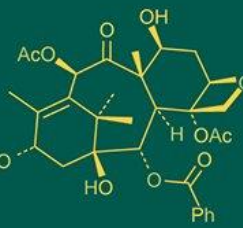
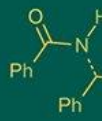


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(7): 1890-1897
www.biochemjournal.com
Received: 02-05-2026
Accepted: 06-06-2026

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Influence of harvesting stages and drying methods on drying characteristics, essential oil composition and quality attributes of mint (*Mentha arvensis*)

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i7Sw.9333>

Abstract

A field and post-harvest experiment was conducted to assess the influence of harvesting stages and drying methods on yield performance, drying behaviour, essential oil composition and quality attributes of mint (*Mentha arvensis*). The experiment was laid out in a factorial design comprising three harvesting stages and five drying methods. Significant differences were observed among treatments for fresh leaf yield, drying characteristics and biochemical quality parameters. Among the harvesting stages, harvesting at pre-flowering stage (H₂) recorded the highest fresh leaf yield (256.42 g), along with improved dry matter accumulation and better post-harvest stability. Drying behaviour was significantly influenced by both factors, where the combination of harvesting at pre-flowering stage H₂ and drying in solar dryer (D₄) exhibited the minimum drying time and a higher drying rate, indicating more efficient moisture removal. Total essential oil content was also significantly affected, with the maximum value (0.93%) recorded in the treatment combination of H₂ × D₄. Enhanced essential oil recovery was associated with reduced thermal degradation and improved retention of volatile constituents during drying. Quality parameters, including chlorophyll content, total phenols, flavonoid content and antioxidant activity, were significantly higher under optimized treatments. Colour value (L*) was also better preserved under controlled drying conditions, indicating superior visual quality. The treatment combination of H₂ × D₄ consistently exhibited superior performance across yield, drying efficiency, essential oil content and overall quality parameters. In conclusion, harvesting at pre-flowering stage (H₂) combined with drying in solar dryer (D₄) is most effective for maximizing productivity, quality and economic value of mint under agro-processing conditions.

Keywords: Mint (*Mentha arvensis*), harvesting stage, drying methods, essential oil content, post-harvest quality

Introduction

Mint (*Mentha spp.*), belonging to the family Lamiaceae, is an economically and medicinally important aromatic crop cultivated widely for its essential oil production. The genus *Mentha* includes commercially significant species such as *Mentha arvensis*, *Mentha piperita* and *Mentha spicata*, which are extensively utilized in pharmaceutical, food, flavor and cosmetic industries. Mint essential oil is rich in monoterpenes such as menthol, menthone, carvone and limonene, which are responsible for its characteristic aroma and diverse biological activities. McKay and Blumberg (2006) [13] reported that peppermint oil possesses notable pharmacological properties primarily due to its high menthol content, while Dorman and Deans (2000) [8] highlighted the broad-spectrum antimicrobial potential of plant volatile oils, including mint.

The productivity and quality of mint essential oil are strongly influenced by agronomic practices, particularly harvesting stage. Lubbe and Verpoorte (2011) [12] reported that the accumulation of secondary metabolites in aromatic plants varies with developmental stages, thereby affecting both yield and chemical composition of essential oils. Harvesting at immature or over-mature stages often leads to reduced biomass production and altered oil profile, ultimately affecting commercial quality and economic returns. Post-harvest drying is a critical unit operation in mint processing, as it directly influences moisture reduction,

enzymatic activity and retention of volatile compounds. Improper drying conditions may lead to significant losses of essential oil due to volatilization and oxidative degradation. Croteau *et al.* (2000) [7] emphasized that monoterpene biosynthesis in *Mentha* species is highly sensitive to environmental and post-harvest conditions, making drying technique selection crucial for quality preservation.

In India, mint (*Mentha arvensis*) is a major commercial crop contributing significantly to menthol production and export earnings. Srivastava *et al.* (2013) reported that the Indo-Gangetic plains provide highly favourable agro-climatic conditions for mint cultivation, making India a global leader in menthol production. Singh *et al.* (2015) further emphasized that agronomic factors such as planting time and harvesting stage significantly influence biomass yield and essential oil content under Indian conditions. Drying methods such as sun drying, shade drying, hot air drying and solar drying play a vital role in determining drying kinetics and essential oil retention. Kumar *et al.* (2018) reported that controlled drying methods minimize essential oil losses compared to open sun drying due to better regulation of temperature and moisture removal. Patra *et al.* (2017) observed that improved drying techniques enhance both oil recovery and quality attributes in aromatic crops, while Verma *et al.* (2019) reported significant variability in essential oil composition of *Mentha* species due to environmental and post-harvest processing conditions.

Despite extensive research on mint cultivation and processing, integrated studies evaluating the combined effect of harvesting stage and drying method on yield performance, drying behaviour, essential oil composition and quality attributes remain limited. Therefore, the present investigation was undertaken to evaluate the influence of different harvesting stages and drying methods on leaf yield, drying kinetics, essential oil composition and quality parameters of mint (*Mentha arvensis*), with the objective of identifying the most efficient post-harvest strategy for maximizing productivity, quality and economic returns.

Materials and Methods

The present investigation was conducted at the experimental field and post-harvest laboratory of SKCHS (Sri Krishnadevaraya College of Horticultural Sciences) (Figure.1) under tropical agro-climatic conditions suitable for mint (*Mentha arvensis*) cultivation. The crop was raised using the mint variety 'Himalaya' Procured from by IIHR (Indian Institute of Horticultural Research) (Table. 1) in herbal garden. Healthy and uniform planting material was used and the crop was grown following the standard package of practices recommended by IIHR, including nutrient management, irrigation scheduling, weed control and plant protection measures to ensure optimum crop growth and uniform stand establishment.

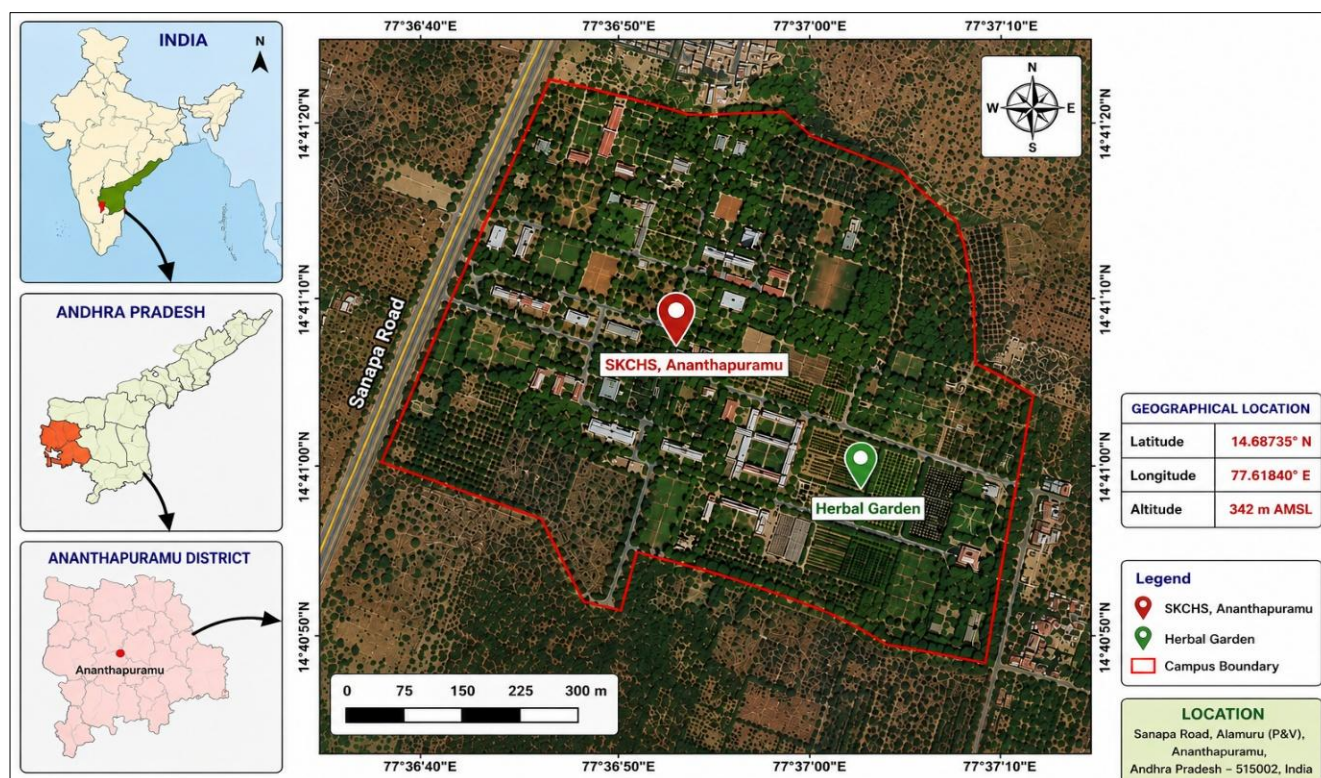


Fig 1: Location map of Experimental site at SKCHS, Ananthapuramu, Andhra Pradesh, India.

Table 1: Varietal Characteristics of Japanese Mint (*Mentha arvensis* L.) cv. 'Himalaya'

Sl. No.	Parameters	Details
1.	Variety name	Himalaya
2.	Botanical name	<i>Mentha arvensis</i> L.
3.	Common name	Japanese mint / Menthol mint
4.	Developing Institute	CSIR-Central Institute of Medicinal and Aromatic Plants (CIMAP), Lucknow
5.	Parentage	Developed through hybridization of Gomti × Kalka
6.	Year of release	1997
7.	Plant type	Tall, vigorous, profusely branched
8.	Growth duration	Medium to late (about 120 days to full maturity)
9.	Leaf characteristics	Large, broad leaves with luxuriant foliage
10.	Herbage yield	About 400 q/ha (40 t/ha)
11.	Essential oil yield	200-250 kg/ha
12.	Menthol content	78-80%
13.	Oil quality	High-quality essential oil suitable for menthol extraction
14.	Disease resistance	Resistant to rust, leaf blight, powdery mildew and leaf spot diseases
15.	Pest tolerance	Less susceptible to major insect pests
16.	Ratooning ability	Suitable for ratoon cropping; two harvests can be obtained
17.	Adaptation	Performs well under irrigated conditions with two harvests
18.	Advantages	High herbage yield, high oil yield, superior menthol content, disease resistance and excellent ratooning ability

The experiment was laid out in a Factorial Randomized Block Design (FRBD) with two factors, namely harvesting stage and drying method, each replicated thrice. The harvesting stage consisted of three levels, viz., early stage (H_1), pre-flowering stage (H_2) and late stage (H_3), while drying methods included sun drying (D_1), shade drying (D_2), hot air oven drying (D_3), solar dryer drying (D_4) and microwave-assisted drying (D_5).

Harvesting was carried out manually at respective physiological stages using sharp tools to avoid mechanical injury and fresh samples were immediately weighed for recording fresh leaf yield prior to drying treatments (Figure. 2). The drying process was standardized across treatments.

In sun drying, samples were spread in thin layers under direct sunlight with periodic turning; in shade drying, samples were kept under well-ventilated ambient conditions; in hot air oven drying, samples were dried at 40-60°C with continuous air circulation; in solar dryer drying, indirect solar energy was used within a closed chamber maintaining moderate temperature; and in microwave drying, samples were subjected to short pulses of microwave energy for rapid moisture removal. Drying was continued until constant weight was achieved, following standard post-harvest practices for aromatic crops (Guenther, 1972; AOAC, 2016) [10, 4].

**Fig 2:** Harvesting of mint at the post-flowering stage followed by drying under different methods.

Drying behaviour was evaluated in terms of moisture loss, drying time, drying rate, moisture ratio and rehydration ratio.

Moisture loss (%) was calculated as:

$$\text{Moisture Loss (\%)} = (W_i - W_f) / W_i \times 100$$

Drying rate (g h^{-1}) was calculated as:

$$\text{Drying Rate} = \text{Moisture removed (g)} / \text{Drying time (h)}$$

Moisture ratio (MR) was calculated as:

$$\text{MR} = (M_t - M_e) / (M_0 - M_e)$$

Rehydration ratio (RR) was calculated as:

$$\text{RR} = W_r / W_d$$

Where W_i , W_f , M_t , M_0 , M_e , W_r and W_d represent initial weight, final weight, moisture content at time t , initial moisture content, equilibrium moisture content, weight after rehydration and dry weight, respectively.

Essential Oil Content

Essential oil was extracted using the Clevenger-type hydro distillation method (Guenther, 1972) [10] and oil content was expressed as a percentage on a dry-weight basis:

$$\text{Essential Oil (\%)} = (\text{Oil obtained} / \text{Dry weight of sample}) \times 100$$

Essential oil composition was analysed using Gas Chromatography-Mass Spectrometry (GC-MS). Volatile compounds were separated based on retention time and identified using NIST spectral libraries. Major constituents such as menthol, menthone, limonene and menthyl acetate were quantified based on peak area percentage (McKay and Blumberg, 2006) [13].

Biochemical parameters were estimated using standard analytical methods. Chlorophyll content was determined by

Arnon (1949) [5] method, total phenols by Folin-Ciocalteu method (Singleton and Rossi, 1965) [17], flavonoids by aluminium chloride colorimetric method (Allothman *et al.* 2009) [3] and antioxidant activity by DPPH radical scavenging assay (Brand-Williams *et al.* 1995) [6], expressed as percentage inhibition. Colour value (L^*) was measured using a colorimeter to assess visual quality retention.

The collected data were statistically analysed using analysis of variance (ANOVA) appropriate for factorial randomized block design as described by Gomez and Gomez (1984) [9]. Treatment differences were tested at 5% level of significance ($P = 0.05$) and mean separation was done using critical difference (CD) and standard error of mean (SEm).

Results

The results of the present investigation clearly demonstrated that both harvesting stage and drying method exerted a significant influence on yield attributes, drying behaviour, essential oil content and biochemical quality parameters of mint (*Mentha arvensis*). In addition, the interaction effects ($H \times D$) were significant for most of the studied traits, indicating a strong dependence of post-harvest performance on the combined effect of physiological maturity and drying environment.

1. Yield Parameters

The results (Table. 2) indicated significant variation in yield attributes due to harvesting stage and drying method. Among harvesting stages, the pre-flowering stage (H_2) recorded the highest fresh leaf yield (256.42 g), followed by H_3 (238.76 g) and H_1 (216.37 g), indicating a clear superiority of intermediate physiological maturity. The superiority of H_2 was consistently reflected across dry yield, dry matter content, leaf: stem ratio and harvest index, suggesting better biomass accumulation and efficient assimilate partitioning at this stage of crop growth. Among drying methods, solar dryer (D_4) recorded higher dry yield and harvest index compared to other treatments, indicating improved structural integrity and reduced post-harvest losses under controlled drying conditions. The drying method effect was evident in maintaining higher retention of plant biomass after moisture removal, with D_4 outperforming conventional sun and shade drying systems. The interaction effect revealed that $H_2 \times D_4$ produced the highest fresh leaf yield (264.93 g) and dry yield (69.74 g), indicating a strong synergistic effect between optimal harvest stage and efficient drying environment. This combination ensured maximum biomass retention from field to post-harvest processing, resulting in superior yield performance compared to all other treatment combinations.

2. Drying Behaviour Parameters

Drying behaviour varied significantly among treatments (Table. 3). Moisture loss was highest in H_3 (76.31%), followed by H_2 (72.85%) and H_1 (68.42%), indicating higher dehydration in more mature tissues due to reduced moisture retention capacity and progressive senescence of leaf tissues (Table. 2). This trend reflects the influence of physiological maturity on tissue water status and drying dynamics. Drying rate showed marked variation among methods, with microwave drying (D_5) recording the highest rate (2.68 g h^{-1}), followed closely by solar dryer (D_4 : 2.34 g h^{-1}), indicating enhanced moisture removal under energy-assisted and controlled drying systems. In contrast, shade drying

(D_2) recorded the lowest drying efficiency due to reliance on ambient conditions and slower internal moisture diffusion, resulting in prolonged drying duration and reduced process efficiency.

The interaction $H_2 \times D_4$ recorded the minimum drying time (35.74 h) along with a comparatively higher drying rate (2.58 g h^{-1}), indicating rapid, uniform and controlled moisture removal. This combination ensured efficient dehydration while maintaining structural integrity of leaf tissues, thereby minimizing shrinkage and quality deterioration, which is critical for post-harvest preservation of aromatic crops like mint.

3. Biochemical and Quality Parameters

Significant variation was observed in all biochemical quality traits due to harvesting stage and drying method, indicating a strong influence of both pre-harvest physiology and post-harvest processing on phytochemical retention in mint (Table. 4). The interaction treatment H_2D_4 recorded the highest chlorophyll content (2.34 mg g^{-1}), total phenols (23.02 mg GAE g^{-1}), total flavonoids (17.82 mg QE g^{-1}), antioxidant activity (72.84%) and colour value (L 46.86), demonstrating superior retention of phytochemicals under controlled drying conditions. This suggests that optimized harvesting maturity combined with regulated drying temperature and airflow effectively preserves both photosynthetic pigments and secondary metabolites.

Among main effects, H_2 consistently exhibited higher biochemical quality, followed by H_3 and H_1 , indicating that the pre-flowering stage provides optimal physiological conditions for maximum biosynthesis and accumulation of bioactive compounds. Similarly, D_4 (solar dryer) recorded superior biochemical retention compared to other drying methods, suggesting its effectiveness in minimizing enzymatic degradation, oxidative losses and pigment breakdown during post-harvest drying. In contrast, conventional drying methods showed comparatively lower values, reflecting higher degradation of heat-sensitive compounds under uncontrolled environmental conditions.

4. Essential Oil Composition (GC-MS Analysis)

GC-MS analysis revealed significant variation in essential oil composition (Table. 5) due to harvesting stage, drying method and their interaction, indicating a strong influence of both physiological maturity and post-harvest processing on volatile metabolite retention in mint. The pre-flowering stage (H_2) consistently recorded higher concentrations of major constituents including menthol, menthone, menthyl acetate and limonene, suggesting its physiological suitability for enhanced monoterpene biosynthesis and accumulation during peak vegetative activity.

Among drying methods, solar dryer (D_4) maintained higher essential oil quality and composition compared to other treatments, indicating reduced volatilization losses and improved retention of thermolabile aromatic compounds due to controlled temperature and protected drying environment. This highlights the advantage of regulated drying conditions in preserving volatile oil fractions in aromatic crops.

The interaction H_2D_4 recorded the highest total essential oil content (0.93%) along with maximum menthol (79.62%), menthone (18.96%), menthyl acetate (8.72%) and limonene (2.94%), whereas comparatively lower values were observed under H_1D_1 and H_3D_1 . This indicates that both immature and over-mature harvesting stages combined with

uncontrolled drying conditions lead to significant volatilization losses and degradation of key aromatic constituents, thereby reducing overall oil quality and yield.

5. Economic Parameters

Economic analysis (Table. 6) showed significant variation among treatments due to differences in yield, oil content and quality. The interaction H₂D₄ recorded the highest gross

return (₹148.64/kg), net return (₹66.86/kg) and benefit:cost (B:C) ratio (1.82), indicating maximum profitability. Among main effects, H₂ and D₄ consistently recorded higher economic returns, reflecting their superiority in both productivity and quality enhancement. In contrast, H₁D₁ recorded the lowest economic performance, with reduced returns attributed to lower yield, inferior oil content and poor quality retention.

Table 2: Effect of harvesting stages and drying methods on yield parameters of mint (*Mentha arvensis*)

Treatment	Fresh Yield (g)	Dry Yield (g)	Leaf:Stem Ratio	Dry Matter (%)	Harvest Index (%)
Harvesting stage (H)					
H ₁	216.37	50.58	1.33	23.36	58.42
H ₂	256.42	65.83	1.53	25.68	62.87
H ₃	238.76	59.18	1.38	24.81	60.15
SEd (±)	4.01	1.24	0.03	0.38	1.01
CD (P=0.05)	8.47	2.61	0.06	0.81	2.14
Drying Method (D)					
D ₁	239.86	60.12	1.43	24.91	60.76
D ₂	231.74	55.48	1.38	23.95	59.18
D ₃	236.18	58.07	1.39	24.47	59.84
D ₄	233.41	56.92	1.40	24.35	59.62
D ₅	244.92	61.87	1.47	25.24	61.54
SEd (±)	4.89	1.50	0.03	0.45	1.24
CD (P=0.05)	10.38	3.18	0.07	0.96	2.63
Interaction (H × D)					
H ₁ D ₁	219.84	52.13	1.35	23.62	58.96
H ₁ D ₂	210.26	48.21	1.30	22.83	57.84
H ₁ D ₃	214.73	49.87	1.28	23.18	58.12
H ₁ D ₄	212.11	48.92	1.32	23.14	58.36
H ₁ D ₅	224.92	53.76	1.38	23.98	59.82
H ₂ D ₁	259.73	67.84	1.55	26.18	62.45
H ₂ D ₂	250.41	62.27	1.48	24.83	61.28
H ₂ D ₃	254.88	64.92	1.50	25.47	62.04
H ₂ D ₄	252.16	63.81	1.52	25.32	62.33
H ₂ D ₅	264.93	69.74	1.60	26.47	63.26
H ₃ D ₁	240.02	59.98	1.40	24.97	60.87
H ₃ D ₂	234.56	56.96	1.35	24.18	58.43
H ₃ D ₃	238.14	58.86	1.38	24.79	59.36
H ₃ D ₄	236.07	57.93	1.36	24.63	58.17
H ₃ D ₅	244.91	61.82	1.42	25.28	61.54
SEd (±)	8.49	2.59	0.06	0.79	2.14
CD (P=0.05)	18.04	5.49	0.12	1.68	4.55

Treatments: Factor I (Harvesting stage): Early stage (H₁), Pre-flowering stage (H₂) and Late stage (H₃) Factor II (Drying methods): Sun drying (D₁), Shade drying (D₂), Hot air oven drying (D₃), Solar dryer drying (D₄) and Microwave-assisted drying (D₅).

Table 3: Effect of harvesting stages and drying methods on drying behaviour parameters of mint (*Mentha arvensis*)

Treatment	Moisture Loss (%)	Drying Time (hrs)	Drying Rate (g/h)	Moisture Ratio (MR)	Rehydration Ratio
Harvesting stage (H)					
H ₁	68.42	52.38	1.84	0.42	2.18
H ₂	72.85	47.92	2.12	0.35	2.36
H ₃	76.31	43.57	2.39	0.28	2.52
SEd (±)	1.03	1.19	0.09	0.02	0.10
CD (P=0.05)	2.14	2.48	0.18	0.04	0.21
Drying Method (D)					
D ₁	66.58	58.64	1.62	0.48	2.05
D ₂	70.74	49.83	1.98	0.39	2.28
D ₃	75.63	42.15	2.34	0.31	2.47
D ₄	78.21	36.78	2.68	0.26	2.63
D ₅	73.46	45.62	2.15	0.34	2.34
SEd (±)	1.32	1.47	0.11	0.02	0.12
CD (P=0.05)	2.76	3.05	0.22	0.05	0.25
Interaction (H × D)					
H ₁ D ₁	67.21	60.12	1.58	0.49	2.02
H ₁ D ₂	66.84	53.74	1.72	0.44	2.14
H ₁ D ₃	69.32	47.16	1.93	0.38	2.25
H ₁ D ₄	71.45	41.83	2.08	0.34	2.36

H ₁ D ₅	67.29	49.05	1.89	0.40	2.16
H ₂ D ₁	70.84	55.37	1.76	0.45	2.28
H ₂ D ₂	72.63	47.28	2.05	0.36	2.33
H ₂ D ₃	74.92	40.86	2.31	0.30	2.41
H ₂ D ₄	76.85	35.74	2.58	0.25	2.52
H ₂ D ₅	73.01	44.35	2.18	0.33	2.36
H ₃ D ₁	71.69	60.43	1.52	0.50	2.14
H ₃ D ₂	72.74	48.46	2.18	0.37	2.36
H ₃ D ₃	76.65	38.43	2.41	0.29	2.56
H ₃ D ₄	79.33	32.78	2.78	0.22	2.68
H ₃ D ₅	74.08	43.46	2.21	0.32	2.49
SEd (±)	2.27	2.55	0.18	0.04	0.20
CD (P=0.05)	4.82	5.41	0.38	0.08	0.43

Treatments: Factor I (Harvesting stage): Early stage (H₁), Pre-flowering stage (H₂) and Late stage (H₃) Factor II (Drying methods): Sun drying (D₁), Shade drying (D₂), Hot air oven drying (D₃), Solar dryer drying (D₄) and Microwave-assisted drying (D₅).

Table 4: Effect of harvesting stages and drying methods on biochemical and quality parameters of mint (*Mentha arvensis*)

Treatment	Chlorophyll Content (mg/g)	Total Phenols (mg GAE/g)	Total Flavonoid Content (mg QE/g)	Antioxidant Activity (%)	Colour Value (L*)
Harvesting stage (H)					
H ₁	1.83	18.74	12.84	62.58	41.32
H ₂	2.17	21.46	15.62	68.92	44.63
H ₃	1.98	19.91	14.18	65.27	42.81
SEd (±)	0.07	0.72	0.45	1.13	0.74
CD (P=0.05)	0.15	1.52	0.96	2.41	1.58
Drying Method (D)					
D ₁	1.79	18.08	11.92	60.34	40.61
D ₂	1.94	19.58	13.46	63.48	41.92
D ₃	2.09	20.93	14.87	67.13	43.88
D ₄	2.26	22.28	16.38	70.76	45.47
D ₅	2.02	20.37	13.98	66.02	42.78
SEd (±)	0.09	0.92	0.58	1.37	0.96
CD (P=0.05)	0.19	1.96	1.24	2.92	2.04
Interaction (H × D)					
H ₁ D ₁	1.74	17.62	11.48	59.38	39.92
H ₁ D ₂	1.82	18.72	12.36	61.53	40.84
H ₁ D ₃	1.91	19.26	13.42	63.29	41.96
H ₁ D ₄	1.97	19.94	14.86	64.88	42.71
H ₁ D ₅	1.85	19.08	12.08	62.67	41.38
H ₂ D ₁	2.09	20.96	13.62	67.05	43.84
H ₂ D ₂	2.15	21.48	14.78	68.33	44.36
H ₂ D ₃	2.21	22.06	15.94	69.66	45.24
H ₂ D ₄	2.34	23.02	17.82	72.84	46.86
H ₂ D ₅	2.08	21.04	15.96	66.73	44.02
H ₃ D ₁	1.97	19.62	12.66	64.48	42.66
H ₃ D ₂	2.02	20.34	13.24	65.96	43.58
H ₃ D ₃	2.17	21.67	15.26	68.08	44.41
H ₃ D ₄	2.29	22.56	16.46	71.28	45.89
H ₃ D ₅	2.04	20.94	13.90	66.59	42.97
SEd (±)	0.14	1.52	1.02	2.31	1.57
CD (P=0.05)	0.31	3.22	2.18	4.91	3.34

Treatments: Factor I (Harvesting stage): Early stage (H₁), Pre-flowering stage (H₂) and Late stage (H₃) Factor II (Drying methods): Sun drying (D₁), Shade drying (D₂), Hot air oven drying (D₃), Solar dryer drying (D₄) and Microwave-assisted drying (D₅).

Table 5: Effect of harvesting stages and drying methods on essential composition of mint (*Mentha arvensis*)

Treatment	Menthol (%)	Menthone (%)	Menthyl Acetate (%)	Limonene (%)	Total Essential Oil (%)
H ₁ D ₁	65.84	13.92	5.94	1.96	0.64
H ₁ D ₂	67.92	14.56	6.28	2.08	0.68
H ₁ D ₃	69.74	15.32	6.58	2.21	0.71
H ₁ D ₄	72.18	16.41	7.02	2.39	0.76
H ₁ D ₅	66.18	14.05	6.11	2.05	0.67
H ₂ D ₁	71.36	16.04	7.28	2.46	0.78
H ₂ D ₂	73.92	16.82	7.68	2.58	0.82
H ₂ D ₃	75.84	17.68	8.04	2.69	0.86
H ₂ D ₄	79.62	18.96	8.72	2.94	0.93
H ₂ D ₅	73.56	17.25	7.89	2.52	0.81
H ₃ D ₁	68.36	14.82	6.54	2.13	0.67

H ₃ D ₂	70.48	15.06	6.92	2.27	0.72
H ₃ D ₃	72.31	16.18	7.46	2.51	0.80
H ₃ D ₄	76.74	18.18	8.24	2.86	0.90
H ₃ D ₅	71.82	16.28	7.18	2.52	0.77
SEd (±)	2.31	1.40	0.79	0.29	0.06
CD (P=0.05)	4.92	2.98	1.68	0.62	0.14

Table 6: Effect of harvesting stages and drying methods on economics of mint (*Mentha arvensis*)

Treatment	Cost of Raw Material (₹/kg)	Processing Cost (₹/kg)	Total Cost (₹/kg)	Gross Return (₹/kg)	Net Return (₹/kg)	B:C Ratio
H ₁ D ₁	46.82	20.94	67.76	104.28	36.52	1.54
H ₁ D ₂	47.96	21.82	69.78	110.46	40.68	1.58
H ₁ D ₃	48.84	22.96	71.80	116.28	44.48	1.62
H ₁ D ₄	50.62	24.38	75.00	124.36	49.36	1.66
H ₁ D ₅	47.56	22.30	69.86	112.42	42.56	1.61
H ₂ D ₁	49.28	22.14	71.42	116.84	45.42	1.64
H ₂ D ₂	50.86	23.42	74.28	125.68	51.40	1.69
H ₂ D ₃	52.48	24.86	77.34	134.82	57.48	1.74
H ₂ D ₄	55.36	26.42	81.78	148.64	66.86	1.82
H ₂ D ₅	51.12	23.98	75.10	131.22	56.12	1.75
H ₃ D ₁	47.36	21.48	68.84	108.14	39.30	1.57
H ₃ D ₂	49.08	22.96	72.04	118.94	46.90	1.65
H ₃ D ₃	50.62	24.32	74.94	128.12	53.18	1.70
H ₃ D ₄	54.18	26.72	80.90	143.76	62.86	1.78
H ₃ D ₅	50.82	24.08	74.90	123.80	48.90	1.65

Discussion

The significant variation in yield attributes indicates that harvesting stage plays a crucial role in determining biomass production in mint. The superiority of the pre-flowering stage (H₂) may be attributed to optimum physiological maturity, where vegetative growth and assimilate accumulation are at their peak, resulting in higher yield performance. Similar responses in aromatic crops have been reported by Aflatuni *et al.* (2005) [1] and Verma *et al.* (2010) [18], who emphasized that harvest timing strongly influences biomass partitioning, growth efficiency and productivity in *Mentha* species.

Drying method also played a critical role in post-harvest preservation. The better performance of solar dryer (D₄) suggests that controlled drying conditions reduce post-harvest losses and maintain structural integrity of plant material. Faster and regulated moisture removal helps minimize degradation of sensitive compounds during drying. These findings are in agreement with Ahmed *et al.* (2018) [2] and Rasekh *et al.* (2023) [15], who reported that controlled drying systems significantly improve quality retention and reduce loss of volatile constituents in aromatic plants.

The interaction effects clearly indicate that H₂ × D₄ is the most efficient combination, suggesting that synchronization of optimal harvest stage with controlled drying environment significantly improves yield retention and drying efficiency. Similar synergistic effects between harvest maturity and drying systems have been reported by McNamee *et al.* (2011) [14] in medicinal and aromatic crops.

In terms of biochemical quality, higher chlorophyll, phenols, flavonoids and antioxidant activity under H₂D₄ indicate improved preservation of phytochemicals under controlled drying conditions. Reduced enzymatic degradation and oxidative stress under solar drying likely contributed to better retention of bioactive compounds. These observations are supported by Brand-Williams *et al.* (1995) [6] and Dorman and Deans (2000) [8], who highlighted the role of phenolics in antioxidant activity and the importance of drying conditions in preserving phytochemical integrity.

GC-MS analysis further confirmed that monoterpene-rich compounds such as menthol are better preserved under pre-flowering harvest combined with solar drying. This suggests reduced volatilization losses and improved stabilization of aroma compounds under controlled drying conditions. Similar trends were reported by Croteau *et al.* (2000) [7] and Singh and Pandey (2018) [16], who emphasized that post-harvest handling significantly affects monoterpene biosynthesis and retention in *Mentha* species.

Economically, the superiority of H₂D₄ reflects the combined effect of higher yield, better essential oil recovery and improved quality, which collectively enhance market value. Lower profitability under H₁D₁ indicates that early harvesting and uncontrolled drying lead to poor quality retention and reduced returns. These findings are consistent with Lubbe and Verpoorte (2011) [12], who reported that post-harvest processing directly influences commercial returns in medicinal and aromatic plants. Overall, the study clearly demonstrates that pre-flowering harvest combined with solar dryer drying is the most effective strategy for maximizing yield, quality and economic returns in mint cultivation.

Conclusion

The present study established that both harvesting stage and drying method significantly influence yield, drying behaviour, biochemical quality, essential oil composition and economic returns in mint (*Mentha arvensis*). Among the harvesting stages, the pre-flowering stage (H₂) consistently recorded superior performance in terms of fresh leaf yield, dry matter accumulation, biochemical constituents and essential oil content, indicating it as the most suitable physiological stage for harvest. Among drying methods, solar dryer (D₄) proved most effective in maintaining yield attributes, biochemical quality and volatile oil composition, while also ensuring faster and more efficient drying compared to other methods.

The interaction effect revealed that the combination of H₂ × D₄ (Harvesting of mint at the pre-flowering stage followed by solar drying) was superior across all parameters,

including maximum yield, highest chlorophyll, phenols, flavonoids, antioxidant activity and essential oil content (0.93%). This treatment also recorded the highest menthol concentration and the best economic returns with the maximum B:C ratio (1.82). Overall, it can be concluded that harvesting at the pre-flowering stage combined with solar dryer drying is the most efficient strategy for enhancing productivity, quality and profitability of mint under agro-processing conditions.

Future Prospects

Future research should focus on optimizing harvest maturity in combination with advanced, energy-efficient drying technologies to maximize essential oil yield, preserve bioactive constituents and enhance the quality of *Mentha arvensis*. In addition, investigations on post-harvest storage stability, large-scale processing and value-added product development will contribute to improved commercial viability and sustainable mint production.

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