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Application of Selected Essential Oils to Enhance Shelf Life and Maintain Quality of Packaged Lemons and Peppers during Storage

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إلى من قدما لي كل الحب والثقة

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List of abbreviations

FLASC: *Fusarium lactis* species complex

CA: Controled Atmosphere

MA: Modified Atmosphere

XccA : *Xanthomonas citri* pv. citri pathotype A

LDPE: Low Density Polyethylene

HDPE: High Density Polyethylene

EOs: Essential Oils

ROS: Reactive Oxygen Species

pH: Potential Hydrogen

Introduction

The global demand for fresh fruits and vegetables has notably increased in recent decades, driven by rising health awareness and a shift toward plant-based diets. However, maintaining the quality and safety of these perishable commodities remains a major challenge, particularly in postharvest stages where microbial spoilage leads to significant economic losses (Barth *et al.,* 2009).

Algeria's rural development relies heavily on agriculture, agricultural crops, including pepper and lemon, are among the most important components of the national economy (Laoubi & Yamao, 2009).

Despite their importance, both crops are highly vulnerable to various postharvest deterioration factors, including pathogenic attacks, environmental stresses, and improper handling practices (Jain *et al.,* 2023).

Traditional preservation methods often rely on synthetic chemical agents, which although effective have raised concerns due to their potential health risks and environmental impacts. Consequently, the search for safer and eco-friendly alternatives has intensified in recent years (Anand & Sati, 2013 ; Lisboa *et al.,* 2024).

Among the most promising natural solutions are essential oils extracted from aromatic plants, which possess well-documented antimicrobial, antifungal, and antioxidant properties (Hyldgaard *et al.,* 2012). Their application for controlling bacterial and fungal infections in and through food preservation offers an innovative approach that aligns with current consumer preferences for natural, minimally processed, and chemical-free products (Soković *et al.,* 2010).

In this context, the current research aims to investigate the application of selected essential oils to enhance the shelf life and maintain the quality of packaged fresh peppers and lemons during storage. This includes evaluating their potential to inhibit spoilage microorganisms and to reduce physical deterioration such as color changes, weight loss, and wilting.

The central hypothesis of the study is that essential oils, when properly extracted and applied, can significantly mitigate microbial and physiological spoilage, thereby preserving the freshness and marketability of these horticultural products.

The specific objectives of this study are:

• To conduct a field survey assessing the varieties of peppers and lemons grown in Algeria, major postharvest deterioration factors, storage practices, and types of packaging materials used.

• To extract essential oils from selected aromatic plants using conventional methods.

• To evaluate the effectiveness of these essential oils in preserving the quality and extending the shelf life of fresh peppers and lemons during storage, by limiting microbial growth and reducing physical quality losses (such as discoloration, dehydration, and wilting).

The thesis is structured into two main parts:

• The first part presents a theoretical review, including the economic importance of peppers and lemons, factors influencing their deterioration, postharvest handling practices, and an overview of essential oils and their extraction methods.

• The second part describes the practical study, detailing the field investigation, essential oil extraction processes, and experimental evaluation of their preservative and antimicrobial efficacy, with a focus on microbial spoilage, visual quality changes, and physiological weight loss during storage.

Through this research, we hope to contribute valuable insights into sustainable postharvest preservation strategies that are both effective and environmentally responsible, promoting better food security and economic stability in Algeria.

First part
Bibliographic synthesis

Chapter 1
Generalities about peppers and lemons

1. Pepper (*Capsicum*)

1.1. Definition and origin

Pepper (*Capsicum*) is an annual Solanaceae family plant. It is a vegetable or spice in general use but biologically a fruit, ranging from sweet green bell pepper to extremely pungent habaneros (Parvez, 2017).

Peppers are native to tropical and temperate Americas. Capsaicinoids (the secondary metabolite responsible for pungency) are produced uniquely in the genus *Capsicum*, which has approximately 35 species. Five species are widely domesticated and cultivated (*C. annuum, C. frutescens, C. chinense, C. baccatum,* and *C. pubescens*) (Perry *et al.,* 2007).

The classification of *capsicum* according to (Pickersgill, 1984 ; Pérez-Castañeda *et al.,* 2015) is as follows:

Kingdom: Plantae	Class: Magnoliopsida	Family: Solanaceae
Subkingdom: Tracheobionta	Subclass: Asteridae	Genus: *Capsicum*
Division : Magnoliophyta	Order : Solanales	

1.2. Varieties of pepper in Algeria

Capsicum annuum is the most important species of the genus *Capsicum* as it is cultivated widely on a commercial scale (Greenleaf, 1986 ; P. Singh *et al.,* 2014 ; R. Singh *et al.,* 2014) .

Ten pepper cultivars (*Capsicum annuum L*) that are: Doux D'Alger, Sonar, Esterel, Doux, Marconi, Magister, Belconi, Italico II, Lipari, Arabal, and Doux d'Espagne commercially grown in Algeria (Messaouda *et al.,* 2015).

1.3. Economic importance

Pepper growing plays a key role in Algeria's agricultural economy. Nearly 12,000 ha are devoted to pepper cultivation each year, producing an average of production of 2 million quintals, with average yields of around 170 Q /Ha (Anonyme, 2010).

1.4. Deterioration factors

1.4.1. Fungal diseases

A) Botrytis Fruit Rot (Grey Mold Rot)

Causal Agent: *Botrytis cinerea*

Symptoms

Water-soaked spots expand into large yellowish or brown lesions. Irregular, soft lesions form on fruits. Velvet-like fungus grows on lesions in cool, humid conditions. The fungus produces sclerotia and other spores (Reddy, 2016).

B) Anthracnose (black Mold)

Causal agent: *Colletotrichum. capsici, C. coccodes, C. gloeosporioides*

Symptoms

Small, sunken, water-soaked spots appear on fruits and may enlarge and merge. Fruiting bodies form concentrically on lesions, appearing tan or brown with salmon-orange spores. The rot can extend to and infect the seed cavity (Jones *et al.,* 2006).

C) Alternaria fruit rot

Causal agent: *Alternaria alternata*

Symptoms

Water-soaked, gray lesions appear, collapse and darken, becoming velvety with spores. Infection occurs at growth cracks, injuries or blossom-end. Internal colonization can occur from infected flowers without external signs (Jones *et al.,* 2006).

1.4.2. Bacterial diseases

A) Bacterial soft rot

Causal agent: *Erwinia carotovora*

Symptoms

Post-harvest decay begins as sunken, water-soaked areas near wounds or stem ends. These areas soften and expand, often splitting to release watery tissue (Jones *et al.,* 2006).

B) Internal fruit rot

Causal agent: *Fusarium lactis* species complex (FLASC)

Symptoms

A harmful fungus (FLASC) causes necrosis and mycelium on bell pepper ovary and fruit flesh (Frans *et al.,* 2018). It appears as whitish-grey growth on seeds, placenta, and fruit wall (Khan *et al.,* 2020). Infected fruits show minimal external symptoms (Yang *et al.,* 2010). with dark blemishes appearing only in severe cases (Khan *et al.,* 2020).

1.4.3. Physiological and physical disorders

A) Water Loss

Water loss during improper storage is a key defect. Peppers lose firmness at 2% moisture loss or show shriveling at 6% moisture loss within 1 week, depending on temperature and humidity conditions (Smith *et al.,* 2006).

B) Sunscald

Sunscald appears as a wrinkled, soft area lighter than the surrounding tissue on fruit exposed to direct sunlight. In peppers, the affected area collapses, becomes white and papery, and often turns black due to saprophytic fungi (Jones *et al.,* 2006).

C) Chilling injury

Storage below 7°C causes chilling injury, with symptoms including pitting, water-soaked areas, decay, discoloration of seed cavity, and softening. Chilling sensitivity varies by maturity and cultivar, with green peppers being more sensitive than colored ones (Gil & Tudela, 2020).

D) Mechanical damage

Crushing, stem punctures, cracks, and similar issues are very common with peppers, physical injury not only detracts from their visual quality but also leads to increased weight loss and decay (Cantwell, 2004).

1.4. Packaging of fresh *Capsicum*

Fresh *capsicum*, which include both large sweet or slightly pungent types and moderately to highly pungent green chillies harvested before reaching full maturity, are primarily consumed in their production regions and are generally sold alongside other vegetables. In developing nations, these *capsicums* are transported as freshly harvested produce in baskets or burlap bags to nearby markets or trucked to more distant markets for retail purposes. The shelf life of these products is limited to a few days, depending on factors such as variety, cultivar, harvest, maturity, and handling during transport, and storage conditions during retail. Typically, a small portion is discarded due to spoilage or drying before sale. Recent research in cultivar selection has highlighted the significance of pericarp resilience for long-distance transport and the maintenance of fresh gloss and green color to enhance retail longevity (Stoner & Villalon, 1977).

In developed countries, freshly harvested vegetable *capsicum* are transported by truck in crates to packaging centers, where they are washed, sorted, and packaged in flexible films or fiber trays with polymer film wrappers for retail distribution (Anandaswamy *et al.,* 1959).

1.6. Optimum Storage Conditions

1.6.1. Storage Temperature, Humidity, Atmosphere

Storing fruit at the lowest temperature at which the fruit is safe from chilling damage is the most important factor for maintaining its shelf life. Humidity is critical to minimize weight loss during storage and resultant shriveling of the fruit. The storage temperature recommended for capsicum is 7–10°C and humidity recommendation is 95–98% (Kader, 2002 ; Gross *et al.,* 2016). Cantwell (2004) recommends storage at 7.5°C. At-harvest fruit temperature will usually be rather higher than this optimum so good practice is to remove heat in a timely and managed process using precooling technology (Kader, 2002). Forced-air cooling is commonly used for capsicums. Humidity can be controlled through the coolstore technology, or by the use of plastic film packaging (O'Donoghue *et al.,* 2018).

Temperatures higher than 13°C promote ripening, bacterial soft rot (*Erwinia* sp.), and fungal decay (*Botrytis* and *Alternaria*) (Gil & Tudela, 2020).

CA and MA storage involves holding produce in atmospheres different to that of air to delay deteriorative processes such as senescence and ripening. The evidence for CA storage prolonging storage and shelf life of capsicums is not convincing (Leshuk & Saltveit Jr, 1990). CA treatment does not appear to inhibit water loss or softening (Polderdijk *et al.,* 1993). Despite this, the optimal atmosphere conditions for storage of capsicums have been suggested as 2–5% O_2 and 2–5% CO_2 (Saltveit, 2001). Outside these ranges, the atmospheres can result in browning, breakdown, off-odors, calyx discoloration and internal softening. In a test on green capsicums stored at 10°C in a range of O_2 atmospheres from 1% to 7% in N_2, Luo & Mikitzel (1996) reported lower decay, lower internal ethylene and slower ripening in 1% O_2 when compared to higher O_2 concentrations (3% and above). However, decay was still a major quality issue in these field-grown fruit.

Decay reduction has been reported in capsicums stored in 2–3% O_2 , 3% CO_2 at 8°C, an effect remaining after removal to 20°C (Polderdijk *et al.,* 1993 ; Dogan *et al.,* 2016).

2. Lemons (*Citrus limon*)

2.1. Definition and origin

Citrus limon, a significant member of the Rutaceae family, is known for its fleshy, juicy, and edible fruit. Originally from Asia, lemons are now cultivated worldwide in hot, subtropical, and warm temperate regions, as well as in the Mediterranean area (Paliyath & Murr, 2008).

The lemon is a type of berry with a rind. According to the variety, the blossom matures into a ripe fruit. This fruit is round, oblong, or egg-shaped (8 to 12 cm long and 5 to 6 cm wide), with a small protrusion at one or both ends (Espiard, 2002). It remains on the tree for an extended period without losing its taste (Bachés, 2011).

According to Padrini & Lucheroni (1996), Lemon belongs to the following classification :

Kingdom : Plantae	Family : Rutaceae	Species : *Citrus limon*
Division : Magnoliophyta	Genus : Citrus	
Class : Magnoliopsida	Ordre : Sapindales	

2.2. Varieties of lemon cultivated in Algeria

The most widely cultivated lemon varieties in Algeria are: Verna, Berna and Eureka (Bitters, 1973 ; Hardy, 2004).

2.3. Economic importance

Citrus growing is a strategic segment of the Algerian market. According to the latest statistics (MADR, 2006), Citrus growing currently covers a total area of 64,323 ha, with 4,365 ha available for lemon cultivation, with production during the 2011-2012 season totaling 760,823 tons (FAO, 2015).

2.4. Deterioration factors

2.4.1. Insect pests

A) The Mediterranean fruit fly (*Ceratitis capitata*)

Commonly known as Medfly. Lemons are considered conditional hosts for Medfly, with their susceptibility increasing as they mature. Green lemons are not susceptible to infestation, but susceptibility rises as the fruit transitions from light yellow to fully mature or overripe. Harvested lemons become more vulnerable within 24 hours after picking due to changes in the rind's chemistry and thickness. The fly's ovipositor cannot penetrate an intact lemon peel. However, if there are damage to the rind or holes caused by egg laying, females can repeatedly lay eggs inside, facilitating infestation. Larvae can develop inside the lemon pulp once the eggs are laid (Liquido, McQuate, & Nakamichi, 1990).

2.4.2. Bacterial diseases

A) Asiatic citrus cancker

Causal agent: *Xanthomonas citri* subsp. *citri* (XccA)

Symptoms

This disease predominantly affects leaves and fruits, and is characterized by erumpent lesions (cankers) on the fruit, foliage, and young stems of susceptible citrus varieties. Defoliation, dieback, and fruit drop can happen when the disease is severe, making any remaining affected fruit less desirable or completely unsellable (Graham & Gottwald, 1991).

2.4.3. Fungal diseases

A) Green and Blue Mould

Causal agent: *Penicillium digitatum* (green mould) and *Penicillium italicum* (blue mould)

Symptoms

Both moulds develop in damaged fruit rind areas. The infection starts with softening, turning into a water-soaked area, and then forms white fungal growth that turns green or blue with a white margin (larger with green mould) (Hardy, 2004).

B) Sour Rot

Causal agent: *Geotrichum candidum*.

Symptoms

A wounded site with a distinct ridge is surrounded by soft, watery decay that produces white, slimy spores. It does best in temperatures about 30°C and strong humidity (Hardy, 2004).

C) Brown Rot

Causal agent: *Phytophthora citrophthora* or *Phytophthora parasitica*.

Symptoms

Brown rot that is soft and leathery and smells strongly. Rain splash is how the fungus spreads (Hardy, 2004).

There are also other fungal diseases such as: **Alternaria, Anthracnose, Gray Mold** (Fullerton *et al.,* 1999 ; Cantwell & Suslow, 2002).

2.4.4. Physiological disorders

A) Oleocellosis (Oil Spotting)

Cause: Phytotoxic damage from peel oil released due to abrasion, rough handling, or injuries.

Symptoms

Light yellow patches from mild damage or dark brown patches and rind collapse from severe damage (Hardy, 2004).

B) Peteca

Cause: Unknown, but exacerbated by high-concentration oil sprays and cold conditions before harvest.

Symptoms

Sunken areas or pitting on the rind after packing.

There are also other physiological disorders such as: Cold damage, …etc. (Hardy, 2004).

2.5. Picking

Lemons can be harvested at any time of the year, but most of them reach the appropriate size for picking during the winter months, when demand is relatively low. Luckily, lemons harvested in this season can be stored for several months without spoiling (Harvey, 1946).

2.6. Storage and its conditions

In actuality, storing enhances fruit quality, making lemons more resilient to marketing and shipping processes. The majority of lemons require conditioning to develop their color, juice content, and flavor before they are fit for consumption. Typically, conditioning is carried out in refrigerated warehouses that are kept between 13 °C and 15.5 °C and 85 and 90% relative humidity. To eliminate ethylene and maybe other metabolic products made by molds and the lemons themselves, ventilation is supplied (Harvey, 1946).

Lemons should last one to four, and occasionally even six months, when stored in a ventilated environment. They lose two to three percent of their body weight each month (Rygg & Harvey, 1959 ; Rygg, 1961).

It has been observed that storing lemons at temperatures significantly below 14.5 °C can sometimes lead to pitting, membrane staining between segments, and red blotches. Conversely, temperatures above 15.5 °C encourage the proliferation of decay-causing organisms and reduce the storage duration. Lemons that are picked when they are appropriately sized and dark green tend to have the longest shelf life. In contrast, tree-ripened yellow lemons do not store well and should be sold immediately. The storage quality of lemons varies depending on their production area. Storing lemons at terminal markets carries a substantial risk, as much of their storage life may be depleted before shipping, making them more prone to decay. Therefore, understanding the lemons' prior history is beneficial. Only lemons with good storage potential should be kept for extended periods at terminal markets. For storage durations of less than four weeks, these lemons can be stored at any convenient temperature between 7 °C and 13 °C. However, for longer storage, a temperature range of 11 °C to 13 °C is recommended to avoid pitting and membrane staining at lower temperatures (Harvey, Friedman, Atrops, & others, 1952 ; Harvey, Wiant, Friedman, & others, 1952 ; Eaks, 1961 ; B. L. Wild *et al.,* 1977).

A storage environment with a low oxygen content of 5–8% can slow down deterioration and postpone color changes (Biale & Young, 1947 ; Rygg & Wells, 1962 ; Grierson, 1966). However, flavor may suffer if carbon dioxide levels climb above 10% for an extended length of time or if oxygen levels drop below 3%. Eliminating ethylene from the air might help lessen the growth of mold (B. Wild *et al.,* 1976).

2.7. Other conditions

2.7.1. Hygiene

To prevent the spread of infection, decayed or mouldy fruit should not be allowed into washing and fungicide treatment tanks, as the absence of a sterilizing agent may lead to the release of spores and the contamination of healthy fruit. It is also essential to thoroughly clean bulk bins that previously contained mouldy fruit to avoid further contamination. Moreover, sorting out mouldy fruit before it enters the packing line helps minimize the risk of spore contamination during processing (Hardy, 2004).

2.7.2. Sorting

On the packing line, fruits are sorted to eliminate those that are blemished or damaged and to classify them according to market standards. Any fruit that is not intended for packing should be identified and removed from the line before applying fungicide and waxing. Sorting can be performed manually or with electronic sorting equipment on the packing line. When sorting by hand, adequate lighting is crucial. Sorters must also be well-informed about which fruits need to be removed or culled. Photographic charts or posters illustrating the acceptable type and level of blemishes on fruit are among the most effective methods used (Hardy, 2004).

2.7.3. Sizing

Fruits are typically sized using mechanical methods like belts or rollers, electronic systems, or by weight. When sizing lemons mechanically, it is advisable to use slow belt speeds. Weight-based sizing is not recommended for pattern packing fruit due to the significant variation, which can result in poor presentation (Hardy, 2004).

2.7.4. Packing

In order to extend the shelf life of fruits during storage, packaging materials are employed to modify the atmospheric conditions surrounding the fruits and create a low oxygen zone. LDPE (low density polyethylene), HDPE (high density polyethylene), cling film, and shrink film are among the most often used packaging materials (Singh, 2019). Fruit can be packaged as either "loose fill" or "pattern packed," depending on the target market. Pattern packing can be categorized as either "open pocket" or "closed pocket." Typically, fruit is packed in cardboard cartons with a capacity of either 30 or 15 liters. Each fruit package should be sorted to ensure uniformity in size, shape, color, and condition (blemish level) (Hardy, 2004).

Chapter 2
Generalities about Essential Oils

1. Definition

Essential oils, often referred to as volatile or ethereal oils, are highly concentrated, aromatic, water-repellent, and easily evaporated substances. They are derived from various parts of plants, including flowers, buds, seeds, leaves, twigs, bark, wood, fruits, and roots (Brenes & Roura, 2010 ; Negi, 2012) The complex combinations of secondary metabolites that make up essential oils include terpenes and low-boiling-point phenylpropenes (Greathead, 2003). From the perspective of essential oils, the three most significant families are Apiaceae (Umbelliferae), Lamiaceae (Labiatae), and Asteraceae (Compositae) (Bernáth & Fuleky, 2009). Essential oils, depending on their type and concentration, can have cytotoxic effects on living cells, though they are not genotoxic. This cytotoxicity is primarily attributed to the presence of phenols, aldehydes, and alcohols (Sacchetti *et al.,* 2005).

2. Characteristics of the used plants

The table presents detailed informations on the plant species used in the essential oil extraction process.

Table 1: Characteristics of the used plants (Rosmary, wormwood, thyme, and fennel) (عزيز وآخرون، 2023)

Plant	Scientific Name	Family	Used Part	Main Chemical Components (Grouped)	Antimicrobial properties
Thyme	*Thymus vulgaris* L.	Lamiaceae	Flowering-plant	Thymol, Carvacrol, Linalool, Borneol , p-Cymene, Rosmarinic acid, Luteolin,	Antibacterial (*Staphylococcus aureus*, *Streptococcus pyogenes*, *Candida albicans, Salmonella Typhimurium,*

				Ursolic acid	*Escherichia coli, Pseudomonas aeruginosa),* Antiviral, Antifungal, and Antiparasitic
Rosemary	*Rosmarinus officinalis*	Lamiaceae	Flowering tops, dried leaves collected after flowering, oil extracted from the leaves	Rosmarinic acid, Carnosolic acid, Ursolic acid, 1,8-Cineole (Eucalyptol), α-Pinene, Camphor, Borneol	Antimicrobial
Wormwood	*Artemisia herba-alba*	Asteraceae	The entire flowering plant except the roots.	Monoterpenes: 1,8-Cineole, camphor, α-, β –Thujone, santolina alcohol, ketone artemisia Sesquiterpene lactones: artemisinin, Santonin, Dehydrolucodin Flavonoids:	Antibacterial, Antifungal, and insect repellent

				Cirsilineol, Hispidulin	
Fennel	*Foeniculum vulgare*	Apiaceae	The fruits, seeds, and essential oil extracted from them	Trans-anethole, Fenchone, Limonene, Estragole, Alpha-pinene, Beta-phellandrene & Alpha-phellandrene, Myrcene, p-Cymene, Petroselinic acid, Oleic acid, Linoleic acid, Palmitic acid	Antibacterial for some types of bacteria

3. Extraction Methods

Extraction methods commonly used include hydrodistillation, steam distillation, hydrodiffusion, solvent extraction, and solvent-free microwave extraction (Aziz *et al.,* 2018).

4. The potential of essential oils in post-harvest protection

Finding safe and efficient natural substances, particularly those derived from plants, is encouraged by the growing need to manage plant diseases and arthropod pests in organic fruit production. Because of the actions of different functional groups including alcohols, aldehydes, phenolics, terpenes, ketones, and other antimicrobial chemicals, essential oils have the potential to have insecticidal, antibacterial, antifungal, and antiviral properties. They also successfully eradicate a number of pests and pathogens (Sartorelli *et al.,* 2007 ; Swamy *et al.,* 2016).

The food sector is becoming more interested in using EOs as natural preservatives to increase food shelf life (Pateiro *et al.,* 2018). Research findings on the application of essential oils as antimicrobial agents indicate that they could serve as promising substitutes for synthetic preservatives in postharvest fruits and vegetables (Taghavi *et al.,* 2018 ; Chen *et al.,* 2019). Nonetheless, potential drawbacks of EOs, such as changes in organoleptic properties (notably smell and taste) and phytotoxic effects on fresh produce, raise concerns among both handlers and consumers (Spréa *et al.,* 2020).

Second part
Experimental part

Chapter 3
Materials and Methods

The work is divided into two parts:

1. Field Investigation

In order to collect accurate and field-based data regarding the conditions of production, packaging, storage, and marketing of pepper and lemon fruits, as well as the biotic and abiotic factors affecting their quality, we conducted several field visits in Biskra Province between November 2024 and February 2025. These visits were as follows:

- On November 14, 2024, we visited the "Covered Market" (fig. 1). Subsequently, on February 16, 2025, we visited a packaging materials store in Mziraa. On February 18, 2025, we explored the Wednesday Market, followed by visits on February 22, 2025, to both "Zegag Ben Ramadan" Market (fig. 2) and "Boukhari" Market.

Figure 1: A packaging store in the covered market in Biskra

Figure 2: Zegag Ben Ramadan market in Biskra

- Finally, on February 23, 2025, we visited a local market in the Laghrous area (fig. 3). During these visits, we observed various types of packaging materials, took some pictures, and purchased selected samples for documentation and comparative analysis.

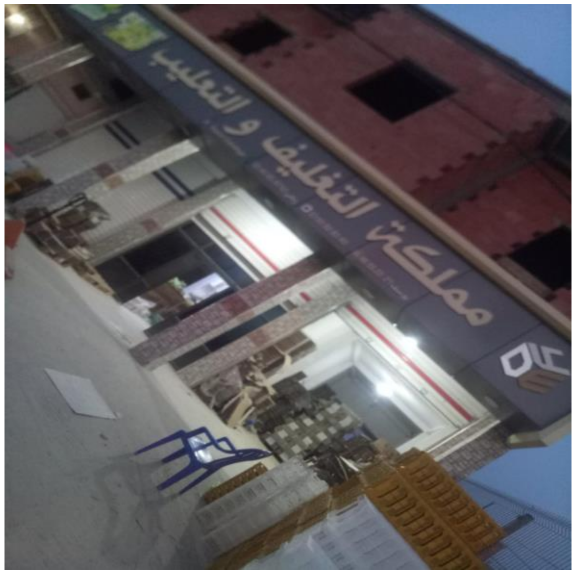


Figure 3: A packaging store in Laghrous in Biskra

- On February 11, 2025, we traveled to the municipality of Mziraa (Biskra Province) (fig. 4), where we interviewed two peasants. We addressed questions concerning the type of agriculture practiced, bio aggressors to pepper crops (such as pests and diseases), the packaging materials used, and whether the packaging material varied depending on the stage (immediately after harvesting, during storage, and during marketing). We also inquired about differences in the quantity and quality of the harvest between the beginning and end of the season, and about the methods of controlling bioaggressors of pepper. We asked the farmer to take pictures of the peppers he grows and the greenhouses he uses.

Figure 4: The Agricultural Region of Mziraa (Biskra)

- On the same day, we visited an agricultural engineer who runs a shop selling agricultural supplies. We asked questions regarding aspects related to pepper and lemon crops such as planting and harvesting times, popular varieties, pre- and post-harvest biotic deterioration factors (including pests, fungal, bacterial, and viral diseases), the influence of climate on deterioration factors, post-harvest washing, storage conditions, storage duration, packaging materials, availability of natural alternatives to chemical pesticides, and sorting before packaging.
- On February 16, 2025, we visited Tahraoui Complex – Production Branch in Mziraa (fig. 5), where an agricultural engineer provided information on cultivation systems, the varieties they grow, planting and harvesting time, deterioration factors, and control methods. We took photographs on site.

Figure 5: Tahraoui Complex (Production Branch) in Mziraa (Biskra)

- On the same day, we visited the Tahraoui Complex – Packaging and Marketing Branch (fig. 6), where we discussed aspects related to pepper: types of packaging materials used, usage stages, costs, availability, packaging quality (resistance to breakage, sunlight, and stacking), impact on product quality and shelf life, recyclability, storage conditions, use of preservatives, and transportation challenges. We took photographs on site and were given samples of the packaging materials used.

Figure 6: Tahraoui complex (packaging and materials branch) in Mziraa (Biskra)

- Later the same day, we interviewed a citrus farmer regarding lemon production. We asked about the variety he cultivates, deterioration factors, the problems he faces, post-harvest washing, storage duration, use of cold storage, and the most deterioration-resistant variety. We took photos on-site (fig. 7).

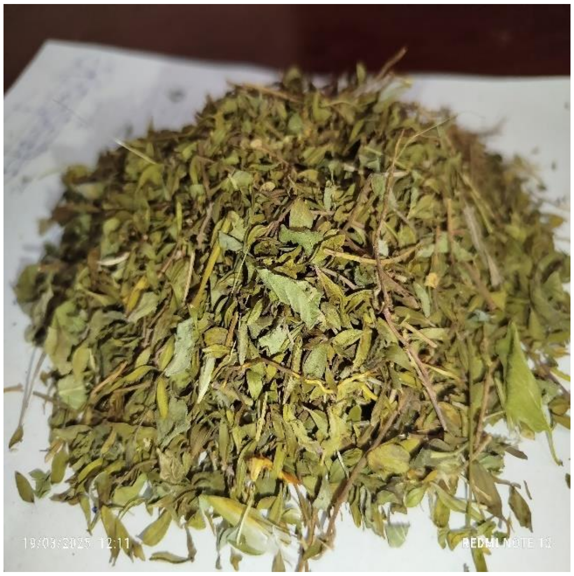
Figure 7: Citrus lemon tree in Mziraa (Biskra)

- On February 24, 2025, we visited a fruit and vegetable vendor in Biskra. We asked questions about the varieties of pepper and lemon sold, box stacking methods, storage duration, observed deterioration factors, types of packaging used, recyclability, and challenges related to product transportation and marketing.

2. Experimental part

2.1. Plant Materials

We purchased totally dried plant materials of rosemary (*Rosmarinus officinalis*), wormwood (*Artemisia herba-alba*), thyme (*Thymus vulgaris*) and fennel (*Foeniculum vulgare*) (fig. 8), from a local herbalist in Biskra, Algeria.



A

B

C

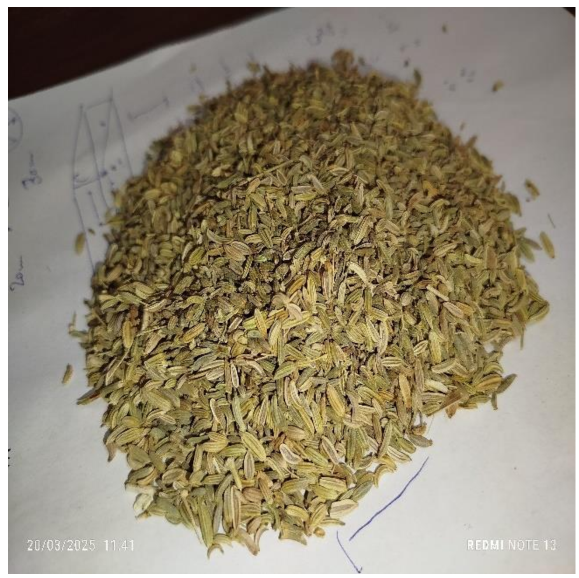


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Figure 8: Dried plant material (A: *Thymus Vulgaris*, B: *Artemisia Herba Alba*, C: *Rosmarinus Officinalis*, D: *Foeniculum Vulgare)*

2.2. Extraction Methods

We employed two extraction techniques:

2.2.1. Hydrodistillation (Clevenger apparatus)

We performed hydrodistillation for the extraction of essential oils from *Rosmarinus officinalis* and *Thymus vulgaris* using a Clevenger apparatus (fig. 9). For *Rosmarinus officinalis*, we processed a total of 1.5 kg of dried rosemary in six separate extractions (250 g each) using a ballon with a 2 liter water capacity. For *Thymus vulgaris*, we used 1.5 kg of dried thyme, processed in ten separate extractions (150 g each) using a mantle with 1liter water capacity. We carried out the distillation under reflux conditions, heating the plant material by an electric resistance set at level 3. The extraction process lasted approximately 4 hours. We obtained approximately 10 mL of essential oil from rosemary and 7 mL from thyme. The essential oils were transferred into glass vials and subsequently stored in a freezer at 4°C.

Figure 9: Clevenger type apparatus used for hydrodistillation

2.2.2. Steam Distillation

We employed steam distillation for *Artemisia herba-alba* and *Foeniculum* vulgare (fig. 10). For *Artemisia herba-alba,* we subjected a total of 1.5 kg of dried wormwood to distillation in two separate batches (750 g each), using a ballon with a 2 liter water capacity and heated in a heating mantle at a constant temperature of 130 °C. For *Foeniculum vulgare*, we distilled 1.5 kg of dried fennel in a single session using a similar setup. Each distillation process lasted approximately 5 hours per batch. We obtained approximately 20 mL of essential oil from approximately 5 hours per batch. We obtained approximately 20 mL of essential oil from *Artemisia herba-alba* and approximately 15 mL from *Foeniculum vulgare*.

Figure 10: Clevenger type apparatus used for hydrodistillation

2.3. Application of Essential Oils on Lemon and Pepper

For the experimental application, we used 3 varieties of hot pepper, one variety of sweet pepper and one variety of lemon.

we bought about 24 kg of lemon (fig. 15), 3 kg of hot pepper (variety 1) “Felfel Arbi” characterized by a Light weight (fig. 14), 5.3 kg of hot pepper (variety 2) “Felfel Arbi” characterized by a Heavyweight (fig. 13), 9.7 kg of hot pepper (variety 3) “Garn Ghezal” (fig. 12), and 12.6 kg of sweet pepper “Messaouda” (fig. 11)

Figure 11: Messaouda variety

Figure 12: Garn Ghezal variety

Figure 13: Felfel Arbi characterized by a Heavy weight

Figure 14: Felfel Arbi characterized by a light weight

Figure 15: Lemon

In addition, we acquired 40 plastic crates (fig. 16), 22 crates with a 3 kg capacity and and 18 crates with a 2 kg capacity (boxes specifications are detailed in the table 2), along with triple-layer paper towels and two meters of tulle fabric from the Covered Market in Biskra.

A B

Figure 16: Plastic crates (A.2 and B.3 kg capacity)

Table 2: Specifications of the used Boxes for Storage of pepper and lemon

Crate type	Volume (cm³)	Dimensions (cm)	Products Stored	Storage Conditions
Small (2kg capacity)	3300	16.5 × 25 × 8	Felfel Arbi + Lemon	Room temperature (22°C) for pepper; Refrigerator for lemon (4 °C)
Large (3 kg capacity)	4860	20 × 27 × 9	Garn Ghezal + Messaouda	Room temperature (22°C)

We began by cutting paper towels into small square pieces, each measuring 2 cm by 2 cm. These squares were then carefully rolled and molded by hand into compact, spherical shapes. After shaping, a single drop of essential oil was applied precisely at the center of each paper ball to allow for even absorption. Each infused ball was subsequently wrapped in a piece of tulle fabric, enclosing it completely to form a breathable covering (fig. 17).

Figure 17: Experiment materials

In each crate, the fruits were arranged in two layers (tiers), with essential oil capsules strategically placed between the layers to ensure effective exposure:

- 8 capsules for the 2 kg crates.

- 12 capsules for the 3 kg crates.

This method relied on indirect contact via vapor phase diffusion (also referred to as contact par odorat) to expose the fruits to the essential oils' volatile compounds.

This technique utilized contact through odor (contact par odor) for essential oil exposure.

2.4. Experimental Setup

For lemons, “Messaouda” and “Garn Ghezal” peppers, we used one control crate (without essential oil) and eight experimental crates, corresponding to four different essential oil types with two replicates each.

For “Felfel Arbi” peppers, which were categorized into two types based on weight:
– Light-weight type: wormwood and rosemary essential oils were used, with two replicates and one control crate for each oil.
– Heavy-weight type: thyme and fennel essential oils were applied, also with two replicates and one control crate for each oil.

2.5. Storage and monitoring

• **Storage Conditions**:

Lemons were stored in a refrigerator at a controlled temperature of 4°C.

Peppers were stored in a shaded room at ambient temperature (approximately 22°C).

• **Storage Duration**:

Lemons: 27 days

Peppers: 18 days

• **Monitoring and Data Collection**:

Lemons and Peppers were monitored on specific days throughout the storage periods.

At each interval, the following actions were performed:

- Fruits were weighed using an electronic scale (fig. 18).
- Observational notes were recorded.

- Photographs were taken to document visible changes.

Figure 18: Electronic scale

- **Evaluated Parameters**
  - Fruit/vegetable wilting
  - Color changes
  - Weight loss
  - Fungal decay

Chapter 4
Results and discussions

1. Results of survey

Data were gathered through direct engagement with various stakeholders, including small-scale farmers, market vendors, agricultural engineers, and representatives from the Tahraoui Agricultural Group covering both its cultivation and packaging operations.

The collected informations provides a comprehensive overview of the entire value chain, encompassing production practices, crop protection, post-harvest handling, packaging methods, and marketing strategies.

1.1. Peppers

1.1.1. Detorioration factors

A) Pre and post-harvest

- **Pests:** includes whiteflies, thrips (fig. 19, 20), and spider mites (especially *Tetranychus urticae*) (fig. 21), Lepidoptera pests like *Helicoverpa armigera* and *Spodoptera exigua.*

These insects are typically present before harvest and may be transferred to storage facilities after harvest, where they can cause significant damage to the fruit.

Figure 19: Impact of thrips on pepper fruit

Figure 20 : Impact of thrips on pepper plant

Figure 21: Impact of mites on pepper leaf

- **Fungal diseases**: gray mold (*Botrytis cinerea*), white mold (*Sclerotinia sclerotiorum).*
- **Bacterial diseases**: *Pseudomonas syringae.*

Pesticides (fig. 22) can be applied in storage facilities to prevent fungal diseases and control pests such as thrips and mites that may be transmitted from the harvested crop of peppers or lemons.

The interviewed agronomist indicated the use of natural pesticides (natural preservatives) such as neem oil (huile de neem) and bacterial extracts like Spinosyn A and Spinosyn B. The use of these pesticides is not only limited to peppers but also to lemons.

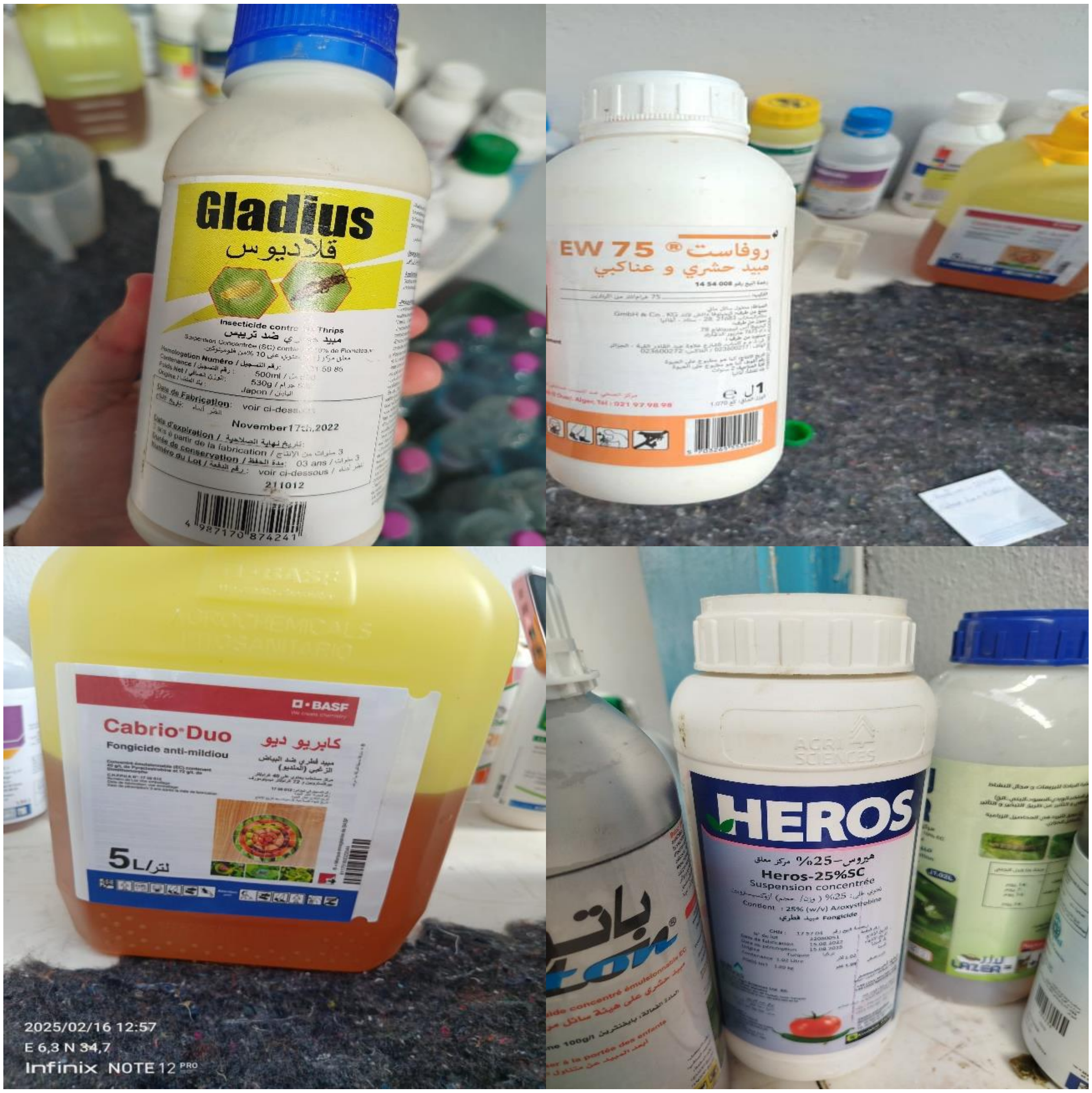

Figure 22: Varieties of used pesticides

B) Post harvesting

Peppers are susceptible to several secondary pathogens such as *Aspergillus*, *Penicillium*, yeasts, *Alternaria* spp., and *Botrytis cinerea*.

- **Physiological disorders**: like wilting, sunscald, and blossom end rot (fig. 23).

In southern areas, high temperatures favor the development of insect pests (especially mites).
In northern regions, where humidity is higher, fungal diseases are more prevalent.
Frost or extreme temperatures affect the product's shelf life and its quality.

Figure 23: Blossom end rot symptoms on pepper fruit

1.1.2. Varieties of pepper

Farmers reported cultivating varieties such as "Karam", "Maqam" (fig. 29), "Racime", "Prince", "Garn Ghezal" (fig. 31), and "Felfel Arbi" (fig. 30), for hot peppers, "Messaouda", "Tahat", and "Dzil", for sweet peppers.

Tahrawi Complex produces various known and experimental varieties, including "Ateed" (noted for longer shelf-life) (fig. 28), "Messaouda" (fig. 25), "TNT" (fig. 26), "Startar" (fig. 27), "Maqam", and "Tricolor" (fig. 24).

Figure 24: Sweet pepper (Tricolor)

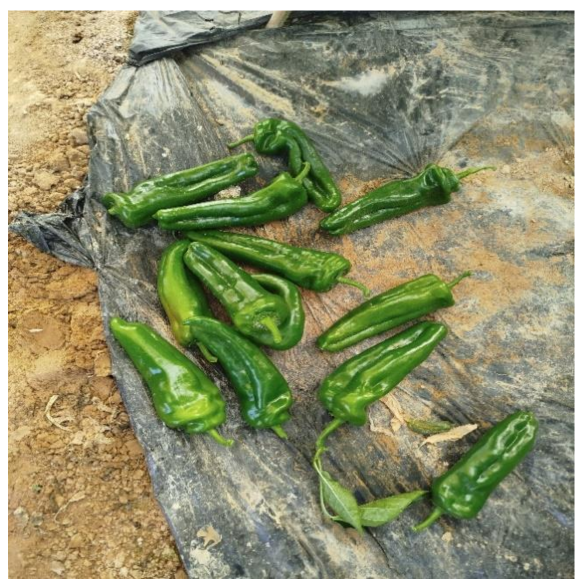

Figure 25: Sweet pepper (Messaouda)

Figure 26: Hot pepper (TNT)

Figure 27: Hot pepper (Startar)

Figure 28: Hot pepper (Aatid)

Figure 29: Hot pepper (Maqam)

Figure 30: Hot pepper (Felfel Arbi)

Figure 31: Hot pepper (Garn Ghezal)

1.1.3. Planting and Harvesting Calendar

Planting: September to May.
Harvesting: December to end of May.

1.1.4. Pepper harvest

Peppers need about three months to reach full production maturity. Once they start producing, harvesting takes place approximately every 20 days manually, ensuring a continuous yield throughout the season.

At the beginning of the harvest season, yields are abundant, production levels are high, fruit sizes are large, and overall quality is generally excellent.
However, toward the end of the harvest season, there is a noticeable decline in quantity, size, and quality.

1.1.5. Postharvest handling and packaging

The harvested peppers were packed by Beginner farmers in woven plastic bags (50 kg semolina bags) for transport and storage before transferring them into cartons for packaging. In contrast, experienced farmers perform simultaneous harvesting and packaging.
in term of packaging, most farmers and sellers reported using plastic or medium-sized cardboard boxes (fig. 32, 33). while wooden crates are rarely used. These findings are consistent with the recommendations of Paneru *et al.* (2022), who found that plastic and cardboard containers offer

suitable ventilation and protect fruits from mechanical injury. However, the study also warned that cardboard tends to absorb moisture, increasing the risk of fungal development if not stored in dry environments.

Figure 32: Cardboard containers

Figure 33: Medium sized crates

According to Complex Tahraoui. Pepper fruits are moved from the production unit to the packaging section with large plastic crates (fig. 34).

Figure 34: Process of pepper packaging after harvest

The vendor uses plastic or cardboard boxes for packaging. These boxes are typically not fully packed, as overstacking can lead to product damage. He noted that spoilage generally begins by the third day when stored at room temperature, and occurs even more rapidly during summer months in the absence of refrigeration.

1.1.6. Sorting Operations

The initial stage in the packing process at the Tahraoui Complex involves sorting, a task primarily performed by women assigned to the packing lines. The main objective of this step is to remove any non-compliant fruits to ensure only high-quality products proceed to the next stages (fig. 35). Rejection criteria include:

Shape abnormalities: Fruits that exhibit deformities or irregular forms.

Color defects: Fruits with uneven, immature, or otherwise undesirable coloration.

Physical injuries: Fruits showing signs of cuts, bruises, or mechanical damage.

Surface blemishes: Fruits affected by stains, spots, or other external imperfections.

Figure 35: Sample of rejected (not high quality) peppers after sorting process

1.1.7. Grading (Source: Complex Tahraoui)

Grading is the process of categorizing fruits according to their size and color (fig. 36). Each size category, must be packed separately, with peppers of the same caliber placed together in the same carton horizontally. This operation ensures product uniformity.

Figure 36: Process of grading of pepper in complex Tahraoui

In some cases, certain packaging-related errors and deformations These issues were mainly attributed to inappropriate handling or improper stacking, particularly when packaging materials such as cardboard boxes or plastic crates were overfilled. Commonly observed damages included box deformation, tears, and compression of pepper fruits (fig. 37), which can negatively impact their marketability and shelf life during transport and storage.

Figure 37: Damaged fruit during packaging

1.1.8. Storage and shelf Life of pepper

Among all farmers, peppers are carefully harvested and placed into plastic crates, which are kept in a shaded area to protect the produce from heat and direct sunlight. Later in the evening, the harvested peppers are promptly transported directly to local markets for sale.

In Winter: peppers can remain fresh for 2 to 3 days before starting to wilt if stored under natural (ambient) conditions without refrigeration.

In Summer: due to the higher temperatures, peppers start wilting after just one day if kept outside without cooling.

In Cold Storage: When placed in refrigerated rooms, peppers can stay fresh for up to 15 days before they start to wilt or lose quality.

1.1.9. Transporting

Transport operators face challenges; longer distances increase potential damage. Produce must be protected from sun-related injuries.

Peppers for long-distance transport (to Oran, Algiers, or other provinces) are harvested slightly immature to preserve quality. Fully ripe peppers are usually marketed locally due to higher perishability.

1.1.10. Types of Packaging materials and their characteristics

Materials: cardboard, plastic

Types: plastic crates and cardboard boxes (fig. 38), plastic trays (Ravi) (fig. 39), cellophan films (fig. 40).

Figure 38: Cardboard and plastic crates

Figure 39: Plastic tray (Ravi)

Figure 40: Cellophane film

A) Availability and Cost

According to the Tahrawi complex, the cost of packaging materials is generally economical and not a major issue. The availability is regular:

- Cardboard boxes are ordered every three months.
- Plastic crates are reusable and used for longer periods.
- Plastic trays are ordered about once per month.

B) Strength and Durability

Plastic crates are the most resistant to breakage and sun exposure. They are made from materials that protect the product from sunlight.

Cardboard and “Ravi” do not resist sun or moisture well and may become weak or damaged over time.

All three types (plastic, cardboard, Ravi) can be stacked during storage and transport.

C) Packaging and Contamination

Packaging must be clean and free from any dirt or foreign material.

Plastic crates can spread dirt and bacteria if they are reused without proper cleaning and disinfection.

Plastic trays protect peppers from direct contamination but can trap moisture, encouraging the growth of fungi.

Cardboard boxes are clean when new, but they quickly absorb moisture and dirt, which can create a suitable environment for mold and bacteria if not replaced often.

D) Exposure to Pests

Open plastic crates may attract insects and rodents, especially during long storage or transport.

“Ravi” reduce pest risk, but not completely, especially if storage conditions are poor.

Cardboard is more vulnerable to insects and rodents, especially in humid storage conditions, and can become weak and useless if it gets wet.

E) Effects on Product Quality and Shelf Life

Plastic wrapping traps moisture, especially if the peppers are not fully dry, which can cause faster spoilage.

Open plastic crates allow better air circulation, but they may also cause water loss, leading to shriveling of peppers.

Cardboard can absorb extra moisture, but if not ventilated well, it may become wet and allow mold to grow inside.

F) Protection and Safety

Plastic wrapping protects the peppers from scratches and physical damage.

Plastic crates protect against pressure but do not stop water loss unless covered.

Cardboard boxes offer moderate protection from shocks, but they are weaker than plastic. If they get wet, they lose strength and can no longer protect the product properly.

G) Awareness of Health and Environmental Risks

The field survey showed that most people involved in pepper handling pay attention to hygiene.

The Tahrawi complex uses cardboard boxes and “Ravi” trays only once, and ensures they are clean. Only plastic crates are reused after proper cleaning.

Vegetable and fruit vendors use cardboard boxes once to avoid contamination and mold. They also noted that leaks or humidity can attract insects if boxes are reused

1.2. Lemons

1.2.1. Common Lemon Varieties

All sources (the agronomist, farmer, and vendor) confirm that the dominant lemon variety cultivated and marketed in the Mziraa and Biskra region is the Four Seasons Lemon (fig. 41). This variety is recognized for its capacity to produce fruit throughout the year. This observation is supported by Ladaniya (2008), who identified “Four Seasons” as a commonly grown cultivar in Mediterranean regions due to its continuous fruiting capacity and adaptability.

Figure 41: Lemon tree (four seasons variety)

Acording to the Farmer the trees produce abundantly and with good quality during the first seven years, after which the production gradually declines. Acording to (Barry & Castle, 2007), this decline in productivity can be attributed to age-related physiological limitations, soil nutrient depletion, and cumulative biotic stress.

1.2.2. Diseases and Pests

Agronomist identified several key phytosanitary threats: Leaf miners (*Liriomyza* sp.), Parasitic gummosis caused by *Phytophthora* Spider mites (*Tetranychus* sp.), Mediterranean fruit fly (*Ceratitis capitata*), completing its life cycle in 15–30 days depending on warm conditions. A farmer confirmed the presence of spider mites and Ceratitis infestations, which are consistent with findings reported by the University of California's IPM program.

He also reported that excessive irrigation leads to soil depletion and deficiencies in iron and magnesium, affecting tree health, also that Small, ripe lemons indicate potassium and calcium deficiency. This is confirmed by Ferguson (2013) & Ferguson *et al.* (2022).

An agronomist mentioned that secondary infections post-harvest include yeasts, green mold (Fig. 42), and *Aspergillus* spp.

Figure 42: Lemon fruit affected by green mold

A vendor Noticed deterioration factor on lemons after 5 days of storage (fig. 43), surface scratches, bruises, deformation, and lemon juice leakage likely consequences of pest damage or handling. These findings are supported by Nunes et al. (2007), who emphasized that postharvest quality loss in citrus is significantly influenced by mechanical injuries and poor handling.

Figure 43: Infected fruits during storage

1.2.3. Storage and Shelf Life

Storage practices and recommendations varied across interviewers:

Agronomist Recommended storage at 20–25 °C, shaded, with good ventilation to avoid humidity. Without chemical treatment, lemons last 4–5 days which follows ISO (2019) guidelines; with fungicide (thiophanate-methyl), storage can extend to 10–15 days. The use of cold rooms is also a common practice for extending the shelf life of lemons.

Farmer stated that lemons can last up to one month without cold storage if pests (mainly *Ceratitis*) are controlled. Without using cold rooms, he packs lemons in plastic crates and sells them immediately. if cold storage were employed, the storage duration of lemons could be extended from 3 to 6 months.

Vendor Confirmed that lemons stored at 24–26 °C with air conditioning last 4–5 days before spoilage appears.

After 5 days, diseases start to appear and the lemon starts to spoil. Scratches and wounds may appear on the lemon, the packaging may be deformed and the lemon water may leak.

1.2.4. Post-Harvest Handling and Packaging

Farmers typically do not wash lemons after harvest, by market agreements. unless requested, a practice that helps reduce microbial contamination by avoiding surface moisture accumulation (do Nascimento Nunes, 2009). He also reported that he does not currently utilize cold rooms in his production system. Instead, harvested lemons are directly packed into plastic crates (see fig. 44), and sold either on site or transported immediately to local markets. Crates are stacked if not full. Spoiled lemons must be discarded to prevent contamination of other fruits. He emphasized the importance of protecting lemons from high temperatures and sunlight. During transport, merchants use covers to minimize heat damage.

Figure 44: Packaged lemon fruit

On the other hand, vendors adopt slightly more diverse packaging materials, including plastic crates (fig. 47), baskets, alveoli (fig. 45), and occasionally mesh bags (fig. 46). The choice of packaging varies according to the local practices and market demands. While the use of alveoli and trays helps minimize direct fruit-to-fruit contact, thereby reducing mechanical damage and pathogen transmission, improper stacking or reuse of damaged containers remains a challenge.

Figure 45: Alveoli

Figure 46: Mesh bag

Figure 47: Plastic crates for lemon

2. Experimental part

In this experiment, we aim to evaluate the effectiveness of some essential oils (which are wormwood, thyme, fennel, rosemary) in extending the shelf life of peppers and lemons and inhibiting the onset of mould, compared to a control sample (without oils).

An average was created for each type of oil: Repitition 1 + Repitition 2 / 2 and for all parameters.

2.1. Wilting rate

Wilting was assessed through visual inspection using a standardized 4-point scale to quantify the severity of water loss and tissue dehydration in the fruits. The scale was defined as follows:

1 (First degree wilting): Minimal signs of wilting; the fruit appears mostly fresh with only slight signs of drooping or loss of firmness.

2 (Slight wilting): Noticeable but mild wilting; some areas of the fruit may show softening or curling, but the overall structure remains largely intact.

3 (Moderate wilting): Clear signs of dehydration and tissue collapse; the fruit shows visible drooping, shriveling, or wrinkling, indicating significant water loss.

4 (Severe wilting): Extensive wilting; the fruit is visibly shriveled, limp, and significantly compromised in texture and firmness, often indicating advanced deterioration.

This visual scale allowed for consistent and repeatable evaluation of wilting intensity throughout the storage period.

The means were calculated using the formula: (repetition 1 + repetition 2) / 2, were:

Repetition 1: the average of wilted fruits in the box 1
Repetition 2: the average of wilted fruits in the box 2

- **For Garn Ghezal pepper**

The table 3 presents the mean wilting scores, calculated by averaging the scores from multiple fruits and repeated trials for each treatment group. These scores were recorded on different dates for the control group and for fruits treated with various essential oils: wormwood, rosemary, thyme, and fennel.

Table 3: Wilting rate of Garn Ghezal pepper under different essential oils treatments during storage

The date	Control	Wormwood	Rosemary	Thyme	Fennel
25/03/2025	0.0769	0.1726	0.1064	0.125	0.0937
26/03/2025	0.1538	0.2878	0.2128	0.375	0.1562
27/03/2025	0.1923	0.2878	0.2954	0.2812	0.25
28/03/2025	0.2692	0.4917	0.4495	0.375	0.2812
29/03/2025	0.4230	0.5756	0.6974	0.53	0.4687
05/04/2025	1.6923	1.7684	1.7044	1.4375	1.3437
10/04/2025	2.7307	2.7384	2.7044	2.1562	1.875

The control group (untreated fruits) showed a progressive increase in wilting, starting at 0.0769 on 25/03/2025 and rising steadily to reach 2.7307 by 10/04/2025. Among the essential oil treatments, thyme and fennel demonstrated the most significant reductions in wilting compared to the control:

Thyme: Final wilting value = 2.1562 ; Fennel: Final wilting value = 1.875.

In contrast, wormwood and rosemary exhibited results very close to or even worse than the control: Wormwood: Final wilting value = 2.7384; Rosemary: Final wilting value = 2.7044.

These findings indicate that wormwood and rosemary were not effective in reducing wilting and may even have contributed to similar or accelerated deterioration.

The most effective essential oil in reducing wilting was fennel, followed by thyme. On the other hand, wormwood and rosemary showed poor performance, with wilting values close to or exceeding those of the untreated control.

- **For Sweet pepper Messaouda**

The table 4 presents the mean wilting scores, calculated by averaging the scores from multiple fruits and repeated trials for each treatment group.

Table 4: Wilting rate of sweet pepper (Messaouda Variety) under different essential oil treatments during storage

Date	Control	Wormwood	Rosemary	Thyme	Fennel
25/03/2025	0.2857	0,1878	0,14555	0,1875	0,1875
26/03/2025	0.3571	0,224	0,1813	0,29165	0,28125
27/03/2025	0.4285	0,30515	0,21975	0,5	0,34375
28/03/2025	0.6428	0,3681	0,36805	0,875	0,53125
29/03/2025	0.9285	0,5559	0,5137	0,91665	0,625
30/03/2025	1	0,7272	0,6236	1,2083	0,78125
03/04/2025	1.9285	1,542	1,5906	2,2604	1,59375
10/04/2025	3.5714	3.0551	3.5192	3.0625	3.0937

The control group exhibited a continuous and pronounced increase in wilting, starting at 0.2857 on 25/03/2025 and reaching a high value of 3.5714 by 10/04/2025. In the early days of storage, all four essential oils demonstrated better performance than the control, with lower wilting values. Even in the long term (by 10/04/2025), all essential oil treatments remained effective in reducing wilting compared to the untreated group.

Wormwood was the most effective essential oil in reducing wilting over the long term. It was followed by thyme and fennel, which also demonstrated good protective effects. Rosemary was the least effective among the oils, but still performed slightly better than the untreated control.

- **For Felfel Arbi heavy weight**

The table 5 presents the mean wilting scores, calculated by averaging the scores from multiple fruits and repeated trials for each treatment group.

Table 5: Wilting rate of hot pepper (Felfel Arbi heavy weight) under different essential oil treatments during storage

The date	Control	Thyme	fennel
25/03/2025	0	0.0757	0.0606
26/03/2025	0.1212	0.0909	0.0606
27/03/2025	0.1212	0.1060	0.0909
28/03/2025	0.1818	0.1515	0.1969
29/03/2025	0.3030	0.2878	0.2727
05/04/2025	0.9090	1.2424	1.1666
10/04/2025	2.2424	2.0151	1.9696

Wilting in the control group started at 0.000 on 25/03/2025 and gradually increased to 2.2424 by 10/04/2025. Thyme and fennel essential oils showed the ability to reduce wilting during the early days of storage, recording lower wilting values than the control group.

Although the essential oils especially fennel contributed to reducing wilting over the long term compared to the control, the control group performed better on 05/04/2025. This indicates that the effect of the oils was not consistent. Therefore, these essential oils cannot be considered fully effective, and further tests are recommended, possibly with adjusted concentrations or repeated applications.

- **For Felfel Arbi light weight**

The table 6 presents the mean wilting scores, calculated by averaging the scores from multiple fruits and repeated trials for each treatment group.

Table 6: Wilting rate of hot pepper (Felfel Arbi light wight) under different ssential oil treatments during storage

The date	Control	Wormwood	Rosemary
25/03/2025	0.108	0.0845	0.0793
26/03/2025	0.2608	0.1919	0.1476
27/03/2025	0.4565	0.3127	0.2555
28/03/2025	0.9347	0.7185	0.5006
29/03/2025	1.2826	0.7475	1.2141
01/04/2025	2.5434	2.4830	2.5277
10/04/2025	4	3.83	3.855

Wilting in the control box began at 0.108 on 25/03/2025 and gradually increased, reaching 4.000 by 10/04/2025. Both essential oils wormwood and rosemary demonstrated relatively good performance in reducing wilting compared to the control, with noticeable differences throughout most of the storage period.

Although wormwood and rosemary essential oils showed some ability to reduce wilting compared to the control particularly wormwood the recorded differences were relatively small. This suggests that their effectiveness in reducing wilting in the "Felfel Arbi–Light Weight" variety may be limited. Therefore, these oils might not be the most suitable choice if the goal is to significantly reduce postharvest wilting.

- **For Lemon**

Wilting was quantitatively evaluated based on the percentage of weight loss over time, calculated using the following formula: Wilting (%) = [(Initial Weight − Final Weight) / Initial Weight] × 100.

To facilitate interpretation, wilting severity was categorized into three classes based on the percentage of weight loss:

0–5%: No wilting ; 6–12%: Moderate wilting (Wilting Score = 1)

12%: Severe wilting with visible shrinkage (Wilting Score = 2).

The table 7 presents the mean wilting scores, calculated by repeated trials for each treatment group.

Table 7: Wilting rate of lemon under different essential oil treatments during storage

Date	Control	Wormwood	Rosemary	Thyme	Fennel
27/03/2025	0	0	0	0	0
31/03/2025	0	0	0	0	0
11/04/2025	1	1	1	1	1
20/04/2025	1	2	1	1.5	1.5

During the initial two dates, no wilting was observed in any group. On 11/04/2025, all treatments matched the control (wilting score = 1), indicating no visible improvement or deterioration. On 20/04/2025: Wormwood led to a higher wilting score = 2 compared to the control = 1, indicating increased deterioration. Thyme and Fennel showed a wilting score of 1.5, slightly worse than control. Rosemary matched the control with no further increase in wilting.

Compared to the untreated control, Rosemary maintained the same level of wilting, showing no additional deterioration. Thyme and Fennel showed moderate deterioration. Wormwood performed the worst, increasing wilting above the control level.

2.1. Color Change Assessment

Color change was assessed visually using a standardized 4-point scale to evaluate the degree of ripening and pigmentation shift in the fruits. The scale was defined as follows:

- 0 (Initial green stage): The fruit maintains its original green color with no signs of ripening.
- 1 (Orange stage): The fruit shows a clear orange coloration, indicating early ripening.
- 2 (Red stage): The fruit has developed a noticeable red hue, reflecting moderate ripening.
- 3 (Fully red stage): The fruit displays a uniform, deep red color, indicating full ripeness or complete pigmentation change.

This visual scale enabled consistent and repeatable monitoring of color development across treatments and throughout the storage period.

The mean color change scores were calculated by averaging observations from multiple fruits and repeated trials for each treatment group. These values were recorded on different dates for both the control group and the groups treated with various essential oils: wormwood, rosemary, thyme, and fennel.

To ensure consistency, the means were calculated using the following formula:

Mean = (Repetition 1) + (Repetition) \ 2

where:

• Repetition 1 corresponds to the average color score of fruits stored in box 1,

• Repetition 2 corresponds to the average color score of fruits stored in box 2.

This approach provided a reliable estimation of the average color progression under each treatment during storage.

- **For Hot pepper Garn Ghezal**

The table 8 presents the mean color change scores, calculated by averaging observations from multiple fruits and repeated trials for each treatment group.

Table 8: Color change progression in hot pepper (Garn Ghezal) under different essential oil treatments during storage

The date	Control	Wormwood	Rosemary	Thyme	Fennel
25/03/2025	0.1538	0.0625	0.1302	0.25	0.312
26/03/2025	0.2307	0.1776	0.1302	0.25	0.0937
27/03/2025	0.2692	0.2401	0.2604	0.2812	0.1562
28/03/2025	0.3076	0.4078	0.3193	0.2812	0.3125
29/03/2025	0.3461	0.4391	0.3725	0.5	0.4062
05/04/2025	0.8846	1.1940	1.1316	1.1875	0.9312
10/04/2025	1.7307	2.0148	1.7871	1.4687	1.1562

The progression of color change in hot pepper (Garn Ghezal) shows distinct differences among the treatments: Control (no essential oil) showed a steady increase in color degradation from 0.1538 to 1.7307. Wormwood increased more sharply, reaching the highest value of 2.0148 by the final date, indicating poor effectiveness in preserving color. Rosemary followed a similar trend with a final value of 1.7871. Thyme demonstrated better preservation, ending at 1.4687. Fennel showed the best performance, with the lowest color change (1.1562), suggesting strong efficacy in maintaining pepper appearance.

- **For Sweet Pepper Messaouda**

The table 9 presents the mean color change scores, calculated by averaging observations from multiple fruits and repeated trials for each treatment group.

Table 9: Color change progression in sweet pepper (Messaouda) under different essential oil treatments during storage

The date	Control	Wormwood	Rosemary	Thyme	Fennel
25/03/2025	0.0714	0.2337	0.1217	0.125	0.125
26/03/2025	0.1428	0.2792	0.1634	0.125	0.0937
27/03/2025	0.2857	0.3246	0.1648	0.2187	0.0937
28/03/2025	0.5	0.4675	0.2435	0.3437	0.1875
29/03/2025	0.6428	0.5486	0.3236	0.4375	0.25
30/03/2025	0.7857	0.6655	0.4423	0.4687	0.3437
03/04/2025	0.9285	0.9545	0.9198	0.9062	0.7812
10/04/2025	1.5	1.6655	1.7596	1.5937	1

Wormwood: Started at 0.2337 and increased to 1.6655 This value exceeded the control, indicating that wormwood oil was less effective and did not prevent discoloration; in fact, it may have accelerated the process. Rosemary: Progressed from 0.1217 to 1.7596 Also higher than control, meaning it was ineffective in preserving the color compared to untreated samples. Thyme: Rose from 0.125 to 1.5937 Again, greater than the control; hence, thyme oil did not help reduce color change in this variety. Fennel: Started at 0.125 and reached only 1.0 This was significantly lower than the control, indicating good effectiveness in preserving the color and slowing down discoloration.

Among all treatments, fennel essential oil demonstrated the best performance in delaying color change in sweet pepper (Messaouda variety), with a final score of 1.0, well below the control

(1.5). All other oils including wormwood, rosemary, and thyme showed higher color change values than the control, indicating poor effectiveness or even negative impact on visual quality.

- **For Felfel Arbi heavy weight**

The table 10 presents the mean color change scores, calculated by averaging observations from multiple fruits and repeated trials for each treatment group.

Table 10: Color change progression in hot pepper (Felfel Arbi heavy weight) under different essential oil treatments during storage

The date	Control	Thyme	Fennel
25/03/2025	0.0606	0.1666	0.1212
26/03/2025	0.0606	0.1818	0.1666
27/03/2025	0.0909	0.2121	0.1969
28/03/2025	0.1818	0.2424	0.3484
29/03/2025	0.2121	0.303	0.4242
01/04/2025	0.3939	0.5151	0.8635
10/04/2025	0.8787	0.9696	1.1666

From 25/03 to 10/04/2025, all boxes exhibited increasing color change.

Thyme-treated peppers showed slightly more discoloration than the control, suggesting low effectiveness. Fennel-treated peppers showed the highest color change, significantly exceeding the control, indicating poor performance in preserving color. The control box, despite being untreated, showed less progression of color degradation than the two essential oil treatments. Neither thyme nor fennel demonstrated a protective effect on color preservation in this hot pepper variety. On the contrary, both oils were less effective than no treatment at all, especially fennel, which accelerated color loss the most.

- **For Felfel Arbi light weight**

The table 11 presents the mean color change scores, calculated by averaging observations from multiple fruits and repeated trials for each treatment group.

Table 11: Color change progression in hot pepper (Felfel Arbi light weight) under different essential oil treatments during storage

The date	Control	Wormwood	Rosemary
25/03/2025	0.3918	0.4317	0.4875
26/03/2025	0.4565	0.506	0.5292
27/03/2025	0.5	0.6032	0.7177
28/03/2025	0.6739	0.7874	0.9605
29/03/2025	0.9130	0.9317	1.1366
01/04/2025	1.3695	1.5222	1.8391
10/04/2025	1.9565	2.1038	2.2346

From 25/03 to 10/04/2025, color degradation increased in all boxes.

Wormwood-treated peppers showed slightly more discoloration than the control, indicating a low protective effect. Rosemary-treated peppers recorded the highest color degradation, exceeding the control significantly, which suggests poor effectiveness. The control box, although untreated, showed less discoloration progression compared to both essential oil treatments.

Neither wormwood nor rosemary showed effectiveness in maintaining color in the light-weight hot pepper variety. In fact, both treatments performed worse than the untreated control, especially rosemary, which was associated with the fastest rate of color deterioration.

2.2. Rate of Decay

Decay was assessed by visually inspecting each storage box and counting the number of fruits showing clear signs of rotting, such as softening, discoloration, fungal growth, or tissue breakdown. A simple numerical scale was used to classify the extent of decay based on the number of affected fruits in each box:

- 0 = No decay observed
- 1 = One decayed fruit
- 2 = Two decayed fruits
- 3 = Three decayed fruits
- 4 = Four decayed fruits
- (...and so on, depending on the total number of fruits in the box)

This scale allowed for straightforward quantification of spoilage over time and facilitated comparison between treatments. By recording the number of decayed fruits at different storage intervals, the effectiveness of various essential oils in reducing postharvest decay could be evaluated reliably. Decay was evaluated by counting the number of visibly rotten fruits in each storage box. A simple numerical classification was used to express the level of decay: 0 = No decay observed 1 = One decayed fruit 2 = Two decayed fruits 3 = Three decayed fruits, 4…

- **For Hot pepper Garn Ghezal**

The table 12 presents the number of decayed fruits per box, with the average calculated from two replicates for each type of essential oil.

Table 12: Rate of decay in hot pepper (Garn Ghezal) treated with different essential oils during storage

The date	Control	Wormwood	Rosemary	Thyme	Fennel
25/03/2025	0	0	0	0	0.5
26/03/2025	0	0	0	0	0.5
27/03/2025	1	0.5	0	0.5	0.5
28/03/2025	1	2	1	0.5	0.5
29/03/2025	1	2.5	2	1.5	2
05/04/2025	1	2.5	2.5	1.5	2.5
10/04/2025	1	2.5	2.5	1.5	2.5

The untreated control exhibited the most stable and minimal decay level (fixed at 1) from March 27 through April 10. In contrast, most essential oil treatments particularly *Artemisia herba-alba*, *Rosmarinus officinalis,* and *Foeniculum vulgare* led to higher decay values, reaching up to 2.5. Only *Thymus vulgaris* (showed a relatively lower increase, yet still comparable to or worse than the control. This indicates that the applied essential oils did not enhance preservation, and in some cases may had a negative or neutral effect under the given storage conditions. These findings suggest that either the concentrations used were suboptimal or the oils themselves were not effective against the microbial agents present on this specific pepper variety.

- **For Sweet pepper Messaouda**

The table 13 presents the number of decayed fruits per box, with the average calculated from two replicates for each type of essential oil.

Table 13: Rate of decay in sweet pepper (Messaouda) treated with different essential oils during storage

Date	Control	Wormwood	Rosemary	Thyme	Fennel
25/03/2025	0	0	0	0	0
26/03/2025	0	0	0	0	0
27/03/2025	0	0	0	0	1
28/03/2025	0	0	0	0	1
29/03/2025	1	1	0	1.5	2.5
30/03/2025	2	1	0.5	1.5	2.5
03/04/2025	2	1.5	1	1.5	2.5
10/03/2025	3	2	1.5	2	3

From 25/03 to 10/04/2025, decay began appearing after the third day, and its severity increased over time in all boxes.

Rosemary was the most effective in delaying decay, reaching only 1.5, significantly lower than the control. Wormwood and Thyme both achieved moderate inhibition, showing slightly less decay than the control (2 vs. 3). Fennel had no protective effect, as its decay level matched or exceeded the control across several days, ending at 3. The control box, as expected, reached a high level of decay.

Essential oils of rosemary and, to a lesser extent, thyme and wormwood were effective in limiting the decay of sweet pepper. Rosemary showed the best preservation effect, while fennel failed to provide any noticeable protection against spoilage.

- **For Felfel Arbi Heavy weight**

The table 14 presents the number of decayed fruits per box, with the average calculated from two replicates for each type of essential oil.

Table 14: Rate of decay in hot pepper (Felfel Arbi heavy weight) treated with different essential oils during storage

The date	Control	Thyme	Fennel
25/03/2025	0	0	0
26/03/2025	0	0	0

27/03/2025	0	0	0
28/03/2025	0	0	0
29/03/2025	0	0.5	0
01/04/2025	0	0.5	0
10/04/2025	1	0.5	0

Control (Untreated): Decay appeared only on the final observation date (April 10) with a score of 1. This suggests that under the prevailing storage conditions, the fruits remained visually unaffected by spoilage for nearly two weeks.

Thymus vulgaris (Thyme): Signs of decay appeared earlier, on March 29 (score: 0.5), and remained constant until the end (0.5). While the severity remained low, the earlier onset compared to the control indicates that thyme oil did not delay decay and may have slightly accelerated its appearance.

Foeniculum vulgare (Fennel): remarkably, no decay was recorded throughout the entire monitoring period. This suggests that fennel oil may have provided some protective effect, at least in delaying visible signs of decay beyond that of the control and thyme treatment.

Thyme oil did not improve postharvest preservation and may have even allowed earlier decay onset. Meanwhile, fennel oil demonstrated promising preservation ability in this variety, with zero decay until the final date.

- **For Felfel Arbi light wight**

The table 15 presents the number of decayed fruits per box, with the average calculated from two replicates for each type of essential oil.

Table 15: Rate of decay in hot pepper (Felfel Arbi light weight) treated with different essential oils during storage

The date	Control	Wormwood	Rosemary
25/03/2025	0	0	0
26/03/2025	0	0	0
27/03/2025	0	0	0
28/03/2025	0	0	0

29/03/2025	0	0	0
01/04/2025	1	0	0.5
10/04/2025	2	1	1.5

Control (Untreated): Decay was first observed on April 1 (score: 1), increasing to 2 by April 10. This progression highlights natural deterioration over time in the absence of any treatment.

Artemisia herba-alba (Wormwood): No decay was recorded until the final date, where a mild score of 1 was observed. Compared to the control, wormwood delayed the onset of decay and reduced its intensity, suggesting a moderate protective effect.

Rosmarinus officinalis (Rosemary): Similarly, no symptoms appeared before April 1, with a decay score of only 0.5 on that date, rising to 1.5 by April 10. While rosemary did not completely inhibit spoilage, the overall decay remained lower than the untreated group.

Both wormwood and rosemary demonstrated a protective effect against decay in Felfel Arbi light weight. Wormwood showed slightly better performance in delaying spoilage onset, whereas rosemary limited the severity of decay. However, neither treatment fully prevented decay by day 16.

- **For Lemon**

The table 16 presents the number of decayed fruits per box, with the average calculated from two replicates for each type of essential oil.

Table 16: Rate of decay in lemon treated with different essential oils during storage

Date	control	Wormwood	Rosemary	Thyme	Fennel
27/03/2025	0	0	0	0	0
31/03/2025	0	0.5	0	0	0
11/04/2025	1	1.5	0.5	1	0
20/04/2025	2	2.5	2.5	1.5	0.5

Control (no essential oil): No mold until 31/03. Reached score 2 on 20/04. Shows progressive fungal development without treatment.

Wormwood (*Artemisia herba-alba*): Early increase starting from 31/03. Reached 2.5, highest level among all treatments. Least effective; even worse than the control.

Rosemary (*Rosmarinus officinalis*): No mold until 31/03, then a delayed increase. Jumped to 2.5 by 20/04, same as wormwood. Not effective, failed to significantly reduce fungal decay.

Thyme (*Thymus vulgaris*): Mold appeared only after 11/04. Reached 1.5 at the end. Moderately effective, better than control and rosemary.

Fennel (*Foeniculum vulgare*): No mold until 11/04. Only 0.5 by 20/04. Most effective, strongly limited fungal growth.

2.3. Weight loss

Fruit weight was monitored daily throughout the storage period using an electronic scale. Measurements were taken on designated dates for each case (Case 1 and Case 2), and the average of the two repetitions was calculated for each treatment. This regular monitoring enabled accurate tracking of weight reduction, which reflects moisture loss and dehydration. By analyzing these daily variations, the effectiveness of different treatments in minimizing weight loss during storage was assessed.

- **For Messaouda pepper**

The table 17 presents the weights recorded at different time points during storage for each box. The values represent the mean weight (in grams) for each type treatment.

Table 17: Postharvest weight loss of sweet pepper (Messaouda Variety) under essential oil treatments during storage

Date	Control	Wormwood	Rosemary	Thyme	Fennel
26/03/2025	1092	1163	1137.5	1381	1456
27/03/2025	1060	1140.5	1121.5	1360.5	1438.5
28/03/2025	1038	1101.5	1097	1337.5	1414
29/03/2025	1006	1069.5	1066.5	1319.5	1378.5
30/03/2025	979	1046.5	1038	1278	1343.5
03/04/2025	899	979	940.5	1194.5	1267.5
10/04/2025	783	878.5	854	1085	1170

The control group started at 1092 g on 26/03/2025 and decreased to 783 g by 10/04/2025. This indicates a total weight loss of 309 g, which is approximately 28.29% of the initial weight.

Wormwood: From 1163 g to 878.5 g. Total loss: 284.5 g (24.46%). Rosemary: From 1137.5 g to 854 g. Total loss: 283.5 g (24.92%). Thyme: From 1381 g to 1085 g. Total loss: 296 g (21.44%). Fennel: From 1456 g to 1170 g. Total loss: 286 g (19.64%).

All essential oils helped in slowing down weight loss compared to the control. Fennel oil showed the best performance, with the lowest percentage of weight loss.

Essential oils, particularly fennel and thyme, were effective in reducing postharvest weight loss in sweet pepper (Messaouda variety).

- **For Garn Ghezal pepper**

The table 18 presents the weights recorded at different time points during storage for each box. The values represent the mean weight (in grams) for each type treatment.

Table 18: Postharvest weight loss of Garn Ghezal under essential oil treatments during storage

Date	Control	Wormwood	Rosemary	Thyme	Fennel
25/03/2025	895	880.5	923.5	1090.5	1130
26/03/2025	862	853.5	908.5	1077	1103.5
27/03/2025	832	826	865	1052	1067.5
28/03/2025	793	786.5	819	1002	1026
29/03/2025	766	761	788.5	964.5	991
05/04/2025	596	616.5	630	838	852
10/04/2025	498	522.5	510	697	748.5

Control Box: Initial weight (25/03/2025): 895 g Final weight (10/04/2025): 498 g Total weight loss: 397 g, representing approximately 44.36% of the initial weight. Essential Oil Treatments: Wormwood (Artemisia herba-alba): From 880.5 g to 522.5 g Weight loss: 358 g (40.67%) Rosemary (Rosmarinus officinalis): From 923.5 g to 510 g Weight loss: 413.5 g (44.78%) Thyme (Thymus vulgaris): From 1090.5 g to 697 g Weight loss: 393.5 g (36.08%) Fennel (Foeniculum vulgare): From 1130 g to 748.5 g Weight loss: 381.5 g (33.75%).

Although all treatments showed weight loss during the storage period, the application of essential oils helped to reduce this loss compared to the control box. Fennel oil was the most effective in minimizing postharvest weight loss, followed by thyme oil as the second-best treatment. Rosemary oil, on the other hand, was not effective and even recorded the highest weight loss percentage, exceeding that of the control.

Essential oils, especially fennel and thyme, demonstrated promising potential in reducing postharvest weight loss in spicy pepper of the Garn Ghazal variety.

- **For Felfel Arbi heavy weight**

The table 19 presents the weights recorded at different time points during storage for each box. The values represent the mean weight (in grams) for each type treatment.

Table 19: Postharvest weight loss of Felfel Arbi heavy weight under essential oil treatments during storage

Date	Control	Thyme	Fennel
25/03/2025	1130	1079.5	1080.5
26/03/2025	1111	1060	1064.5
27/03/2025	1086	1035.5	1036.5
28/03/2025	1060	1010.5	1007.5
29/03/2025	1032	983.5	982.5
01/04/2025	1000	957	961
10/04/2025	925	887.5	897

Initial and Final Weights: Control Box: Initial weight (25/03/2025): 1130 g Final weight (10/04/2025): 925 g Weight loss: 205 g (18.14%) Thyme (Thymus vulgaris): Initial: 1079.5 g Final: 887.5 g Weight loss: 192 g (17.78%) Fennel (Foeniculum vulgare): Initial: 1080.5 g Final: 897 g Weight loss: 183.5 g (16.98%)

Both thyme and fennel essential oils contributed to reducing weight loss compared to the control box. Fennel oil showed the best performance, resulting in the lowest weight loss percentage. The thyme treatment also performed slightly better than the control.

The results indicate that essential oils, particularly fennel oil, can play a role in minimizing postharvest weight loss in Felfel Arbi (Heavy Weight). This suggests their potential as natural alternatives to synthetic preservation methods for maintaining the quality of peppers during storage.

- **For Felfel Arbi light wight**

The table 20 presents the weights recorded at different time points during storage for each box. The values represent the mean weight (in grams) for each type treatment.

Table 20: Postharvest weight loss of Felfel Arbi light weight under essential oil treatments during storage

Date	Control	Wormwood	Rosemary
25/03/2025	595	595	595
26/03/2025	565	568	569
27/03/2025	533	539	543
28/03/2025	505	512.5	514
29/03/2025	474	479.5	478
01/04/2025	403	410.5	399
10/04/2025	255	270	263

Initial weight (25 March) was identical for all samples (595 g). Throughout the storage period, the control group experienced the greatest loss in weight. On 10 April, final weights were: Control: 255 g Wormwood: 270 g Rosemary: 263 g.

Wormwood consistently preserved more weight compared to control and rosemary. Rosemary showed moderate preservation but slightly less effective than wormwood by the end.

Wormwood essential oil showed the best preservation effect on pepper weight. Rosemary was moderately effective. Control showed the highest weight loss, highlighting the role of essential oils in reducing water loss or degradation.

- **For Lemon**

The table 21 presents the weights recorded at different time points during storage for each box. The values represent the mean weight (in grams) for each type treatment.

Table 21: Postharvest weight loss of lemon under essential oil treatments during storage

Date	Control	Wormwood	Rosemary	Thyme	Fennel
27/03/2025	2327	2450.5	2121.5	2425	2316
31/03/2025	2293	2405	2083	2385	2258.5

11/04/2025	2181	2242	1975	2248.5	2125.5
20/04/2025	2075	2123.5	1881	2141.5	1993.5

Control (No Treatment): Initial weight (27/03/2025): 2327 g Final weight (20/04/2025): 2075 g Total weight loss: 252 g (10.83%) Wormwood (Artemisia herba-alba): Initial weight: 2450.5 g Final weight: 2123.5 g Weight loss: 327 g (13.34%) Rosemary (Rosmarinus officinalis): Initial weight: 2121.5 g Final weight: 1881 g Weight loss: 240.5 g (11.34%) Thyme (Thymus vulgaris): Initial weight: 2425 g Final weight: 2141.5 g Weight loss: 283.5 g (11.69%) Fennel (Foeniculum vulgare): Initial weight: 2316 g Final weight: 1993.5 g Weight loss: 322.5 g (13.93%).

The control group exhibited the least weight loss, suggesting that natural dehydration occurred more slowly without essential oil treatment in this case. Rosemary had the second-lowest weight loss percentage (11.34%), followed closely by thyme (11.69%). Fennel and wormwood recorded the highest weight losses, above 13%, indicating they were less effective in preserving lemon weight.

In this trial, rosemary oil showed relatively better performance in limiting weight loss in lemons, although the control box had the best result. This suggests that essential oils, under the tested conditions, may not significantly reduce weight loss in lemons.

3. Discussions of experimental results

3.1. Wilting

Wilting, driven primarily by moisture loss and turgor pressure decline, was observed to progressively intensify across all fruit samples during storage a well-established postharvest physiological response linked to continued respiration and transpiration processes (Kader, 2002). However, the application of essential oils resulted in notably lower wilting rates compared to untreated controls, indicating that EOs can partially mitigate this deterioration under storage conditions.

Among the tested treatments, thyme and rosemary essential oils stood out as the most effective, particularly during the early phases of storage. This effect can be attributed to the hydrophobic nature and semi-permeable film-forming capacity of the oils, which likely functioned as a barrier to water vapor diffusion, thereby reducing transpirational moisture loss (Rai *et al.,* 2016). Such films may operate similarly to edible coatings, creating a modified microenvironment around the fruit surface.

Additionally, the high antioxidant content of these oils especially compounds like thymol, carvacrol, and rosmarinic acid may have played a role in preserving membrane integrity by counteracting oxidative stress. Oxidative damage is a known contributor to cellular breakdown and tissue collapse during storage (Burt, 2004). Notably, rosemary essential oil has been reported to enhance antioxidant defense responses and reduce reactive oxygen species (ROS) accumulation in stressed plant tissues (Saltveit, 1996).

3.2. Color Change

Color change in fruits and vegetables during storage is a critical indicator of ripening, senescence, and overall postharvest quality degradation. This phenomenon is primarily driven by chlorophyll breakdown and the biosynthesis or transformation of secondary pigments, notably carotenoids and anthocyanins (J. Gross, 1991). These pigment transitions are strongly influenced by ethylene biosynthesis, respiration rate, and oxidative stress, all of which intensify under suboptimal storage conditions.

In the present study, essential oil treatments were observed to delay color development to varying degrees, particularly during the early and mid-stages of storage. This inhibitory effect can be attributed to the bioactive properties of the applied EOs, especially thyme which is rich in antioxidant compounds.

Thyme oil contains thymol and carvacrol, which have well-documented abilities to scavenge reactive oxygen species (ROS) and suppress lipid peroxidation (Bajpai *et al.,* 2012 ; Nieto *et al.,* 2018). Since ROS generation is a key trigger for chlorophyll degradation and the breakdown of pigment-containing membranes, the presence of these antioxidants likely stabilized pigment structures and delayed the onset of chromatic shifts that signal senescence.

Furthermore, these oils may indirectly influence ethylene sensitivity or synthesis pathways, though the exact molecular interactions remain speculative. By maintaining membrane integrity and slowing oxidative stress cascades, EOs create a less conducive internal environment for enzymatic pigment degradation.

It is also worth noting that the effectiveness of EOs varied by crop and cultivar. For example, the Garn Ghezal hot pepper and the Messaouda sweet pepper showed better pigment retention with fennel oil, while light-weight Felfel Arbi peppers exhibited faster degradation even with treatments, particularly under rosemary. These differences are likely due to varietal disparities in:

• Cuticle permeability, which influences EO absorption and vapor diffusion,

• Intrinsic pigment composition, such as total chlorophyll and carotenoid content,

• Baseline antioxidant capacity, which modulates the fruit's response to oxidative stimuli.

In conclusion, while all tested essential oils exhibited some capacity to moderate color change, fennel and thyme showed the most consistent results across cultivars. Nevertheless, the impact of EOs on color preservation is complex, influenced by both chemical composition and crop-specific physiological traits, underscoring the need for tailored postharvest strategies.

3.3. Decay

Among the various postharvest quality parameters assessed, decay progression emerged as the most critical concern especially during the latter stages of storage, when microbial colonization intensifies under prolonged exposure to ambient or semi-controlled conditions. As anticipated, the untreated control groups across all fruit types demonstrated substantial decay incidence, highlighting the vulnerability of fresh produce to fungal and bacterial spoilage in the absence of protective interventions.

In contrast, fruits treated with essential oils exhibited notably reduced decay levels, with thyme and wormwood oils demonstrating the most effective antimicrobial performance. These findings are consistent with established literature, where thyme oil’s high content of thymol and carvacrol has been repeatedly shown to inhibit a broad range of foodborne pathogens and spoilage organisms, including *Botrytis cinerea*, *Penicillium* spp., and *Alternaria* spp. (Hyldgaard *et al.,* 2012 ; Tzortzakis, 2024). Wormwood oil, though less studied, also proved effective. Its activity is attributed to a diverse phytochemical profile including artemisinin, thujone, camphor, and sesquiterpene lactones, all of which possess strong antifungal and bacteriostatic properties (Tomás-Barberán & Espín, 2001). The mechanism of action likely involves inhibition of spore germination, alteration of membrane permeability, and disruption of mitochondrial function in pathogens colonizing the fruit surface.

The extent of protection provided by these EOs appears to depend not only on their chemical composition but also on the vapor-phase diffusion delivery method used in this study. This method allowed for continuous release of volatile compounds, which likely maintained a localized antimicrobial environment within the fruit crates an advantage over direct surface treatments that are more prone to uneven distribution or rapid dissipation.

The lemon samples exhibited overall greater resistance to decay compared to all pepper varieties, regardless of EO treatment. This can be attributed to multiple intrinsic defense factors in citrus fruits:

• A thicker and waxier cuticle, which provides a physical barrier to microbial entry;

• Higher citric acid content, which lowers surface pH and inhibits pathogen growth;

• Presence of natural antifungal constituents in the peel, such as limonene, flavonoids, and phenolic acids (Tripathi & Dubey, 2004). When EO treatment was combined with these natural defenses, a synergistic effect likely occurred, enhancing lemon's shelf life and resistance to microbial deterioration beyond what either strategy could achieve alone.

Conversely, peppers especially those with thinner cuticles or higher surface moisture content were more susceptible to rapid fungal colonization, particularly when stored at ambient temperature. The variation in decay rate among pepper types also reflected differences in cultivar resilience, fruit morphology, and initial microbial load.

In conclusion, the data validate the antimicrobial efficacy of thyme essential oil in postharvest decay control, particularly when applied in a vapor-phase delivery system. The integration of EO treatment with crop-specific physiological advantages, as seen with lemons, offers a promising and eco-friendly alternative to synthetic fungicides for enhancing the postharvest stability of perishable horticultural commodities.

3.4. Weight Loss

Weight loss is a critical postharvest quality indicator, tightly linked to both transpiration and respiration, and significantly impacts marketability, texture, and visual appeal of fresh produce. In this study, weight reduction was observed across all samples during storage, with variation in intensity depending on fruit type, storage conditions, and essential oil (EO) treatment.

3.4.1. Mechanisms of Weight Loss

Primarily, weight loss in stored fruits and vegetables occurs due to:

• Water loss through transpiration, which leads to wilting and surface shrinkage.

• Carbon loss through respiration, where stored sugars and organic acids are metabolized, releasing CO_2 and water vapor.

Both processes are temperature and humidity-dependent, and are accelerated under ambient storage compared to refrigerated conditions, as seen with peppers versus lemons in this study (Kader, 2002).

3.4.2. EO Effects on Weight Loss

Fruits treated with essential oils exhibited moderated weight loss compared to controls. This may be attributed to:

• The hydrophobic barrier formed by EO vapors, which limits moisture diffusion from the fruit surface.

• The antioxidant properties of oils like thyme and rosemary, which may stabilize cell membranes and reduce electrolyte leakage and water loss (Burt, 2004 ; Ben Saad *et al.,* 2024).

• Possible reduction in respiration rates due to EO-induced mild stress signaling, which can slow metabolic activity and delay senescence (Tzortzakis, 2024).

Among the tested oils, fennel and thyme showed relatively strong performance in reducing weight loss consistent with their efficacy in wilting and decay control. Conversely, treatments with wormwood and rosemary produced variable effects, with rosemary at times accelerating desiccation, likely due to phytotoxic interactions or overconcentration of volatiles.

3.4.3. Fruit-Specific Variability

Peppers (especially light-weight Felfel Arbi) demonstrated higher relative weight loss, attributable to their thin cuticle, high surface-to-volume ratio, and storage under non-refrigerated conditions, which promote water evaporation and metabolic activity.

Lemons, while having a thicker rind and being stored under cold conditions, still exhibited weight reduction especially in EO-treated samples suggesting that EO interaction with the porous lemon peel may have compromised epidermal integrity, enhancing transpirational water loss (Valero & Serrano, 2010 ; Munir *et al.,* 2024).

3.4.4. Adverse Outcomes in Some EO Treatments

In several lemon samples, particularly those exposed to high EO concentrations, weight loss was comparable or worse than the control, which may reflect:

- Cuticle degradation and increased permeability due to EO compounds like thujone or limonene.
- Accelerated transpiration caused by localized tissue damage or chemical burns (Miguel, 2010 ; Turek & Stintzing, 2013).
- Rapid volatilization of EOs, failing to maintain a stable microenvironment around the fruit, thus offering only transient protection.

Weight loss, much like wilting and decay, is a multifactorial outcome shaped by the interplay of fruit physiology, EO chemistry, and environmental conditions. While certain EOs (notably thyme and fennel) offer protective benefits, their effects are highly dependent on dosage, delivery method, and fruit-specific tolerance. As with decay and color preservation, weight retention through EO treatment demands precision in formulation and deployment, particularly for sensitive fruits like lemon.

3.5. Discussion on Interaction Effects and Variability

The outcomes of this study revealed complex interaction effects between essential oil (EO) type, fruit variety, and storage duration, influencing all key quality parameters wilting, color change, and decay. These interactions underscore the non-uniform and dynamic behavior of natural treatments in postharvest systems and highlight the need for context-specific optimization.

Notably, certain essential oils demonstrated time-dependent efficacy. For instance, rosemary oil showed better results during the early storage period, while thyme oil maintained its antimicrobial and antioxidant activity longer into storage. This variation may reflect differences in volatility, chemical degradation rates, and the rate of controlled vapor-phase release from the application medium (Bakkali *et al.,* 2008). Such volatility-dependent behavior is especially important in the context of indirect contact methods, where sustained release governs the protective effect.

3.5.1. Variability Between Cultivars

A consistent and noteworthy observation throughout the study was the significant variability in response between different pepper cultivars to identical essential oil treatments. For instance, varieties such as Garn Ghezal, Felfel Arbi (light and heavy types), and Messaouda displayed markedly different patterns of wilting, color change, decay, and weight loss, even when stored under the same environmental conditions and treated with the same EO at equal dosages.

This differential response highlights the critical role of intrinsic varietal characteristics in modulating postharvest behavior. Several physiological, anatomical, and biochemical features are likely responsible for these discrepancies:

A) Cuticle Thickness and Composition

The cuticle acts as a primary barrier against water loss, microbial invasion, and external chemical absorption. Cultivars with thicker or more structured cuticles (e.g., high cutin and wax content) may be less permeable to EO volatiles, resulting in a slower and more controlled absorption of antimicrobial compounds. Conversely, cultivars with thinner cuticles or more porous structures may absorb EO components more rapidly, which can either enhance efficacy or lead to phytotoxic effects, depending on the oil's potency (Parsons *et al.,* 2012 ; Lara *et al.,* 2019).

B) Epidermal Cell Architecture

Variations in epidermal cell shape, size, and arrangement influence the mechanical strength and permeability of the fruit surface. Cultivars with tighter, denser epidermal layers may exhibit greater resistance to dehydration and microbial ingress, while others with looser surface architecture are more vulnerable to rapid wilting and infection factor that may explain why Felfel Arbi (light weight) showed more rapid deterioration compared to its heavier counterpart (Brizzolara *et al.,* 2020 ; Santos *et al.,* 2023).

C) Surface Microstructure and Wax Morphology

The epicuticular wax layer plays a key role in modulating fruit-environment interactions. Differences in wax crystal morphology, such as platelets, tubes, or amorphous forms, affect surface hydrophobicity and EO adhesion. Some cultivars may allow better retention of volatile oil compounds, prolonging their antimicrobial activity on the fruit surface, while others may exhibit poor adhesion and reduced efficacy (Szakiel *et al.,* 2012 ; Rebora *et al.,* 2020).

D) Stomatal Density and Orientation

Higher stomatal density or horizontal stomatal orientation on the fruit surface may accelerate transpiration and gas exchange, making certain cultivars more susceptible to rapid weight loss and wilting, especially under ambient conditions. This anatomical trait also impacts the absorption and diffusion of EO vapors into internal tissues (Lufu *et al.,* 2020 ; Chua & Lau, 2024).

E) Biochemical Defense Mechanisms

Cultivar-specific differences in endogenous antioxidant capacity, phenolic content, and natural antimicrobial compounds influence how a fruit responds to oxidative stress and microbial challenge. Some varieties may possess stronger intrinsic defenses, enabling synergistic action with applied EOs, while others may be more dependent on external treatments to maintain postharvest quality (Cheng *et al.,* 2025).

F) Fruit Size and Surface Area-to-Volume Ratio

Smaller fruits or those with higher surface area relative to volume (e.g., Felfel Arbi light type) are more prone to rapid water loss, faster EO absorption, and greater exposure to oxidative degradation. These physical traits may amplify the effects positive or negative of EO treatments (Díaz-Pérez *et al.,* 2007).

The efficacy of essential oil treatments cannot be generalized across cultivars. Even under standardized treatment conditions, pepper varieties demonstrate distinct postharvest responses, shaped by their morphological, anatomical, and biochemical make-up. This finding underscores the necessity of tailoring postharvest treatments including EO type, concentration, and application method to the specific physiological profile of each cultivar. Failure to do so may compromise effectiveness or inadvertently cause damage, particularly in sensitive or high-transpiration varieties.

3.6. Unexpected Outcomes and Limitations

In certain cases, particularly with lemon samples, EO-treated boxes yielded similar or worse results than the untreated controls. These outcomes raise valid concerns regarding the potential adverse effects of high EO concentrations or suboptimal application techniques.

3.6.1. High Concentration Effects

While higher concentrations are often presumed to offer greater antimicrobial efficacy, the reality is more nuanced. Excessively concentrated EOs can cause:

• Rapid evaporation of volatiles, shortening their effective duration.

• Phytotoxicity, including cuticle damage, tissue burns, and increased water loss.

• Accelerated fruit senescence, including shrinkage, color degradation, and surface lesions (Burt, 2004 ; Turek & Stintzing, 2013 ; Ummarat & Seraypheap, 2021; Barreto *et al.,* 2023).

3.6.2. Application Method and Vapor Distribution

Despite using tulle-wrapped paper tissues to avoid direct oil-to-fruit contact, occasional leakage or high vapor concentration may have caused:

• Localized surface burns, especially in thin-skinned fruits like some pepper varieties.

• Uneven distribution of volatiles, creating zones of under- or over-exposure (Bakkali *et al.,* 2008 ; Turek & Stintzing, 2013).

3.6.3. Storage Environment Sensitivity

Environmental conditions within storage containers including oxygen levels, humidity, light exposure, and temperature directly influence EO stability and effectiveness:

High temperatures and oxygen can promote EO degradation and reduce antimicrobial potency.

Closed systems risk creating anaerobic microenvironments or condensation, both of which can stress the fruit or accelerate spoilage (Miguel, 2010 ; Hyldgaard *et al.,* 2012 ; Turek & Stintzing, 2013 ; Tongnuanchan & Benjakul, 2014).

3.6.4. Case Study: Lemon Variability and Sensitivity

Lemons exhibited unique sensitivity to EO application, often responding poorly unless combined with protective agents. Literature suggests that lemon essential oil alone is insufficient to maintain postharvest quality, whereas combined treatments with chitosan, calcium chloride, or natamycin offer better outcomes (Burt, 2004 ; Zhang *et al.,* 2022).

Several fruit-specific factors explain lemon's vulnerability:

• Peel Composition and Reactivity

The lemon rind is rich in volatile compounds like limonene, and its high porosity can facilitate deep EO penetration. This may trigger oxidative degradation of peel components or chemical interactions due to the fruit's low pH (2–3), leading to surface damage (Nguyen *et al.,* 2009 ; Valero & Serrano, 2010 ; Jentzsch *et al.,* 2024 ; Munir *et al.,* 2024).

• Water Content and Wilting Risk

Lemons possess high water content, and damage to the epidermis from concentrated EOs can accelerate moisture loss, resulting in wilting, weight reduction, and increased microbial susceptibility (Ghanem *et al.,* 2012).

These findings highlight that essential oil efficacy is not universal. Their application must consider:

• Volatility and degradation kinetics

• Fruit-specific anatomy and physiology

• Appropriate dosage and delivery mechanisms

• Storage microenvironmental control

Failure to optimize these variables may negate benefits or even worsen postharvest quality. Thus, EO-based preservation strategies should be precisely tailored to the target commodity, using synergistic combinations and controlled-release systems to achieve consistent, scalable, and safe results.

Conclusion

This study set out to evaluate the preservative and antimicrobial potential of essential oils extracted from thyme, fennel, wormwood, and rosemary in mitigating postharvest physiological and microbial deterioration in peppers and lemons, two economically and nutritionally important horticultural products in Algeria. By combining a comprehensive field survey in the Biskra region with controlled experimental trials, the research provided both contextual and empirical insights into the challenges and possibilities of EO-based preservation.

The field investigation highlighted widespread issues contributing to postharvest spoilage: mechanical injuries during harvesting and transport, exposure to high humidity and unsuitable storage temperatures, cross-contamination through packaging or infected fruits, and delayed marketing. The interviews with farmers, vendors, and agronomists further underscored the absence of sustainable and non-toxic preservation strategies at the smallholder level providing strong justification for the search for eco-friendly, plant-based alternatives.

Laboratory findings revealed notable variability in the effectiveness of essential oils, driven by factors such as fruit type, cultivar characteristics, EO composition, concentration, and storage conditions. While thyme and fennel oils demonstrated moderate efficacy in reducing wilting and weight loss likely due to their antioxidant and semi-permeable film-forming properties their impact on color retention and decay control was inconsistent. In several cases, EO treatments produced results comparable to or even worse than the control, especially in lemons, where higher EO concentrations may have triggered phytotoxic effects or accelerated tissue degradation.

Wormwood and rosemary oils, despite containing biologically active compounds, generally showed limited or counterproductive effects, likely due to volatility, high reactivity, or incompatibility with fruit surface physiology. These outcomes reinforce a critical finding: essential oils are not universally effective and can pose risks if improperly formulated or applied.

Importantly, the study identified strong varietal-dependent responses, particularly among different pepper cultivars, which varied in their tolerance to EO treatments based on surface anatomy, wax composition, and water retention capacity. This underscores the necessity of fruit-specific preservation protocols, tailored to the microstructural and biochemical properties of the produce.

Overall, this research suggests that essential oils hold promise as natural postharvest agents, but their efficacy is highly context-dependent. Key variables concentration, exposure time, delivery system, cultivar sensitivity, and environmental conditions must be meticulously calibrated. Furthermore, the risks of over-application including tissue damage, moisture loss, or accelerated decay should not be overlooked.

Perspectives:

- Future studies should explore synergistic combinations of essential oils with other natural preservatives such as chitosan, organic acids, or plant-based waxes, which may enhance stability and spectrum of action.
- Research should also consider encapsulation technologies (e.g., nanoemulsions or slow-release films) to control EO volatility and extend efficacy over longer storage periods.
- Sensory evaluation and consumer acceptability testing should be integrated to ensure that EO treatments do not negatively affect taste, aroma, or visual appeal.
- Finally, there is a need to scale up experimental results to pilot and commercial levels, assessing feasibility in real-world logistics, market demands, and regulatory frameworks.

Final Reflection:

By integrating traditional agricultural knowledge, on-the-ground realities, and laboratory experimentation, this study contributes to the development of sustainable, low-cost, and safe preservation methods suitable for Algerian producers. It affirms the potential of essential oils not as universal solutions, but as strategically deployable tools within a broader system of postharvest management and food safety. With careful optimization, essential oils could support the shift toward chemical-free, environmentally responsible agriculture, aligning with both consumer health trends and national food security goals.

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Annexes

Annex 1: Observation tables of pepper and lemon varieties

Date	Control	Thyme (*Thymus vulgaris*)		Fennel (*Foeniculum vulgare*)	
		Replay No. 1	Replay No. 2	Replay No. 1	Replay No. 2
25/03/2025					
27/03/2025					
29/03/2025					
03/04/2025					

10/04/2025					

Date	Control	wormwood (*Artemisia herba-alba*)		rosemary (*Rosmarinus officinalis*)	
		Replay No. 1	Replay No. 2	Replay No. 1	Replay No. 2
25/03/2025					
26/03/2025					
27/03/2025					
28/03/2025					

					
29/03/2025					
30/03/2025					
03/04/2025					
10/04/2025					

Date	Control	Thyme (*Thymus vulgaris*)		Fennel (*Foeniculum vulgare*)	
		Replay No. 1	Replay No. 2	Replay No. 1	Replay No. 2
25/03/2025					
27/03/2025					
29/03/2025					
05/04/2025					

10/04/2025					

Date	Control	Wormwood (*Artemisia herba-alba*)		Rosemary (*Rosmarinus officinalis*)	
		Replay No. 1	Replay No. 2	Replay No. 1	Replay No. 2
25/03/2025					
26/03/2025					
27/03/2025					

28/03/2025					
29/03/2025					
05/04/2025					
10/04/2025					

Hot pepper: Felfel Arbi (Light-weight type)					
Date	Control	Wormwood (*Artemisia herba-alba*),		Rosemary (*Rosmarinus officinalis*)	
		Replay No. 1	Replay No. 2	Replay No. 1	Replay No. 2

25/03/2025					
26/03/2025					
27/03/2025					
28/03/2025					
29/03/2025					

01/04/2025					
10/04/2025					

Hot pepper : Felfel Arbi (Heavy-weight type)					
Date	Control	Wormwood (*Artemisia herba-alba*),		Rosemary (*Rosmarinus officinalis*)	
		Replay No. 1	Replay No. 2	Replay No. 1	Replay No. 2
25/03/2025					
27/03/2025					

29/03/2025					
01/04/2025					
10/04/2025					

Date	Control	Wormwood (*Artemisia herba-alba*),		Rosemary (*Rosmarinus officinalis*)	
		Replay No. 1	Replay No. 2	Replay No. 1	Replay No. 2
27/03/2025					
31/03/2025					

					
11/04/2025					
20/04/2025					

Date	Control	Thyme (*Thymus vulgaris*)		Fennel (*Foeniculum vulgare*)	
		Replay No. 1	Replay No. 2	Replay No. 1	Replay No. 2
27/03/2025					

31/03/2025					
11/04/2025					
20/04/2025					

الملخص

تتناول هذه الدراسة استخدام الزيوت الأساسية المستخلصة من أربع نباتات عطرية الزعتر(*Thymus vulgaris*) ، البسباس(*Foeniculum vulgare*) ، الشيح (*Artemisia herba-alba*)، وإكليل الجبل (*Rosmarinus officinalis*) في الحد من التلف الذي يصيب الفلفل والليمون أثناء التخزين بعد الحصاد.

تضمنت الدراسة تحقيقًا ميدانيًا مفصلًا في ولاية بسكرة، وتجارب مخبرية تم فيها تقييم فعالية الزيوت من خلال تتبع فقدان الوزن، الذبول، تغير اللون، والعفن.

تم استخلاص الزيوت الأساسية باستعمال التقطير المائي والبخاري، وتطبيقها على عدة أصناف من الفلفل والليمون تحت ظروف تخزين مضبوطة وطبيعية. أظهرت النتائج تباينًا في الفعالية حسب نوع الزيت والثمرة والمعيار المقاس. أبدى كل من الزعتر والبسباس أداءً واعدًا في بعض الاختبارات، لكنه كان غير ثابت وأحيانًا أقل من الشاهد. بينما سجل كل من الشيح وإكليل الجبل فعالية محدودة أو سلبية.

تبرز هذه الدراسة الإمكانات الواعدة للزيوت الأساسية كبدائل طبيعية للمواد الحافظة الكيميائية، مع ضرورة إجراء أبحاث إضافية لتحسين استخدامها وصيغتها ضمن تطبيقات حفظ المنتجات الفلاحية الطازجة بعد الحصاد.

الكلمات المفتاحية: الزيوت الأساسية، الفلفل، الليمون، النشاط المضاد للميكروبات، تلف ما بعد الحصاد، مستخلصات نباتية

Abstract

This study investigates the use of essential oils extracted from four aromatic plants; thyme (*Thymus vulgaris*), fennel (*Foeniculum vulgare*), wormwood (*Artemisia herba- alba*), and rosemary (*Rosmarinus officinalis*), to reduce spoilage in peppers and lemons during postharvest storage.

The research included a detailed field investigation in Biskra Province and laboratory experiments that assessed oil effectiveness using weight loss, wilting, color change, and microbial decay as indicators. Essential oils were extracted through hydrodistillation and steam distillation, and applied to different pepper and lemon varieties stored under controlled and ambient conditions.

The results demonstrated variable efficacy depending on the oil type, fruit variety, and evaluation parameter. While thyme and fennel showed relatively promising performance in some tests, their effects were inconsistent and occasionally inferior to the control. Wormwood and rosemary exhibited limited or negative preservation effects.

This study highlights the potential of essential oils as eco-friendly alternatives to synthetic preservatives but also emphasizes the need for further research to optimize their use and formulation for reliable postharvest application in fresh produce preservation.

Keywords : Essential oils, peppers, lemons, antimicrobial activity, postharvest spoilage, plant extracts.

Résumé

Cette étude porte sur l'utilisation des huiles essentielles extraites de quatre plantes aromatiques le thym (*Thymus vulgaris*), le fenouil (*Foeniculum vulgare*), l'armoise blanche (*Artemisia herba-alba*) et le romarin (*Rosmarinus officinalis*) pour réduire l 'altération des poivrons et des citrons pendant le stockage post-récolte.

Le travail comprend une enquête de terrain approfondie dans la wilaya de Biskra ainsi que des essais en laboratoire, évaluant l'efficacité des huiles selon la perte de poids, le flétrissement, le changement de couleur et la pourriture microbienne. Les huiles essentielles ont été extraites par hydrodistillation et distillation à la vapeur, puis appliquées à différentes variétés de poivrons et de citrons conservés dans des conditions ambiantes ou réfrigérées.

Les résultats ont montré une efficacité variable en fonction du type d'huile, de la variété de fruit et du paramètre évalué. Le thym et le fenouil ont montré une certaine efficacité, mais leurs effets étaient parfois instables ou inférieurs au témoin. L'armoise et le romarin ont présenté des effets limités ou négatifs.

Cette étude souligne le potentiel des huiles essentielles comme alternatives écologiques aux conservateurs chimiques, tout en insistant sur la nécessité de recherches supplémentaires pour optimiser leur application dans la conservation post- récolte des fruits et légumes frais.

Mots-clés : Huiles essentielles, poivrons, citrons, activité antimicrobienne, altération post-récolte, extraits de plantes.

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