ISSN: 2775-5118 VOL.5 NO.4 (2026) I.F. 9.1

THE EFFECT OF ECOLOGICAL FACTORS ON THE ACCUMULATION OF BIOLOGICALLY ACTIVE SUBSTANCES IN MEDICINAL PLANTS

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Abstract. This article analyzes the influence of ecological factors on the accumulation of biologically active substances in selected medicinal plants. The study focused on light intensity, soil moisture, air temperature and soil reaction as key environmental determinants of secondary metabolite formation. Four medicinal species, Melissa officinalis L., Lavandula angustifolia Mill., Mentha piperita L. and Calendula officinalis L., were evaluated under irrigated valley, foothill dry and shaded moist conditions. The methodology included biometric observations, sampling of dry raw material and comparative assessment of total phenolics, flavonoids, essential oil and ascorbic acid. The highest total phenolic accumulation was recorded under foothill dry conditions, while essential oil content increased with higher light intensity and moderate water stress. The results confirm that ecological factors regulate both quantitative productivity and biochemical quality of medicinal raw material.

Keywords. Medicinal plants, ecological factors, biologically active substances, secondary metabolites, phenolics, flavonoids, essential oil, soil moisture, light intensity, raw material quality.

Introduction

Medicinal plants are important biological resources for pharmacy, phytotherapy, cosmetics, food technology and preventive medicine. Their therapeutic value is determined not only by biomass yield, but also by the concentration and stability of biologically active substances accumulated in leaves, flowers, stems, roots and other organs. These compounds include phenolics, flavonoids, essential oils, alkaloids, glycosides, terpenoids, tannins, organic acids and vitamins [1].

The accumulation of biologically active substances is a dynamic physiological process controlled by plant genotype, developmental stage and environmental conditions. Ecological factors such as temperature, light intensity, soil moisture, air humidity, soil reaction and mineral nutrition influence photosynthesis, respiration, enzymatic activity and the biosynthesis of secondary metabolites. Therefore, the same medicinal plant species may show different biochemical quality when grown in different ecological environments [2].

From a biological point of view, secondary metabolites perform protective, adaptive and regulatory functions. Phenolic compounds and flavonoids participate in antioxidant defense and protection against ultraviolet radiation, while essential oils are involved in plant interaction with pollinators, herbivores and microorganisms. Under moderate ecological stress, many medicinal plants increase the synthesis of protective metabolites, which may improve the pharmacological value of the raw material [3].

The relevance of this research is associated with the need to determine how local ecological conditions affect the quality of medicinal plant raw material. This is especially important for regions with contrasting seasonal temperatures, variable irrigation regimes and differences in solar radiation. The scientific problem is that high vegetative productivity does not always correspond to high biochemical quality. Therefore, biological productivity and metabolite accumulation must be studied together.

The aim of this article is to evaluate the influence of ecological factors on the accumulation of biologically active substances in selected medicinal plants and to identify the ecological conditions that are more favorable for obtaining high-quality medicinal raw material. The novelty of the study is the comparative assessment of several medicinal plant species under different ecological regimes using both environmental and biochemical indicators.

Materials and Methods

The research object consisted of four medicinal plant species: lemon balm (Melissa officinalis L.), lavender (Lavandula angustifolia Mill.), peppermint (Mentha piperita L.) and pot marigold (Calendula officinalis L.). These species were selected because they differ in morphological structure, raw material type and dominant groups of biologically active substances.

Field observations were organized under three ecological conditions: irrigated valley, foothill dry and shaded moist plots. The selected conditions differed in air temperature, soil moisture, light intensity, soil pH, humus content, rainfall and irrigation regime. For each species and ecological condition, thirty uniformly developed plants were selected for observation and sampling.

Environmental indicators were recorded during the active vegetation period. Air temperature was measured as a seasonal mean value, soil moisture was determined in the 0-30 cm layer, and light intensity was recorded at midday using a luxmeter. Soil pH and humus content were assessed from composite soil samples.

Plant raw material was collected at the biologically appropriate harvesting stage: lemon balm and peppermint at the budding-beginning flowering stage, lavender during mass flowering, and pot marigold during active flower head formation. Samples were dried under shaded and ventilated conditions until constant mass.

The content of total phenolics was expressed as mg gallic acid equivalents per gram of dry weight (mg GAE/g DW), total flavonoids as mg quercetin equivalents per gram of dry weight (mg QE/g DW), essential oil as ml/kg of dry weight, and ascorbic acid as mg/g DW. The results were summarized as mean numerical values for comparative biological analysis [4].

Results

The ecological parameters of the experimental plots are presented in Table 1. These indicators make it possible to compare the environmental background under which the medicinal plants formed vegetative biomass and accumulated biologically active substances.

Table 1. Ecological conditions of the experimental plots during the vegetation period

Ecological condition	Mean air temperature, °C	Soil moisture, %	Light intensity, klux	Soil pH	Humus, %	Rainfall, mm	Irrigation water, m^3/ha
Irrigated valley	25.4	21.8	74.5	7.4	1.18	126	4200
Foothill dry	28.7	14.6	92.3	7.8	0.91	118	2800
Shaded moist	23.1	25.9	48.6	7.2	1.35	136	3600

Table 1 shows that the foothill dry condition had the highest mean air temperature, 28.7 °C, and the highest light intensity, 92.3 klux, but the lowest soil moisture, 14.6%. The shaded moist condition was characterized by lower temperature, 23.1 °C, higher soil moisture, 25.9%, and lower light intensity, 48.6 klux. The irrigated valley condition occupied an intermediate position, with 25.4 °C air temperature, 21.8% soil moisture and 74.5 klux light intensity.

Table 2. Accumulation of biologically active substances in medicinal plants under different ecological conditions

Plant species	Ecological condition	Total phenolics, mg GAE/g DW	Flavonoids, mg QE/g DW	Essential oil, ml/kg DW	Ascorbic acid, mg/g DW
Melissa officinalis L.	Irrigated valley	34.2	22.6	4.8	1.9
Melissa officinalis L.	Foothill dry	41.7	26.4	5.6	1.6
Melissa officinalis L.	Shaded moist	29.8	20.1	3.9	2.2
Lavandula angustifolia Mill.	Irrigated valley	31.6	18.4	14.6	1.2
Lavandula angustifolia Mill.	Foothill dry	38.9	21.7	16.8	1.0
Lavandula angustifolia Mill.	Shaded moist	27.5	16.3	11.4	1.4
Mentha piperita L.	Irrigated valley	39.5	21.8	18.2	2.4
Mentha piperita L.	Foothill dry	47.3	25.6	21.1	2.0
Mentha piperita L.	Shaded moist	33.2	18.7	14.9	2.8
Calendula officinalis L.	Irrigated valley	42.1	29.2	2.1	3.6
Calendula officinalis L.	Foothill dry	45.0	31.8	1.9	3.1
Calendula officinalis L.	Shaded moist	35.1	25.4	1.7	4.0

The data in Table 2 indicate that metabolite accumulation differed both by plant species and ecological condition. The highest total phenolic content was recorded in Mentha piperita L. under foothill dry conditions, 47.3 mg GAE/g DW. Calendula officinalis L. also accumulated a high amount of phenolics under the same condition, 45.0 mg GAE/g DW. In contrast, shaded moist conditions reduced total phenolic accumulation in all studied species.

Flavonoid content was highest in Calendula officinalis L., reaching 31.8 mg QE/g DW under foothill dry conditions. Essential oil accumulation was most intensive in Mentha piperita L., with 21.1 ml/kg DW in the foothill dry plot and 18.2 ml/kg DW in the irrigated valley plot. Lavandula angustifolia Mill. also showed high essential oil content, especially under foothill dry conditions, 16.8 ml/kg DW. Ascorbic acid showed a different tendency: its highest values were observed under shaded moist conditions, particularly in Calendula officinalis L. with 4.0 mg/g DW and Mentha piperita L. with 2.8 mg/g DW.

Figure 1. Mean total phenolic accumulation under different light regimes

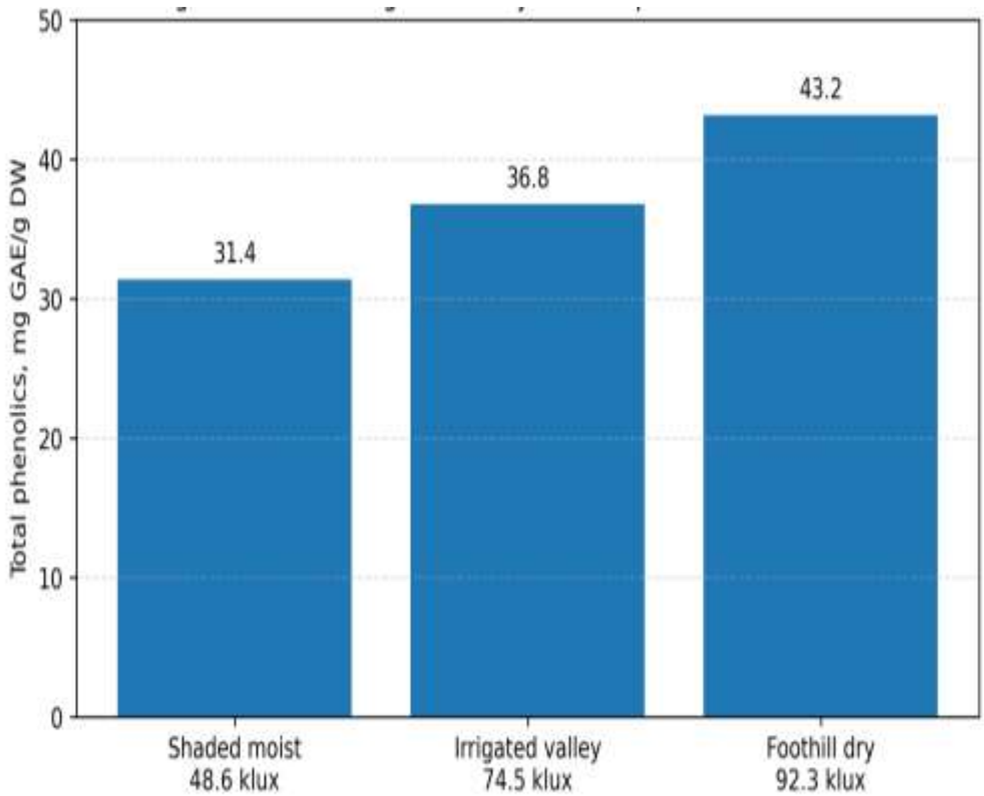

Figure 1 demonstrates that mean total phenolic accumulation increased as light intensity increased. Under shaded moist conditions with 48.6 klux light intensity, the mean phenolic content was 31.4 mg GAE/g DW. In the irrigated valley condition with 74.5 klux, this value increased to 36.8 mg GAE/g DW. The highest mean value, 43.2 mg GAE/g DW, was recorded under foothill dry conditions with 92.3 klux light intensity.

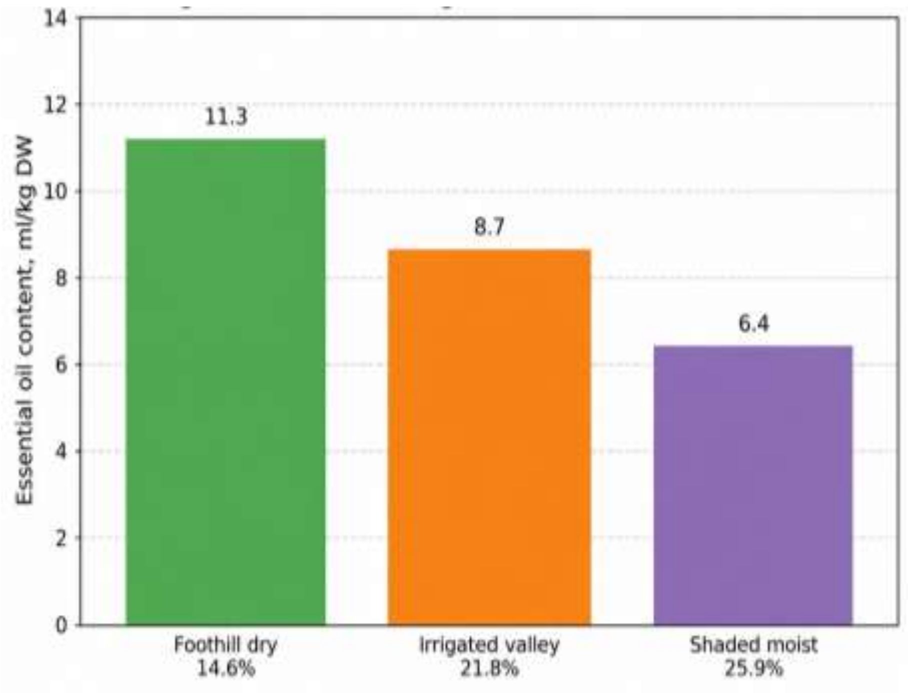

Figure 2. Mean essential oil accumulation under different soil moisture regimes.

Figure 2 shows that mean essential oil accumulation was higher under lower soil moisture conditions. At 14.6% soil moisture in the foothill dry plot, the mean essential oil content reached 11.3 ml/kg DW. In the irrigated valley condition with 21.8% soil moisture, the value was 8.7 ml/kg DW. Under shaded moist conditions, where soil moisture was 25.9%, the mean essential oil content decreased to 6.4 ml/kg DW.

Discussion

The results confirm that ecological factors have a substantial influence on the accumulation of biologically active substances in medicinal plants. According to Table 1, the foothill dry plot combined high air temperature, high light intensity and reduced soil moisture. These conditions created moderate ecological stress, which stimulated the accumulation of total phenolics, flavonoids and essential oils in several species. This pattern is biologically reasonable because phenolic compounds and essential oils are closely associated with stress adaptation and plant defense mechanisms [5].

Table 2 shows that the highest total phenolic content was observed in Mentha piperita L. under foothill dry conditions, 47.3 mg GAE/g DW. This value was 7.8 mg higher than the irrigated valley value, 39.5 mg GAE/g DW, and 14.1 mg higher than the shaded moist value, 33.2 mg GAE/g DW. Therefore, increased light intensity and moderate water deficit appear to activate phenolic biosynthesis in peppermint. A similar tendency was observed in Melissa officinalis L., where total phenolics increased from 29.8 mg GAE/g DW in shaded moist conditions to 41.7 mg GAE/g DW in foothill dry conditions.

ISSN: 2775-5118 VOL.5 NO.4 (2026) I.F. 9.1

Calendula officinalis L. showed the highest flavonoid accumulation among the studied plants. Its flavonoid content reached 31.8 mg QE/g DW under foothill dry conditions, while the irrigated valley and shaded moist values were 29.2 and 25.4 mg QE/g DW, respectively. This indicates that pot marigold is especially valuable as a flavonoid-rich medicinal raw material. The increase in flavonoid concentration under brighter and drier conditions may be associated with the protective role of flavonoids against oxidative and ultraviolet stress.

Essential oil accumulation was strongly influenced by light and soil moisture. Figure 2 demonstrates a clear numerical trend: mean essential oil content was 11.3 ml/kg DW at 14.6% soil moisture, 8.7 ml/kg DW at 21.8% soil moisture and 6.4 ml/kg DW at 25.9% soil moisture. This suggests that excessive moisture and reduced light may weaken essential oil accumulation. Mentha piperita L. and Lavandula angustifolia Mill. responded most clearly to this ecological pattern, with maximum essential oil values of 21.1 and 16.8 ml/kg DW under foothill dry conditions.

However, not all biologically active substances responded identically. Ascorbic acid showed higher values under shaded moist conditions. For example, Calendula officinalis L. accumulated 4.0 mg/g DW ascorbic acid under shaded moist conditions compared with 3.1 mg/g DW under foothill dry conditions. Mentha piperita L. showed 2.8 mg/g DW in shaded moist conditions and 2.0 mg/g DW under foothill dry conditions. This indicates that water availability and lower thermal stress may support the preservation or synthesis of water-soluble antioxidant compounds.

Figure 1 shows that the mean total phenolic content increased from 31.4 mg GAE/g DW at 48.6 klux to 43.2 mg GAE/g DW at 92.3 klux. This 11.8 mg numerical difference highlights the biological role of light as a regulator of secondary metabolism. Since phenolic compounds often participate in photoprotection, higher light intensity can stimulate their synthesis in leaves and flowers.

From the point of view of medicinal plant biology, these findings show that raw material quality cannot be evaluated only by plant size or yield. Ecological conditions determine not only biomass formation, but also the biochemical direction of metabolism. For essential oil-rich plants such as peppermint and lavender, brighter and moderately dry conditions may be more suitable. For plants valued for water-soluble antioxidants, such as pot marigold, moisture conditions may also be important.

Overall, the tables and diagrams demonstrate that ecological regulation of biologically active substances is species-specific. Therefore, cultivation recommendations for medicinal plants should consider the target compound group. If the aim is to obtain essential oil-rich raw material, high light intensity and controlled moderate water stress may be useful. If the aim is to obtain flavonoid-rich or antioxidant raw material, the optimal balance between light, temperature and moisture must be selected for each species separately.

Conclusion

The study showed that ecological factors significantly influence the accumulation of biologically active substances in medicinal plants. Light intensity, soil moisture and temperature changed the levels of total phenolics, flavonoids, essential oil and ascorbic acid in the studied species.

The highest mean total phenolic accumulation, 43.2 mg GAE/g DW, was observed under foothill dry conditions with 92.3 klux light intensity. The highest mean essential oil content, 11.3 ml/kg DW, was recorded in the same ecological condition at 14.6% soil moisture. This confirms that moderate ecological stress can stimulate the formation of several secondary metabolites.

Mentha piperita L. and Lavandula angustifolia Mill. were distinguished by high essential oil content, whereas Calendula officinalis L. showed the highest flavonoid accumulation. Melissa officinalis L. demonstrated balanced accumulation of phenolics, flavonoids and essential oil, indicating its stable biological adaptability.

The results may be used to optimize cultivation conditions, harvesting periods and raw material quality assessment in medicinal plant production. Future studies should include seasonal sampling, soil nutrient analysis and chromatographic identification of individual active compounds.

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ISSN: 2775-5118 VOL.5 NO.4 (2026) I.F. 9.1
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