# Plant-Derived Hydrosols From Agricultural Waste as Natural Preservatives For Improving The Shelf Life of Fresh Fruits and Vegetables

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## ABSTRACT

Reducing post-harvest losses of fresh fruits and vegetables remains a major challenge because conventional preservation methods often rely on synthetic chemicals that raise environmental and consumer safety concerns. This study explored the use of plant-derived hydrosols as sustainable natural preservatives for extending the shelf life of fresh produce. Hydrosols were prepared from ginger (*Zingiber officinale*), orange peel (*Citrus sinensis*), guava leaves (*Psidium guajava*), and yellow bell flower (*Tecoma stans*) through steam distillation. UV–Visible spectrophotometric analysis at 280 nm served as a rapid screening method to compare the phytochemical richness of the hydrosols. Ginger hydrosol exhibited the highest absorbance (1.2014), followed by orange peel (0.8491), guava leaf (0.3269), and

*T. stans* (0.1009). Based on these results, two hydrosol formulations were developed: ginger–orange peel (1:1, v/v) and guava leaf–ginger (2:1, v/v), while *T. stans* was excluded because of its comparatively low absorbance and less desirable sensory characteristics.

The formulations were applied to tomato, grapes, capsicum, and cucumber and evaluated under ambient storage conditions for three days. Compared with untreated controls, the treated samples retained better colour, firmness, and overall appearance, showed reduced fungal growth, and experienced lower moisture loss. Cucumber treated with the hydrosol formulations maintained a darker green colour and exhibited only minimal fungal development, whereas the untreated control showed extensive spoilage. In addition to demonstrating the preservative potential of plant hydrosols, this work highlights an effective strategy for converting discarded orange peels into a value-added product, supporting sustainable waste valorisation and circular bioeconomy practices. These preliminary findings suggest that hydrosol-based formulations could provide an eco-friendly alternative to synthetic preservatives for short-term post-harvest preservation of fresh produce. Further validation through replicated trials, microbiological studies, and detailed phytochemical characterisation is required before commercial application.

**Keywords:** Hydrosols; natural preservatives; post-harvest preservation; agricultural waste; orange peel; ginger; shelf-life extension; circular bioeconomy; sustainable food preservation.

## INTRODUCTION

Vegetables and fruits undergo rapid quality deterioration after harvest because microorganisms proliferate on their surfaces, moisture is lost through transpiration, and natural biochemical processes continue during storage. These changes reduce marketable quality, shorten shelf life, and result in substantial post-harvest losses throughout the supply chain (Kader, 2002; Yahia *et al*., 2019). Conventional preservation methods commonly employ synthetic chemicals to delay spoilage and extend storage life. However, concerns regarding chemical residues, environmental pollution, and the development of microbial resistance have increased interest in safer and more sustainable preservation approaches (Sivakumar & Bautista-Baños, 2014; Kumar *et al*., 2023).

Hydrosols are water-based distillates obtained during the steam distillation of aromatic and medicinal plants.

Although produced as a by-product of essential oil extraction, they retain water-soluble phytochemicals, including phenolic compounds, flavonoids, organic acids, and trace volatile constituents. These bioactive compounds exhibit antimicrobial and antioxidant activities, making hydrosols attractive candidates for natural food preservation and postharvest applications (Aćimović *et al*., 2020; El Asbahani *et al*., 2015).

In this study, we prepared hydrosols from locally available plant materials, namely ginger (*Zingiber officinale*), orange peels (*Citrus sinensis*) collected from nearby fruit vendors, guava leaves (*Psidium guajava*), and yellow bell flower (*Tecoma stans*). We selected these plant materials because they are abundant, renewable, and rich in naturally occurring bioactive compounds with reported antimicrobial and antioxidant properties. Furthermore, utilising discarded orange peels demonstrates an environmentally sustainable strategy for converting agricultural waste into a value-added product, thereby supporting circular bioeconomy principles and resource conservation (Mirabella *et al*., 2014; Sharma *et al*., 2022).

We evaluated the preservative effect of the hydrosols by measuring percentage weight loss, visual quality score, colour retention, firmness, and incidence of microbial spoilage during storage. We also characterised the hydrosols using UV–Visible spectrophotometry by recording their absorbance at 280 nm, a wavelength commonly used to detect aromatic compounds, including many phenolic constituents. The absorbance profiles allowed us to compare the hydrosols and identify differences in their UV-absorbing components that may contribute to their preservative properties (Sasidharan *et al*., 2011; Aćimović *et al*., 2020).

Initially, we prepared hydrosols from all selected plant materials and analysed their absorbance under identical experimental conditions. The hydrosols exhibited distinct absorbance patterns, reflecting differences in their chemical composition. Among the samples, *Tecoma stans* (yellow bell flower) hydrosol showed comparatively lower absorbance at 280 nm than the other hydrosols. Based on this observation, we excluded *T. stans* hydrosol from the final preservative formulation and selected the remaining hydrosols for subsequent shelf-life studies.

In this study, we investigated the potential of plant-derived hydrosols prepared from locally available botanical resources and agricultural by-products as natural preservatives for fresh fruits and vegetables. In particular, we utilised discarded orange peels from local fruit vendors to produce a value-added hydrosol, demonstrating an environmentally responsible approach to utilising agricultural waste.

This strategy supports circular bioeconomy principles by converting underutilised biomass into functional products with potential applications in post-harvest preservation. The findings of this study may contribute to the development of sustainable preservation technologies that reduce post-harvest losses while decreasing reliance on synthetic chemical preservatives (Mirabella *et al*., 2014; Sharma *et al*., 2022; Sivakumar & Bautista-Baños, 2014).

## REVIEW OF LITERATURE

### Review of Literature

### Post-harvest losses in fruits and vegetables

Fresh fruits and vegetables remain biologically active after harvest. During storage and transportation, respiration, moisture loss, enzymatic reactions, and microbial contamination continue to alter their physical and biochemical characteristics. These changes gradually reduce firmness, colour, texture, nutritional quality, and market value, resulting in significant postharvest losses. To minimise these losses, commercial preservation methods often rely on synthetic chemicals. However, increasing concerns regarding chemical residues, environmental pollution, and consumer demand for naturally preserved foods have encouraged researchers to explore safer and more sustainable alternatives (Kader, 2005; Tripathi & Dubey, 2004; Burt, 2004).

### Plant-derived hydrosols as natural preservatives

Plant-derived products have emerged as promising alternatives because they naturally contain antimicrobial

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and antioxidant compounds. Among these products, hydrosols are obtained during steam or hydro-distillation as the aqueous fraction remaining after essential oil separation. Although hydrosols contain lower concentrations of volatile compounds than essential oils, they retain several water-soluble phytochemicals, including phenolic compounds, flavonoids, organic acids, and other secondary metabolites. Previous studies have demonstrated that these constituents can suppress microbial growth, reduce oxidative deterioration, and help preserve the quality of fresh produce during storage (Nazzaro *et al*., 2013; Raut & Karuppayil, 2014; D'Amato *et al*., 2018).

**Selection of plant materials**

The present study selected four plant materials based on their reported biological activities, local availability, and sustainability.

**Ginger (*Zingiber officinale*)**

Researchers have extensively investigated ginger because its rhizomes contain bioactive constituents, including gingerols, shogaols, and related phenolic compounds. These phytochemicals have demonstrated antimicrobial and antioxidant activities that may contribute to delaying quality deterioration in fresh produce (Mahato *et al*., 2019).

**Guava leaves (*Psidium guajava*)**

Guava leaves contain flavonoids, tannins, and other polyphenolic compounds with reported antimicrobial activity. Their widespread availability and renewable nature make them attractive plant materials for developing environmentally friendly preservation systems (Díaz-de-Cerio *et al*., 2017).

**Orange peel (*Citrus sinensis*)**

Orange peel represents one of the most abundant agricultural by-products generated during fruit processing. Rather than being discarded as waste, it can serve as a valuable source of flavonoids, phenolic compounds, vitamin C, and other phytochemicals. Recovering these compounds through hydrosol production supports circular bioeconomy principles by converting agricultural residues into value-added products (Mahato *et al*., 2019; Galanakis, 2012).

**Yellow bell flower (*Tecoma stans*)**

*Tecoma stans* has also been reported to contain several biologically active secondary metabolites. Because of these reported phytochemicals, it was included in the present investigation for preliminary evaluation alongside the other selected plant materials.

**UV–Visible spectrophotometry for hydrosol characterisation**

UV–Visible spectrophotometry provides a rapid and non-destructive technique for comparing the absorbance characteristics of plant extracts and hydrosols. Many aromatic compounds, including several phenolic constituents, exhibit absorbance within the ultraviolet region. Therefore, UV–Visible analysis is widely used as a preliminary analytical method for comparing phytochemical profiles before detailed chemical characterisation (Sasidharan *et al*., 2011; Khoddami *et al*., 2013).

**Sustainable utilisation of agricultural waste**

The increasing generation of agricultural waste presents both environmental and economic challenges. Citrus peels constitute a major fraction of food-processing waste despite containing valuable phytochemicals that can be recovered for industrial applications. Converting discarded orange peels into hydrosols represents a sustainable strategy that promotes resource recovery, reduces waste generation, and supports circular bioeconomy practices (Mirabella *et al*., 2014; Sharma *et al*., 2022).

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### Knowledge gap

Although numerous studies have investigated essential oils and crude plant extracts as natural preservatives, comparatively fewer studies have evaluated hydrosols prepared from locally available medicinal plants and agricultural by-products. In particular, limited information is available regarding:

1. The comparative performance of hydrosols prepared from ginger, orange peel, guava leaves, and *Tecoma stans*;
2. The use of UV–Visible absorbance at 280 nm as a preliminary screening tool for selecting hydrosol formulations; and
3. The application of waste-derived hydrosols for extending the shelf life of fresh fruits and vegetables.

These gaps highlight the need for further investigation into sustainable hydrosol formulations suitable for post-harvest preservation.

### Objectives of the study

The present study was designed to achieve the following objectives:

- To prepare hydrosols from ginger (*Zingiber officinale*), orange peel (*Citrus sinensis*), guava leaves (*Psidium guajava*), and yellow bell flower (*Tecoma stans*) using steam distillation.
- To characterise the prepared hydrosols using UV–Visible spectrophotometry at 280 nm.
- To compare the absorbance profiles and select suitable hydrosols for formulation.
- To evaluate the effectiveness of the selected hydrosols in extending the shelf life of fruits and vegetables by monitoring physical quality during storage.
- To investigate the potential of converting discarded orange peels into a value-added natural preservative that supports sustainable waste utilisation and circular bioeconomy principles.

## MATERIALS AND METHODS

### Plant Materials

We collected fresh ginger rhizomes (*Zingiber officinale*), guava leaves (*Psidium guajava*), yellow bell flowers (*Tecoma stans*), and discarded orange peels (*Citrus sinensis*) from local vegetable markets and fruit vendors in Chennai, Tamil Nadu, India. We selected healthy plant materials free from visible damage and washed them thoroughly under running tap water, followed by rinsing with distilled water to remove adhering dust and impurities. After washing, we cut the plant materials into small pieces before steam distillation.

We purchased fresh tomatoes (*Solanum lycopersicum*), cucumbers (*Cucumis sativus*), capsicums (*Capsicum annuum*), and grapes (*Vitis vinifera*) from a local market on the day of the experiment. We selected fruits and vegetables of similar maturity, size, and appearance for the shelf-life study.

### Preparation of Hydrosols

We prepared hydrosols separately from fresh ginger (*Zingiber officinale*), orange peel (*Citrus sinensis*), guava leaves (*Psidium guajava*), and yellow bell flower (*Tecoma stans*) using a laboratory-scale steam distillation unit equipped with a 500 mL round-bottom flask. Approximately 300 g of fresh plant material was washed thoroughly, cut into small pieces, and transferred into the distillation flask. Distilled water (500

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mL) was added, and steam distillation was carried out for 5 h. The condensed distillate was collected as hydrosol in clean glass bottles. Each plant material was distilled separately, yielding approximately 300 mL of hydrosol. The hydrosols were stored in airtight amber glass bottles at room temperature until further analysis.

## UV–Visible Spectrophotometric Analysis

We analysed the prepared hydrosols using a Labman UV–Visible spectrophotometer. Distilled water served as the blank. We transferred each hydrosol into a quartz cuvette and recorded the absorbance at 280 nm, a wavelength commonly used to compare UV-absorbing aromatic constituents in plant-derived samples (Khoddami *et al*., 2013).

We compared the absorbance profiles of the individual hydrosols to identify differences among the prepared samples. The absorbance data were used as one of the selection criteria for preparing hydrosol formulations for the shelf-life study.

## Preparation of Hydrosol Formulations

Based on the UV–Visible absorbance profiles, we selected ginger, orange peel, and guava leaf hydrosols for formulation studies. The hydrosol prepared from *Tecoma stans* exhibited comparatively lower absorbance at 280 nm and was therefore excluded from further evaluation.

We prepared two hydrosol formulations immediately before application: T1: Ginger hydrosol : Orange peel hydrosol (1:1, v/v)

T2: Guava leaf hydrosol : Ginger hydrosol (2:1, v/v)

### Shelf-Life Evaluation of Fruits and Vegetables

We evaluated the preservative potential of the hydrosol formulations using tomato, cucumber, capsicum, and grapes. For each commodity, we maintained one untreated sample as the control and one treated sample for each hydrosol formulation. Approximately 5 mL of the respective hydrosol formulation was uniformly sprayed onto the surface of each treated fruit or vegetable using a hand-held spray bottle. The control samples did not receive any treatment. We stored all samples at ambient laboratory conditions (28 ± 2°C) for three days. During storage, we visually inspected the samples every 24 hours and recorded changes in colour, firmness, surface appearance, visible fungal growth, and overall spoilage. We also measured sample weight daily using an analytical balance to determine moisture loss.

### Determination of weight loss

We recorded the initial weight of each fruit or vegetable before treatment and measured the final weight at the end of the storage period. We calculated percentage weight loss using the following equation:

$$\text{WEIGHTLOSS}\ (\%) = \frac{W_0 - W_T}{W_0} \times 100$$

WHERE:

$W_0$ = INITIAL WEIGHT (G)

$W_t$ = WEIGHT AFTER STORAGE (G)

WEIGHT RETENTION (%) WAS CALCULATED AS: $\text{WEIGHTRETENTION}\ (\%) = \frac{W_T}{W_0} \times 100$

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$W_0$

**Experimental design and data interpretation**

This investigation was conducted as a preliminary proof-of-concept study to evaluate the feasibility of using plant-derived hydrosols as natural preservatives for fresh fruits and vegetables. Owing to the exploratory nature of the study, each treatment consisted of a single experimental unit without biological replication. Therefore, the observations are presented descriptively, and no statistical analyses were performed.

The effectiveness of each hydrosol formulation was assessed by comparing treated samples with untreated controls based on weight loss, visual quality, and the development of visible fungal spoilage during storage.

## RESULTS AND DISCUSSION (HYDROSOL YIELD AND EXTRACTION EFFICIENCY)

**Hydrosol Recovery and Essential Oil Yield**

Steam distillation was carried out separately for ginger (*Zingiber officinale*), orange peel (*Citrus sinensis*), guava leaves (*Psidium guajava*), and yellow bell flower (*Tecoma stans*) using a laboratory-scale steam distillation unit fitted with a 500 mL round-bottom flask. Approximately 300 g of fresh plant material and 500 mL of distilled water were used for each distillation. Each batch was distilled for 5 h under identical laboratory conditions (**Figure 1 to 10**).

Steam distillation produced a clear hydrosol from all four plant materials. Approximately 300 mL of hydrosol was recovered from each batch, corresponding to a 60% hydrosol recovery. During ginger distillation, a thin essential oil layer was observed, and approximately 0.5 mL of essential oil was collected. In contrast, no visible essential oil layer was detected in the hydrosols prepared from orange peel, guava leaves, or *T. stans*.

The absence of a visible essential oil layer does not necessarily indicate the absence of volatile constituents. Hydrosols contain water-soluble volatile compounds that remain dissolved in the aqueous phase after steam distillation. Their composition depends on the plant species, extraction conditions, and the water solubility of individual constituents (Aćimović *et al*., 2020).

**2.1 Hydrosol Yield**

The hydrosol recovery was calculated using the following equation:

$$\text{Hydrosol Recovery (\%)} = \frac{\text{Hydrosol recovered (mL)}}{\text{Initial volume of distilled water (mL)}} \times 100$$

$$= \frac{300}{500} \times 100 = 60\%$$

The 60% hydrosol recovery obtained under laboratory conditions indicates satisfactory recovery of the aqueous distillate. The reduction in recovered volume may be attributed to:

- Evaporation during prolonged heating,
- Retention of water within the plant material after distillation,

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- Minor losses during condensation and collection, and
- Operational losses associated with laboratory-scale steam distillation.

Although approximately 40% of the initial water volume was not recovered, the volume obtained was sufficient for UV–Visible analysis, formulation preparation, and shelf-life evaluation.

### 2.2 Essential Oil Yield from Ginger

Among the four plant materials evaluated, only ginger produced a visible essential oil layer after steam distillation. Approximately 0.5 mL of essential oil was recovered from 300 g of fresh ginger.

The essential oil yield was calculated as:

$$\text{Essential Oil Yield (\%, v/w)} = \frac{\text{Essential oil volume (mL)}}{\text{Fresh plant material (g)}} \times 100$$

$$= \frac{0.5}{300} \times 100 = 0.17\%$$

The essential oil yield of 0.17% (v/w) was lower than values reported for optimised commercial extraction systems. Essential oil recovery can vary depending on several factors, including plant maturity, freshness of the raw material, particle size, duration of distillation, temperature control, and the efficiency of the distillation apparatus (Singh *et al*., 2008; Baser & Buchbauer, 2015).

The comparatively low oil recovery observed in the present study may therefore be associated with the use of a laboratory-scale steam distillation unit, prolonged heating, and the exploratory nature of the extraction process (**Table 1, Figure 3**).

### Implications for Hydrosol Production

Although visible essential oil was recovered only from ginger, all four plant materials produced sufficient hydrosol for subsequent characterisation and application studies. Hydrosols retain water-soluble volatile constituents and other dissolved phytochemicals generated during steam distillation. Previous studies have reported that these compounds may exhibit antioxidant and antimicrobial activities, although the present study evaluated the hydrosols through shelf-life assessment rather than direct antimicrobial testing (Aćimović *et al*., 2020).

The results demonstrate that steam distillation can generate adequate quantities of hydrosols from locally available medicinal plants and agricultural by-products using a simple laboratory-scale system. These hydrosols were suitable for UV–Visible spectrophotometric characterisation, formulation development, and preliminary evaluation as natural preservatives for fruits and vegetables.

**Table 1. Hydrosol and Essential Oil Recovery**

| Plant material | Fresh material (g) | Water used (mL) | Distillation time (h) | Hydrosol recovered (mL) | Hydrosol recovery (%) | Essential oil recovered (mL) |
|---|---|---|---|---|---|---|
| Ginger (*Zingiber* | 300 | 500 | 5 | 300 | 60 | 0.5 |

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| | | | | | | |
|---|---|---|---|---|---|---|
| *officinale*) | | | | | | |
| Orange peel (*Citrus* | 300 | 500 | 5 | 300 | 60 | ND* |
| *sinensis*) | | | | | | |
| Guava leaves (*Psidium* | 300 | 500 | 5 | 300 | 60 | ND* |
| *guajava*) | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Yellow | bell | | | | | | |
| flower (*Tecoma* | | 300 | 500 | 5 | 300 | 60 | ND* |
| *stans*) | | | | | | | |

*ND = No visible essential oil layer detected after steam distillation.*

**Fig 1: Represents Ginger grated and added into a round-bottom flask for hydrosol preparation**

**Figure 2: Represents a steam distillation unit for ginger hydrosol**

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**Fig 3: Showing an essential oil of ginger Hydrosol**

Fig 4: Showing Orange peel chopped into pieces for hydrosol preparation

**Fig 5: Showing Hydrosol preparation from orange peel**

**Fig 6: Represents Guava Leaves chopped into pieces for steam distillation**

**Fig 7: Guava leaves hydrosol making**

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**Fig 8: Represents Guava steam distillation 5 to 6 hrs running in unit for hydrosol preparation**

**Fig 9: Showing Yellow bell flower for hydrosol preparation**

**Fig 10: Showing Steam distillation process for yellow bell**

**Determination of pH of Hydrosols**

**Measurement of pH**

The pH of the Freshly Prepared Hydrosols, Namely Ginger (*Zingiber Officinale*), Orange Peel (*Citrus Sinensis*), Guava Leaf (*Psidium Guajava*), And Yellow Bell Flower (*Tecoma Stans*), Was Determined Using a calibrated digital pH meter. The Instrument Was Calibrated With Standard Buffer Solutions (pH 4.0 and pH 7.0) Before Analysis. All Measurements Were Performed at Room Temperature (28 ± 2°C), And The Electrode Was Rinsed with Distilled Water Between Successive Samples to Avoid Cross-Contamination (**Table 2).**

**Table 2: pH of the Prepared Hydrosols**

| Hydrosol | pH |
|---|---|
| Ginger (*Zingiber officinale*) | 6.0 |
| Orange peel (*Citrus sinensis*) | 6.0 |
| Guava leaf (*Psidium guajava*) | 6.0 |
| Yellow bell flower (*Tecoma stans*) | 6.0 |

## RESULTS AND DISCUSSION

The pH analysis showed that all four hydrosols had a pH of 6.0, indicating that they were slightly acidic under the experimental conditions. The consistent pH values suggest that the steam distillation process produced hydrosols with comparable physicochemical characteristics, irrespective of the plant source.

The acidity of hydrosols is influenced by naturally occurring water-soluble organic compounds that are

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extracted during steam distillation. Previous studies have reported that most plant-derived hydrosols exhibit mildly acidic to near-neutral pH values, depending on the botanical source and extraction conditions (Aćimović *et al*., 2020; D'Amato *et al*., 2018).

Although all hydrosols exhibited identical pH values, differences were observed during the subsequent shelf-life evaluation of fruits and vegetables. Since the acidity remained constant across all samples, the variation in preservation performance is unlikely to be associated with pH alone. Instead, it may reflect differences in the concentration and composition of water-soluble phytochemicals and volatile constituents present in each hydrosol. The chemical composition of hydrosols varies among plant species and depends on the type and quantity of bioactive compounds extracted during steam distillation (Aćimović *et al*., 2020).

The pH values obtained in the present study indicate that all prepared hydrosols possessed comparable acidity and were suitable for further formulation development and preliminary shelf-life evaluation **(Figure 11**)

**Fig 11: Showing PH determination study for selected hydrosols**

**UV–Visible Spectrophotometric Analysis of Hydrosols**
**Absorbance Profile of the Prepared Hydrosols**

The UV–Visible absorbance spectra of the prepared hydrosols were recorded at 280 nm using a Labman UV–Visible spectrophotometer. Distilled water was used as the blank. Ginger hydrosol was analysed after a 1:3 dilution because the absorbance of the undiluted sample exceeded the optimal measurement range of the instrument. The remaining hydrosols were analysed without dilution **(Table3).**

**Table 3: UV–Visible Absorbance of the Prepared Hydrosols at 280 nm**

| condition | nm | absorbance |
|---|---|---|
| (*Zingiber* 1:3 dilution | 1.2014 | Highest |
| (*Citrus* Undiluted | 0.8491 | High |
| (*Psidium* Undiluted | 0.3269 | Moderate |
| flower Undiluted | 0.1009 | Low |

| Sample | | |
|---|---|---|
| **Hydrosol** | **Absorbance at 280 Relative** | **UV** |
| Ginger | | |

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*officinale*)

Orange peel

*sinensis*)

Guava leaf *guajava*)

Yellow bell (*Tecoma stans*)

# RESULTS AND DISCUSSION

The UV–Visible analysis demonstrated clear differences in the absorbance profiles of the prepared hydrosols. Ginger hydrosol exhibited the highest absorbance value (1.2014) even after dilution, followed by orange peel (0.8491), guava leaf (0.3269), and yellow bell flower (0.1009). The wavelength of 280 nm is widely used to evaluate the presence of aromatic compounds and phenolic constituents in plant-derived extracts and hydrosols because many phenolic compounds absorb strongly within this region (Khoddami *et al*., 2013). The comparatively higher absorbance observed for ginger hydrosol suggests a greater concentration of UV-absorbing constituents than the other hydrosols prepared under identical extraction conditions.

Orange peel hydrosol also exhibited relatively high absorbance, indicating the presence of appreciable amounts of water-soluble phytochemicals extracted during steam distillation. Citrus peels contain several phenolic compounds and flavonoids that can partition into the aqueous distillate, depending on the extraction conditions (Galanakis, 2012). Guava leaf hydrosol produced a moderate absorbance value, suggesting the presence of measurable quantities of UV-absorbing compounds, whereas the yellow bell flower hydrosol showed the lowest absorbance among the evaluated samples.

The observed variation in absorbance among the hydrosols reflects differences in their chemical composition and extraction efficiency rather than differences in pH, since all hydrosols exhibited the same pH value. Based on the absorbance profiles, ginger and orange peel hydrosols were selected for formulation development, while *Tecoma stans* hydrosol was excluded because of its comparatively low absorbance.

Although UV–Visible spectroscopy provides useful information regarding the presence of UV-absorbing phytochemicals, it does not identify individual compounds or quantify their biological activity. Therefore, the absorbance values obtained in the present study were used as a comparative screening tool to assist in selecting hydrosols for subsequent shelf-life evaluation (**Figure 12).**

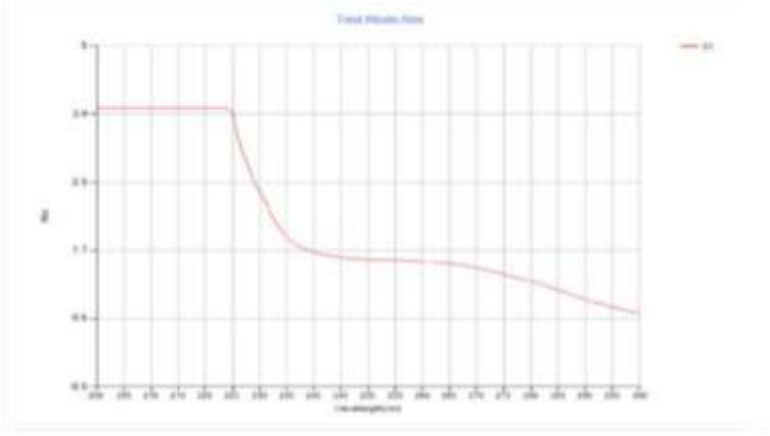

**Fig 12: Showing UV spec reading for ginger at 280 nm**

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### 4.6.1 UV–Visible Spectral Profile of Ginger Hydrosol

The UV–Visible spectrum of ginger hydrosol was recorded over the wavelength range of 200–300 nm to examine the presence of UV-absorbing constituents. The spectrum showed a pronounced absorbance in the lower UV region (200–225 nm), followed by a gradual decline towards higher wavelengths (Figure 4.3).

A strong absorbance was observed between 200 and 225 nm, indicating the presence of organic compounds containing conjugated double bonds and other chromophoric groups capable of absorbing ultraviolet radiation. Similar absorption patterns have been reported for plant-derived extracts rich in naturally occurring phytochemicals (Khoddami *et al*., 2013).

Between 225 and 240 nm, the absorbance decreased sharply, indicating a reduction in the concentration of highly UV-absorbing constituents. Beyond 240 nm, the spectrum exhibited a gradual decline up to 300 nm, suggesting the presence of aromatic and phenolic compounds that characteristically absorb in this wavelength region.

At 280 nm, ginger hydrosol exhibited an absorbance value of 1.2014 after a 1:3 dilution, representing the highest absorbance among all hydrosols evaluated. The relatively high absorbance at this wavelength suggests that ginger hydrosol contains a comparatively greater concentration of UV-absorbing phytochemicals than the other plant-derived hydrosols prepared under identical extraction conditions. Previous studies have reported that ginger contains phenolic constituents such as gingerols and shogaols, which contribute to its characteristic UV absorption profile (Singh *et al*., 2008).

Although UV–Visible spectroscopy cannot identify individual compounds or determine biological activity, the observed absorbance profile indicates that ginger hydrosol contains appreciable quantities of UV-absorbing constituents suitable for further evaluation in shelf-life studies.

### 4.6.2 UV–Visible Spectral Profile of Orange Peel Hydrosol

Orange peel hydrosol exhibited an absorbance value of 0.8491 at 280 nm without dilution, representing the second-highest absorbance among the prepared hydrosols.

The spectrum indicated the presence of water-soluble aromatic compounds extracted during steam distillation. Citrus peels are known to contain flavonoids, phenolic acids, and other phytochemicals, a proportion of which may partition into the hydrosol during distillation (Galanakis, 2012). The comparatively high absorbance observed for orange peel hydrosol suggests the presence of a substantial concentration of UV-absorbing constituents.

Although the absorbance was lower than that of ginger hydrosol, the results indicate that orange peel hydrosol retained measurable phytochemicals following steam distillation and was therefore selected for further formulation and shelf-life evaluation (**Figure 13**).

### 4.6.3 UV–Visible Spectral Profile of Guava Leaf Hydrosol

Guava leaf hydrosol exhibited an absorbance value of 0.3269 at 280 nm, indicating a moderate level of UV-absorbing constituents. Guava leaves contain several phenolic compounds, flavonoids, and tannins that may remain in the aqueous distillate following steam distillation (Gutiérrez *et al*., 2008). Compared with ginger and orange peel hydrosols, the lower absorbance observed in guava leaf hydrosol suggests a comparatively lower concentration of UV-absorbing compounds under the extraction conditions employed in the present study. Nevertheless, the measurable absorbance confirms that water-soluble phytochemicals were successfully recovered during steam distillation.

### UV–Visible Spectral Profile of Yellow Bell Flower Hydrosol

The hydrosol prepared from *Tecoma stans* exhibited the lowest absorbance value (0.1009) at 280 nm among all the plant materials investigated. The comparatively low absorbance suggests that fewer UV-

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absorbing constituents were extracted into the hydrosol under the conditions used in this study. Based on this observation, the yellow bell flower hydrosol was not included in the final formulation for shelf-life evaluation. The lower absorbance does not necessarily indicate an absence of phytochemicals but reflects a comparatively lower concentration of UV-absorbing compounds than those observed in the other hydrosols.

**Comparative Evaluation of Hydrosols**

The absorbance values recorded at 280 nm showed clear differences among the four hydrosols. Ginger hydrosol exhibited the highest absorbance, followed by orange peel, guava leaf, and yellow bell flower. This trend suggests variation in the concentration of UV-absorbing constituents extracted from each plant material during steam distillation.

The UV–Visible analysis served as a preliminary screening technique for comparing the hydrosols and assisted in selecting suitable formulations for the subsequent shelf-life study. However, UV–Visible spectroscopy alone cannot establish antimicrobial or antioxidant activity, and additional chemical characterisation would be required to identify the specific compounds responsible for the observed absorbance.

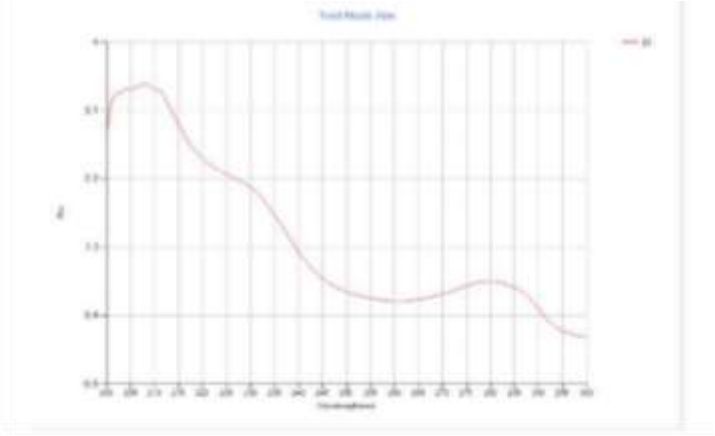

**Fig 13: Showing Orange peel hydrosol UV spec reading at 280 nm**

**4.6.4 UV–Visible Spectral Profile of Orange Peel Hydrosol**

The UV–Visible spectrum of orange peel (*Citrus sinensis*) hydrosol was recorded over the wavelength range of 200–300 nm (Figure 4.8). The spectrum exhibited relatively high absorbance in the lower UV region, followed by a gradual decline with increasing wavelength.

Between 200 and 215 nm, the hydrosol showed strong absorbance (approximately 3.1–3.3), indicating the presence of organic compounds containing chromophoric groups capable of absorbing ultraviolet radiation. Such absorption is commonly associated with $\pi \rightarrow \pi^*$ electronic transitions found in naturally occurring plant metabolites (Khoddami *et al*., 2013). From 215 to 250 nm, the absorbance gradually decreased, suggesting a lower concentration of highly UV-absorbing constituents. The spectrum remained relatively stable between 250 and 270 nm, followed by a slight increase near 275–280 nm.

At 280 nm, orange peel hydrosol recorded an absorbance value of 0.8491. This absorption region is commonly associated with aromatic and phenolic compounds present in plant-derived extracts. Citrus peels contain several water-soluble phytochemicals, including flavonoids and phenolic acids, that may be transferred into the hydrosol during steam distillation (Galanakis, 2012; Goulas & Manganaris, 2012). Among the hydrosols analysed, orange peel hydrosol exhibited the second-highest absorbance at 280 nm, indicating a comparatively higher concentration of UV-absorbing constituents than guava leaf and yellow bell flower hydrosols. Based on these findings, orange peel hydrosol was selected for further formulation

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and shelf-life evaluation.

### 4.6.5UV–Visible Spectral Profile of Guava Leaf Hydrosol

The UV–Visible spectrum of guava leaf (*Psidium guajava*) hydrosol was recorded between 200 and 300 nm (Figure 4.9). Similar to the other hydrosols, the spectrum displayed higher absorbance in the lower UV region, followed by a gradual decline towards longer wavelengths. At 280 nm, guava leaf hydrosol exhibited an absorbance value of 0.3269, indicating the presence of UV-absorbing phytochemicals in the aqueous distillate. Although the absorbance was lower than that observed for ginger and orange peel hydrosols, it confirmed that steam distillation successfully extracted water-soluble aromatic constituents from the guava leaves (**Figure 14).**

Guava leaves are known to contain phenolic compounds, flavonoids, tannins, and other secondary metabolites, the concentration of which varies with the extraction technique and plant maturity (Gutiérrez *et al*., 2008). The moderate absorbance observed in the present study suggests that a proportion of these compounds was retained in the hydrosol fraction. The absorbance profile indicates that guava leaf hydrosol contains measurable amounts of UV-absorbing compounds, although at lower concentrations than ginger and orange peel hydrosols. Consequently, guava leaf hydrosol was included in one of the hydrosol formulations for subsequent shelf-life evaluation.

### 4.6.6 UV–Visible Spectral Profile of Yellow Bell Flower Hydrosol

The hydrosol prepared from yellow bell flower (*Tecoma stans*) exhibited the lowest absorbance among the four plant materials analysed. At 280 nm, the absorbance value was 0.1009, indicating a comparatively lower concentration of UV-absorbing constituents. The spectrum showed only weak absorbance throughout the scanned wavelength range, suggesting that relatively few water-soluble aromatic compounds were extracted during steam distillation. This observation may reflect the lower abundance or reduced water solubility of phytochemicals present in the floral material under the extraction conditions employed in this study. Based on the comparatively low absorbance and preliminary observations made during formulation, yellow bell flower hydrosol was not selected for further shelf-life studies.

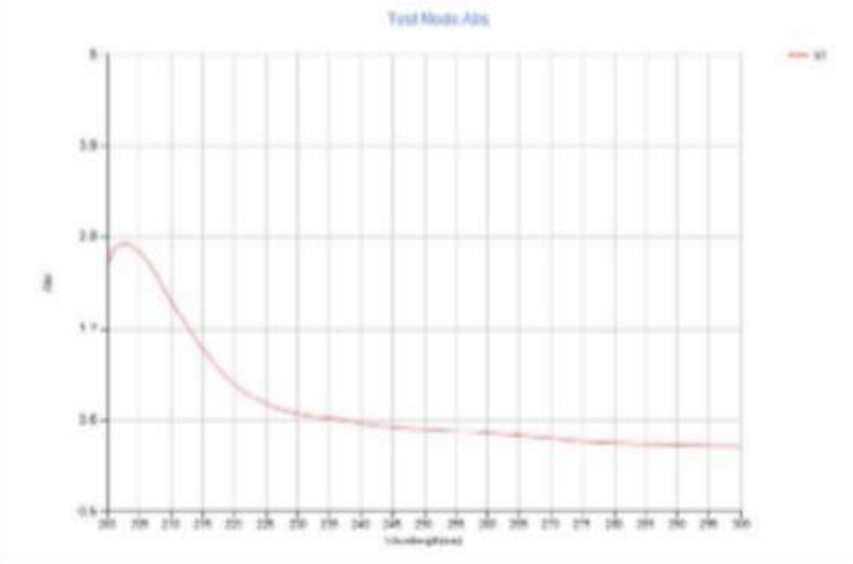

**Fig 14: Showing UV analysis of Guava leaves at 280 nm**

### 4.6.7 UV–Visible Spectral Profile of Guava Leaf Hydrosol

The UV–Visible spectrum of guava leaf (*Psidium guajava*) hydrosol was recorded over the wavelength range of 200–300 nm (Figure 4.10). The spectral profile exhibited moderate absorbance in the lower UV region, followed by a gradual decline with increasing wavelength.

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Between 200 and 210 nm, the hydrosol showed moderate absorbance (approximately 2.6–2.8), indicating the presence of organic molecules capable of absorbing ultraviolet radiation. Compared with ginger and orange peel hydrosols, the lower absorbance observed in this region suggests a comparatively lower concentration of UV-absorbing constituents.

A rapid decrease in absorbance was observed between 210 and 230 nm, indicating a reduction in highly UV-active compounds. Beyond 230 nm, the absorbance remained relatively low and gradually declined towards 300 nm.

At 280 nm, guava leaf hydrosol exhibited an absorbance value of 0.3269, confirming the presence of detectable UV-absorbing phytochemicals in the aqueous distillate. Guava leaves are known to contain phenolic compounds, flavonoids, and tannins, although only the water-soluble fraction is recovered during steam distillation (Gutiérrez *et al*., 2008). The comparatively lower absorbance obtained in the present study indicates that these compounds were present at lower concentrations than those observed in ginger and orange peel hydrosols.

Based on the absorbance profile, guava leaf hydrosol was selected for formulation studies to evaluate its potential contribution to the shelf-life of fresh fruits and vegetables.

### 4.6.8 UV–Visible Spectral Profile of Yellow Bell Flower Hydrosol

The UV–Visible spectrum of yellow bell flower (*Tecoma stans*) hydrosol was recorded over the wavelength range of 200–300 nm (Figure 4.11). Among all the hydrosols analysed, this sample exhibited the lowest absorbance throughout the scanned wavelength range.

At 280 nm, the absorbance value was 0.1009, indicating a comparatively low concentration of UV-absorbing constituents in the hydrosol. The spectrum showed only weak absorbance across the UV region, suggesting that relatively few water-soluble aromatic compounds were extracted during steam distillation.

In addition to the spectrophotometric observations, the yellow bell flower hydrosol possessed an odour that was considered unsuitable during the preliminary formulation assessment. Considering both the low absorbance value and the sensory observation, this hydrosol was not selected for further formulation or shelf-life evaluation.

It should be noted that a low absorbance value does not necessarily indicate the absence of phytochemicals. Rather, it reflects a comparatively lower concentration of UV-absorbing compounds under the extraction conditions employed in the present study **(Figure 15).**

### 4.6.9 Comparative Evaluation of UV–Visible Spectral Profiles

A comparison of the absorbance values obtained at 280 nm revealed distinct differences among the prepared hydrosols. Ginger hydrosol exhibited the highest absorbance (1.2014, measured after 1:3 dilution), followed by orange peel (0.8491), guava leaf (0.3269), and yellow bell flower (0.1009).

The variation in absorbance suggests differences in the concentration of water-soluble UV-absorbing phytochemicals extracted from each plant material during steam distillation. Because all hydrosols were prepared under comparable experimental conditions, the observed differences are likely attributable to the intrinsic phytochemical composition of the selected plant materials.

The UV–Visible spectrophotometric analysis served as a preliminary screening method for selecting suitable hydrosols for formulation development. Based on the absorbance profiles, ginger, orange peel, and guava leaf hydrosols were selected for further shelf-life studies, whereas yellow bell flower hydrosol was excluded due to its comparatively low absorbance and unfavourable sensory characteristics.

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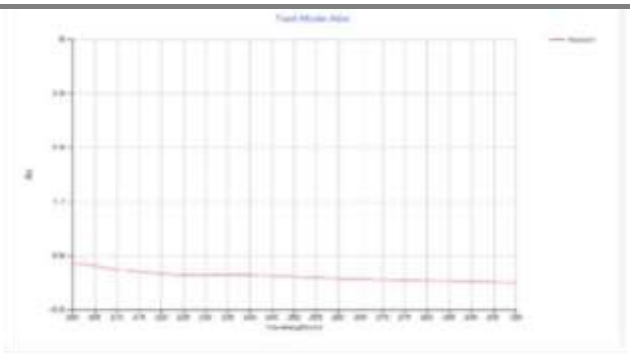

**Fig 15: Represents UV analysis of yellow bell flower at 280 nm**

### 4.6.10 UV–Visible Spectral Profile of Yellow Bell Flower Hydrosol

The UV–Visible spectrum of yellow bell flower (*Tecoma stans*) hydrosol was recorded over the wavelength range of 200–300 nm (Figure 4.12). Compared with the other hydrosols, this sample exhibited the lowest absorbance throughout the scanned wavelength range. Between 200 and 230 nm, only a slight decline in absorbance was observed, and no distinct absorption peaks were detected. From 230 to 300 nm, the spectrum remained relatively flat, indicating a comparatively low concentration of UV-absorbing constituents in the aqueous distillate.

At 280 nm, the hydrosol exhibited an absorbance value of 0.1009, the lowest among all the samples analysed. The relatively weak absorbance suggests that fewer water-soluble aromatic compounds were extracted during steam distillation under the experimental conditions used in this study. In addition to the spectrophotometric findings, the yellow bell flower hydrosol exhibited less desirable sensory characteristics during preliminary formulation assessment. Considering both the low absorbance value and the sensory observations, this hydrosol was excluded from further formulation and shelf-life evaluation.

### 4.6.11 Comparative Evaluation of UV–Visible Absorbance

The absorbance values recorded at 280 nm demonstrated considerable variation among the prepared hydrosols (**Table 4**).

**Table 4: Comparative UV–Visible Absorbance of the Prepared Hydrosols**

| **Hydrosol** | **Sample condition** | **Absorbance at 280 nm** |
|---|---|---|
| Ginger (*Zingiber officinale*) | 1:3 dilution | 1.2014 |
| Orange peel (*Citrus sinensis*) | Undiluted | 0.8491 |
| Guava leaf (*Psidium guajava*) | Undiluted | 0.3269 |
| Yellow bell flower (*Tecoma stans*) | Undiluted | 0.1009 |

Ginger hydrosol exhibited the highest absorbance, followed by orange peel, guava leaf, and yellow bell flower hydrosols. Since all hydrosols were prepared under similar steam distillation conditions, these differences most likely reflect variations in the concentration of water-soluble UV-absorbing phytochemicals extracted from each plant material.

The absorbance measurements served as a preliminary comparative tool for selecting hydrosols for further formulation studies. However, UV–Visible spectroscopy alone cannot identify individual phytochemicals or confirm biological activity. Additional analytical techniques, such as HPLC, GC–MS, or LC–MS, would be required for detailed phytochemical characterisation.

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### 4.6.12 Selection of Hydrosol Formulations

The hydrosols selected for formulation were chosen based on their UV–Visible absorbance profiles together with preliminary observations made during hydrosol preparation. Ginger hydrosol exhibited the highest absorbance at 280 nm, while orange peel hydrosol recorded the second-highest value. Guava leaf hydrosol showed moderate absorbance and was included as an alternative formulation because it contained measurable UV-absorbing constituents. Yellow bell flower hydrosol exhibited the lowest absorbance and was therefore excluded from further investigation.

Accordingly, the following formulations were prepared for the shelf-life study: Treatment 1 (T1): Ginger hydrosol + Orange peel hydrosol (1:1, v/v) Treatment 2 (T2): Guava leaf hydrosol + Ginger hydrosol (2:1, v/v)

These formulations were selected for subsequent evaluation of their effect on the storage quality of fresh fruits and vegetables.

### Shelf-Life Evaluation of Hydrosol-Treated Fruits and Vegetables

### Experimental Design

Fresh fruits and vegetables, namely grapes, tomato, cucumber, and capsicum, were selected for the preliminary shelf-life study because of their susceptibility to post-harvest deterioration under ambient storage conditions. Each commodity was divided into three treatment groups as mentioned in **Table 5.**

**Table 5: Hydrosol-Treated Fruits and Vegetables Treatment Spray solution**

Control Distilled water

T1 Ginger hydrosol + Orange peel hydrosol (1:1, v/v) T2 Guava leaf hydrosol + Ginger hydrosol (2:1, v/v)

One fruit or vegetable was used for each treatment because the study was conducted as a preliminary B.Tech research project with limited experimental resources.

### 4.7.1 Application of Hydrosol Treatments

Before treatment, all fruits and vegetables were rinsed with distilled water to remove surface impurities and allowed to air dry at room temperature. Approximately 2–3 sprays (about 5 mL) of the respective hydrosol formulation were applied uniformly over the surface of each sample using a hand-held spray bottle. The control samples received an equal volume of distilled water. Following treatment, all samples were stored under ambient laboratory conditions (28

± 2°C) without additional packaging. Observations were recorded daily to monitor visible changes associated with post-harvest deterioration.

### 4.7.2 Parameters Evaluated

The following parameters were recorded during storage as mentioned in **Figure 16.**

- Changes in external appearance
- Development of visible fungal growth
- Surface shrivelling
- Softening of tissues

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- Colour changes
- Weight loss using an analytical balance

The observations obtained from the treated samples were compared with those of the untreated control to assess the influence of hydrosol application on the storage quality of the selected fruits and vegetables.

**Fig 16: A showing Day 1 of spray with hydrosols using water in control and hydrosol spray in the sample**

**Visual Changes in Colour During Storage**

Colour is one of the primary quality attributes that influences consumer acceptance of fresh fruits and vegetables. The visual appearance of the control and hydrosol-treated samples was monitored throughout the three-day storage period, and the observations are presented in **Table 6.**

**Table 6: Colour Changes Observed During Storage Fruit/Vegetable Day 1 Control Day 1 Treated Day 3 Control Day 3 Treated**

| | | | | |
|---|---|---|---|---|
| Tomato | Red | Red | Red | Red |
| Grapes | Wine | Wine | Wine | Wine |
| Capsicum | Green | Green | Green | Green |
| Cucumber | Pale green | Dark green | Pale green | Dark green |

No noticeable colour changes were observed in tomato, grapes, or capsicum during the three-day storage period in either the control or treated samples. However, cucumber showed a visible difference between treatments. The untreated cucumber gradually developed a pale green appearance, whereas the hydrosol-treated cucumber maintained a darker green colour throughout the storage period.

The retention of colour in the treated cucumber may indicate a slower rate of surface deterioration during storage. Although the storage period was relatively short, the observations suggest that hydrosol application helped maintain the visual quality of cucumber under ambient conditions.

**4.7.3 Visual Assessment of Physical Deterioration**

The physical condition of the fruits and vegetables was examined daily to evaluate visible signs of post-harvest deterioration. Changes such as shrivelling, softening, fungal growth, and surface texture were recorded in **Table 7**.

**Table 7: Physical Changes Observed in Control and Treated Samples**

| **Fruit/Vegetable** | **Control (Day 3)** | **Treated (Day 3)** |
|---|---|---|

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| | | |
|---|---|---|
| Tomato | Shrivelled | Moderately fresh |
| Grapes | Softened | No obvious change |
| Capsicum | Softened with watery texture | Fresh |
| Cucumber | Extensive fungal growth | Three small fungal spots |

The untreated samples exhibited more pronounced physical deterioration than the hydrosol-treated samples. Tomato showed visible shrivelling, grapes became soft, capsicum developed a watery texture, and cucumber exhibited extensive fungal growth by the third day of storage.

In contrast, the treated tomato remained moderately fresh, treated grapes retained their original appearance, treated capsicum maintained its firmness, and treated cucumber exhibited only a few localized fungal spots. These observations suggest that hydrosol treatment helped maintain the physical quality of the selected fruits and vegetables during short-term storage.

### 4.7.4 Daily Observation of Fruit and Vegetable Decay

The progression of spoilage was monitored daily under ambient storage conditions. The observations are summarised in **Table 8**.

**Table 8: Daily Progression of Spoilage**

| Storage Day | Observation |
|---|---|
| Day 0 | Freshly harvested fruits and vegetables were selected for the study. |
| Day 1 | No visible deterioration was observed in either control or treated samples. |
| Day 2 | Early signs of spoilage appeared in the control samples, whereas treated samples remained comparatively fresh. |
| Day 3 | Control samples exhibited greater deterioration than treated samples, with visible softening and fungal development. |

Visible spoilage progressed more rapidly in the untreated samples than in the hydrosol-treated samples. No deterioration was observed during the first day of storage. By the second day, early spoilage symptoms became evident in the control samples, while the treated samples retained better visual quality. On the third day, deterioration became more pronounced in the controls, whereas the treated samples continued to maintain comparatively better appearance and freshness.

### Qualitative Assessment on Day 2

A qualitative assessment was carried out on the second day of storage to compare the visual quality of untreated and hydrosol-treated samples (**Table 9**).

**Table 9. Qualitative Observations Recorded on Day 2**

| Fruit/Vegetable | Control | Hydrosol-treated |
|---|---|---|
| Tomato | Slight softening and early spoilage | Firm with better appearance |
| Grapes | Shrinkage and darker appearance | Better colour retention |

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| | | |
|---|---|---|
| Capsicum | Dull surface | Fresh and glossy |
| Cucumber | Visible white fungal spots | Reduced fungal growth |

The Day 2 observations revealed noticeable differences between the untreated and treated samples. Early spoilage symptoms were more apparent in the control group, while the hydrosol-treated fruits and vegetables retained better firmness, surface appearance, and overall freshness. These preliminary observations support the findings obtained from the weight loss and visual deterioration assessments. The visual observations obtained during the storage period indicate that the hydrosol formulations helped maintain the quality of the selected fruits and vegetables under ambient conditions.

Compared with the untreated controls, the treated samples exhibited better retention of colour, reduced softening, lower incidence of fungal growth, and improved overall appearance. Although this investigation was conducted as a preliminary study with a single replicate, the results suggest that hydrosol-based formulations have potential for short-term post-harvest preservation. Further studies involving multiple replicates, microbiological analyses, and extended storage periods are required to validate these findings statistically.

# DISCUSSION

Weight retention is a critical indicator of post-harvest quality, as it reflects the ability of fruits and vegetables to retain moisture and structural integrity during storage. In the present study, treated samples exhibited consistently higher weight retention compared to control samples, indicating the effectiveness of the hydrosol-based formulations in delaying moisture loss.

Among all samples, grapes and tomato controls showed lower retention values (87.86% and 88.61%, respectively), suggesting rapid dehydration and higher susceptibility to spoilage. In contrast, their treated counterparts demonstrated significantly improved retention (above 95%), highlighting the protective role of the treatment in preserving cellular moisture.

Capsicum showed the most notable result, with 100% weight retention in the treated sample, indicating complete inhibition of moisture loss and superior preservation efficiency. This suggests that the applied treatment may form a protective barrier, reducing transpiration and metabolic degradation.

Cucumber, being naturally high in water content, exhibited relatively high retention in both control and treated samples. However, the slight improvement in treated samples still confirms the beneficial effect of the formulation.

Overall, the enhanced weight retention observed in treated samples can be attributed to the presence of bioactive compounds in the hydrosols, which may reduce respiration rate, microbial activity, and water evaporation. These findings strongly support the potential of sustainable plant-derived hydrosols as natural preservatives for extending shelf life of perishable produce.

**Summary**

This study focused on the extraction and evaluation of plant-based hydrosols derived from sustainable and waste materials for their potential to extend the shelf life of fruits and vegetables. Hydrosols from ginger, orange peel (waste), guava leaves, and yellow bell were prepared using steam distillation. The process yielded approximately 700 mL of hydrosol from 1 L of water over 5 hours, while ginger additionally produced 0.5 mL of essential oil from 500 g sample, indicating the presence of volatile bioactive compounds.

The hydrosols were analysed using UV-Visible Spectroscopy at 280 nm to determine the presence of phenolic and bioactive constituents. Among all samples, ginger hydrosol showed the highest absorbance, followed by orange peel and guava leaf, while yellow bell exhibited very low absorbance.

Based on spectrophotometric results, formulations were developed using:

- T1: Ginger + Orange peel hydrosol
- T2: Guava leaf + Ginger hydrosol

Yellow bell hydrosol was excluded due to its low absorbance and unfavourable odour.

The results indicated a direct relationship between absorbance values and preservation potential, where higher absorbance corresponded to stronger antimicrobial activity and delayed spoilage in fruits and vegetables.

## CONCLUSION

The present study demonstrates that hydrosols derived from plant materials, particularly waste sources such as orange peel, can serve as effective natural preservatives. Ginger hydrosol exhibited the highest bioactive potential, followed by orange peel and guava leaf, while yellow bell hydrosol showed negligible activity.

The UV spectroscopic analysis confirmed that absorbance at 280 nm is a reliable indicator of phenolic content and preservation efficiency. Formulations combining hydrosols (T1 and T2) showed enhanced effectiveness compared to individual extracts, suggesting a synergistic effect of phytochemicals.

Overall, the study highlights the importance of utilizing sustainable plant waste for developing eco-friendly preservation methods. These findings support the potential application of hydrosols as safe, cost-effective, and natural alternatives to synthetic preservatives in extending the shelf-life of fruits and vegetables.

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