outcomes and determine the most effective treatment.

2 Materials and Methods

The study was conducted using bulb onions (Allium cepa L.), hybrid Burguesa, organically cultivated in the province of Tungurahua, Ambato canton, Cunchibamba parish. After manual harvesting, the onions were transported to the laboratories of the Faculty of Agricultural Sciences and Natural Resources, where pre-classification and cleaning were performed to remove weeds, soil, and stones. Plithogenic n-SuperHyperGraphs were applied in the structural design of the statistical study [14].

The experiment was carried out under greenhouse conditions, where the onions were divided into beds according to the stages of ethylene application: pre-harvest (three days before harvest), harvest with intact stems and roots, and harvest with stems and roots cut. The ethylene doses used were 0.0, 1.0, and 1.25 $mL \bullet L^{-1}$, and sample evaluations were conducted every seven days during the storage period.

A product based on ethephon (Cerone 720), which releases ethylene upon being absorbed by plant tissues, was utilized. The first application took place during the pre-harvest stage when 60% of the bulbs exhibited neck fall. During the harvest stage, applications were performed both on bulbs piled with intact stems and roots and on bulbs with stems and roots cut.

Over a period of 99 days, random samples were taken every seven days across the 27 experimental units. Evaluations included weight, incidence of sprouting, and the presence of pests, diseases, and physiological disorders. Additionally, parameters such as pH, soluble solids content, and moisture were measured.

2.1 Plithogenic n-SuperHyperGraphs

Plithogenic n-SuperHyperGraphs were defined by Smarandache in the field of decision-making in [15] [16]

First, an n-SuperHyperGraph is defined as follows:

Given $V = \{V_1, V_2, \cdots, V_m\}$, where $1 \leq m \leq \infty$ is a set of vertices, containing *Single Vertices* that are classical, *Indeterminate Vertices* which are unclear, vague, partially known, and the *Null Vertices* that are empty or completely unknown.

$P(V)$ is the power set of V including $\emptyset$. $P^n(V)$ is the n-power set of V, which is defined recursively as follows:

$P^1(V) = P(V)$, $P^2(V) = P(P(V))$, $P^3(V) = P(P^2(V))$, … , $P^n(V) = P(P^{n-1}(V))$, for $1 \leq n \leq \infty$.
Where it is also defined as $P^0(V) = V$.

An n-SuperHyperGraph (*n-SHG*) is an ordered pair $n - SHG = (G_n, E_n)$, where $G_n \subseteq P^n(V)$ and $E_n \subseteq P^n(V)$, for $1 \leq n \leq \infty$. Such that, G_n is the set of vertices and E_n is the set of edges.

G_n contains all possible types of vertices in the real world:

- *Single Vertices* (the classics),
- *Indeterminate Vertices* (unclear, vague, partially known),
- *Null Vertices* (empty, totally unknown),

- *SuperVertex* (or *SubsetVertex)* contains two or more vertices of the above types put together as a group (organization).
- *n- SuperVertex* which is a collection of vertices, where at least one of them is a *(n-1)- SuperVertex,* and the others can be *r- SuperVertex* for $r \leq \mathrm{n}-1$.

E_n contains the following types of edges:

- *Single Edges* (the classics),
- *Indeterminate Edges* (unclear, vague, partially known),
- *Null Edges* (totally unknown, empty),
- *HyperEdge* (connecting three or more single vertices),
- *SuperEdge* (connecting two vertices, at least one of them is a SuperVertex),
- *n- SuperEdge* (connecting two vertices, at least one of them is an n- SuperVertex and may contain another that is an r-SuperVertex with $r \leq \mathrm{n}$).
- *SuperHyperEdge* (connects three or more vertices, where at least one of them is a SuperVertex),
- *n-SuperHyperEdge* (contains three or more vertices, at least one of which is an n-SuperVertex and may contain an r-SuperVertex with $r \leq \mathrm{n}$),
- *MultiEdge* (two or more edges connecting the same two vertices),
- *Loop* (an edge that connects an element to itself),

Graphs are classified as follows:

- Directed Graph (the classic one),
- Undirected Graph (the classic one),
- Neutrosophic Directed Graph (partially directed, partially undirected, partially indeterminate directed).

Within the framework of the theory of Plithogenic n-SuperHyperGraphs, there are the following concepts:

Enveloping vertex: A vertex representing an object comprising attributes and sub-attributes in the graphical representation of a multi-attribute decision-making environment.

SuperEnveloping vertex: An enveloping vertex comprises of SuperHyperEdges.

Dominant Enveloping Vertex: An enveloping vertex that is with dominant attribute values.

Dominant Super Enveloping Vertex: A super enveloping vertex with dominant attribute values.

Dominant Enveloping Vertex is classified into *input*, *intervene,* and *output* based on the nature of the object's representation.

Plithogenic Connectors: The connectors associate the input enveloping vertex with the output enveloping vertex. These connectors associate the effects of input attributes with output attributes and these connectors are weighted by plithogenic weights.

3 The Study

3.1 Analysis of the behavior of the frequencies of each variable.

For the development of the study, a Plithogenic n-SuperHyperGraph model was constructed to represent the interactions among the factors (vertices) that influence the preservation of the physical characteristics of onion bulbs. The effects of ethylene treatment on the relationships among vertices, attributes, and sub-attributes were considered. Table 1 presents the structure of the study.

Table 1: Structure of the vertices that affect the physical preservation of the onion bulb. Source: Own elaboration.

SuperVertex		Vertices (V)	Main attributes	Sub-attributes
Treatment (V_1)	Period (V_{11})	Pre-harvest (V_{111})	Days (V_{1111})	Range from 1 to 99 days (V_{11111})
		Harvest with stems and roots (V_{112})	Days (V_{1121})	Range from 1 to 99 days (V_{11211})
		Harvest without stems and roots (V_{113})	Days (V_{1131})	Range from 1 to 99 days (V_{11311})
		Ethylene (V_{114})	Dose (V_{1141})	0 ml/L (V_{11411}) 1.0 ml/L (V_{11412}) 1.25 ml/L (V_{11413})
Bulb preservation (V_2)	Physical characteristics(V_{21})	Weight (variation) (V_{212})	Initial (V_{2121})	grams (g) (V_{21211})
			Final (V_{2122})	grams (g) (V_{21221})
		pH (variation) (V_{213})	Initial (V_{2131})	hybrid, neutral, and acidic (V_{21311})
			Final (V_{2132})	alkaline, neutral, and acidic (V_{21321})
	Environmental conditions (V_{22})	Humidity (variation) (V_{221})	Initial (V_{2211})	% (V_{22111})
			Final (V_{2212})	% (V_{22121})
		Soluble solids (contents) (V_{223})	Initial (V_{2221})	ºBx (Brix degrees) (V_{22211})
			Final (V_{2222})	ºBx (Brix degrees) (V_{22221})
Affects on bulb preservation (V_3)		Sprouts(V_{31})	Sprout appearance (V_{311})	0;1 (V_{3111})
			Sprout growth rate (V_{312})	cm/day (V_{3121})
		Pests, diseases, and physiopathies (V_{32})	Pests (V_{321})	% of plants affected (V_{3211})
			Diseases (V_{322})	% of plants affected (V_{3221})
			Physiopathies (V_{323})	% of bulbs affected (V_{3231})

This Plithogenic n-SuperHyperGraph model provides an integrated representation of the complex interactions among factors influencing the preservation of the physical characteristics of onion bulbs, focusing on the use of ethylene and storage conditions. By understanding the relationships between vertices (factors) and their attributes/sub-attributes, the model evaluates how each factor affects the quality and durability of the bulb, contributing to the optimization of post-harvest management.

In the analysis of ethylene use for onion preservation, the input enveloping vertices include factors such as ethylene concentration and the initial conditions of the bulbs. Output vertices reflect the observed results, such as bulb quality, reduction in pests and diseases, and extended shelf life. Intermediate vertices represent the internal processes that mediate between inputs and outputs, such as the chemical reactions induced by ethylene and their impact on the bulb's physical and biological properties. This vertex-based model enhances the understanding of interactions within the preservation system and supports the optimization of ethylene treatment decisions.

In the study, the dominant super-enveloping vertex is the ethylene treatment, as it directly influences the physical properties and resistance of onion bulbs, impacting both quality and shelf life. Plithogenic connectors include ethylene concentration, which links the treatment to intermediate effects on bulb properties, and environmental storage conditions, which connect intermediate effects to the final conservation outcomes. These connectors facilitate the transition and analysis of interactions among the graph's various vertices.

3.2 Properties of the SuperHyperEdge (SHE_1): Treatment (V_1) and weight (variation) (V_{212}).

The weight variation based on the application period (pre-harvest, harvest with stems and roots, and harvest without stems and roots) does not exhibit statistical significance. However, on days 37, 92, and 99 (see Table 2), the application period influences weight variation, as significant and highly significant statistical differences are observed among the treatments. Regarding the dosage, a significant difference is determined on day 99, while the remaining days show non-significant results, indicating that the treatments behaved similarly in terms of weight variation over time in onion bulbs.

The coefficient of variation (CV) ranges from 16.82 to 258.63, reflecting the behavior of onions during post-harvest. The highest CV values are observed near the end of the experiment, influenced by the presence of diseases and physiopathies. In Tukey's test at 5% for the variation source "period" on days 37, 92, and 99, a marked difference in the ranges is observed. It is highlighted that the lowest weight variation occurs in the pre-harvest application period at 37 days and in the harvest without stems and roots periods at 92 and 99 days.

Table 2: Tukey test at 5% for three application periods in the weight variation variable. Source: authors.

Description	**Average (g)**					
Period (a)	37 days		92 days		99 days	
Pre-harvest	3.44	A	8.33	B	6.67	B
Harvest with stems and roots	4.56	AB	9.22	B	6.44	AB
Harvest without stems and roots	6.22	B	3.89	A	3.89	A

Previous studies have shown that onions harvested at a very mature stage, with 80% leaf tipping, exhibit lower weight, while those harvested with 60% leaf tipping show higher weights. For this reason, the onion bulbs used in this study were harvested when the onions reached a leaf tipping index of 60%, which was clearly reflected in the low weight variation, as the bulbs maintained high weights over time.

On the other hand, Tukey's test at 5% for the ethylene dosage at 99 days indicates that treatments with a 1.25 mL·L^{-1} dosage have a lower weight variation (4.11g) (see Table 3). In comparison with the 0.0 mL·L^{-1} ethylene dosage, where greater weight variation is observed, leading to product losses.

Table 3: Tukey 5% test against dosage on weight variation. Source: authors.

Description	**Average (mL/L-1)**	
Dose(b)	99 days	
0.0	7.11	B
1.0	5.78	AB
1.25	4.11	A

According to previous research, the most critical period for weight loss occurs between days 1 and 14, after which weight loss gradually decreases. In most treatments, onion bulbs show a weight loss of 10 to 20 grams per bulb during the first and second weeks. By the third week, weight loss is between 2 and 5 grams, and from the fifth week onwards, weight loss ranges from 1 to 2 grams until week 13.

3.3 Properties of SuperHyperEdge (SHE_2): Treatment (V_1) and pH (V_{213}).

For the variation source in the application periods at 7 and 59 days, two significant ranges are established. The first range corresponds to treatments with pre-harvest application, where the pH values are slightly acidic. The second range corresponds to treatments with harvest application with stems and roots, showing pH values tending toward neutrality. According to the references consulted, the average pH values for red onion bulbs fluctuate between 5.3 and 5.8.

3.4 Properties of SuperHyperEdge (SHE_4): Treatment (V_1) and humidity (V_{222}).

For the application periods and different dosages at 37 days, two significant ranges were obtained. The first range corresponds to treatments with harvest application with stems and roots, with a dosage of 1.0 mL/L. In this case, a high humidity percentage above 90% is observed, meaning that over time, the onion maintained a high moisture content (see Figure 1). The second range corresponds to treatments with harvest application without stems and roots, with dosages of 1.0 mL·L⁻¹ and 1.25 mL·L⁻¹, which reflect a lower humidity percentage.

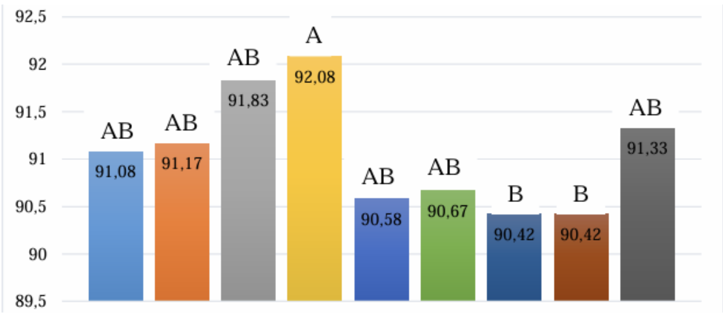

Figure 1: Averages for application periods and doses for the humidity variable (at 37 days). Source: Own elaboration.

Compared to previous studies, it is stated that the component found in the highest quantity in the bulbs is water, with variations ranging between 80% in varieties destined for the dehydration industry, and 94% in those for fresh consumption. As for the moisture content, it decreases by 10%, which corresponds to a 10% weight loss. The moisture percentage in onion bulbs across the treatments over 99 days fluctuates between 8% and 10%, indicating that the use of ethylene contributes to the preservation of the product.

3.5 Properties of SuperHyperEdge (SHE_5): Treatment(V_1) and soluble solids (V_{222}).

For the application periods and dosages at 94 days, two ranges were identified. The first range corresponds to the pre-harvest application period with a dosage of 1.0 mL/L, reflecting a high soluble solids content (ºBx). The second range corresponds to the pre-harvest application period with a dosage of 0.0 mL·L⁻¹, and to the harvest period with stems and roots, with a dosage of 1.0 mL·L⁻¹, showing lower values.

On the other hand, the sweet flavor of onion is provided by glucose, fructose, and sucrose, with these compounds varying in their degree of sweetness. In comparison, the literature has shown that varieties with a higher soluble solids content are more suitable for preservation, as they sprout less and are more resistant to diseases.

3.6 Properties of SuperHyperEdge (SHE_7): Treatment (V_1) and pests, diseases and physiopathies (V_{223}).

During the first days of the experiment, the samples did not show any incidence of pests, diseases, or physiological disorders from the start, so the recording of this variable began on day 58. However, starting from days 65, 72, 79, 92, and 99, the onion samples began to show diseases and physiological disorders, with highly significant differences between the treatments (see Table 4). Therefore, it is observed that the application period and the concentration of the dosage considerably influence this variable.

Table 4: Tukey test at 5% for three periods on the incidence of pests, diseases and physiopathies. Source: authors.

Description	Average									
Period (a)	65 days		72 days		79 days		92 days		99 days	
Pre-harvest	4.44	A	4.44	A	6.67	AB	6.67	AB	6.67	AB
Harvest with stems and roots	2.22	A	2.22	A	2.22	A	2.22	A	2.22	A
Harvest without stems or roots	13.33	B	13.33	B	13.33	B	13.33	B	13.33	B

The coefficient of variation presents values between 82.16 and 133.82 because, during the early days of the experiment, no incidences of pests, diseases, or physiological disorders were recorded. Therefore, in this interval, values of zero were obtained, which do not correspond to a normal distribution of the Gaussian bell curve and the artificial adjustment of the square root of x plus 1 was applied.

For the source of variation related to the application period recorded on days 65, 72, 79, 92, and 99, two significant ranges were established. The first range corresponds to the application period during harvest with stems and roots, as these treatments presented a lower percentage of incidence of pests, diseases, and physiological disorders. The second range corresponds to the treatments applied during harvest without stems and roots, which showed higher percentages of incidence of pests, diseases, and physiological disorders.

According to the referenced literature, one of the main problems encountered in post-harvest is the sprouting of leaves, and roots, fungal and bacterial rot, and weight loss, among others. However, the treatments with ethylene doses showed completely closed stems and even the natural shedding of the outer cataphylls occurred. This led to a decrease in the moisture content of the onions, thereby reducing the likelihood of disease attacks, because of the effect of ethylene.

3.7 Properties of SuperHyperEdge (SHE_8): Treatment (V_1) and Sprouts (V_{32}).

For the variable sprout incidence, no sprouts were recorded during the first days up to day 79. However, for the vertices grouped by application period, the onions began to show incidences of sprouts on days 92 and 99. Therefore, the application period significantly influences sprout incidence (see Table 5).

Table 5: Analysis of variance for sprout incidence with three doses and three application periods. Source: authors.

FV	GL	92 DAYS			99 DAYS		
		SC	PV	NEXT	SC	PV	NEXT
Repetitions	2	562.96			800.00		
Application period (A)	2	2696.30	0.0158	*	2755.56	0.0186	*
Ethylene dose (B)	2	118.52	0.7903	ns	88.89	0.8479	ns
AxB	4	2014.81	0.1385	ns	2488.89	0.0999	ns
Error	16	3970.37			4266.67		
Total	26	9362.96			10400.00		
CV			92.46			81.65	
Average			17.04			20	

For the variation source of application periods, two significance ranges are established. The first range corresponds to treatments where the application period was during harvest with stems and roots, where the least number of sprouts were identified, along with the shortest time to sprout appearance. The second range, corresponding to the application period during harvest without stems and roots, shows high sprout incidence values, with greater presence in these treatments (see Table 6). On the other hand, previous studies indicate that the application of ethephon to onion plants 2 weeks before harvesting reduced sprout incidence by 5% after 32 weeks of storage, data that aligns with the present research.

Table 6: Tukey test at 5% for three application periods and three doses on the variable incidence of sprouts. Source: authors.

Description	Average			
Period (A)	92 days		99 days	
Pre-harvest	11.11	A	17.78	AB
Harvest with stems and roots	8.89	A	8.89	A
Harvest without stems or roots	31.11	B	33.33	B

3.8 Results of the interrelations between SHE_1, SHE_2, SHE_3, SHE_4, SHE_5, SHE_6, SHE_7, SHE_8.

The application of ethylene in the pre-harvest stage was identified as the most effective strategy for preserving the physical properties of the onion bulb. This treatment allowed for a lower weight variation (3.44%), a pH of 5.89, and a high moisture content (92.36%), ensuring better product quality during storage.

On the other hand, the application of ethylene during harvest, by preserving the stems and roots, showed additional benefits by minimizing the incidence of pests, diseases, and physiopathies (2.22%). Furthermore, this approach significantly reduced the development and appearance of shoots (8.89%), favoring both product stability and storage time.

The optimal ethylene dose determined was 1.0 mL•L^{-1}, as it stood out for its ability to extend the shelf life of the bulb during storage. Under this condition, a reduction in weight loss (6.28%) and a lower incidence of pests and physiopathies (2.22%) were observed, preventing significant losses in quality and quantity of the stored product.

Finally, the interaction between the application stage and the dose used revealed that the most efficient treatment was carried out during harvest, with stems and roots, using a dose of 1.0 mL•L^{-1}. This treatment allowed for a high moisture content (92.08%) and minimized the incidence of factors that compromise quality, such as pests and diseases, enhancing its effectiveness in preserving the onion bulb.

4. Conclusion

The application of ethylene during pre-harvest has been shown to be effective in preserving the physical characteristics of onion bulbs by reducing weight variation, maintaining an adequate pH, and a high percentage of humidity, which favors their conservation during storage. In addition, ethylene treatment at harvest, especially with intact stems and roots, has significantly reduced the incidence of pests, diseases and physiopathies, by improving the resistance of the bulbs and prolonging their shelf life. The optimal ethylene dose of 1.0 mL L^{-1} has been key to maintaining bulb quality by reducing weight loss and controlling damage. On the other hand, the integration with Plithogenic n-SuperHyperGraphs in the study has optimized the analysis of the effects of ethylene and its interaction with other factors, by opening new opportunities for the combination of treatments that improve efficiency in agricultural conservation.

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