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Influence of Sanitary and Preventive Measures on Apiary Productivity

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Abstract: Sanitary and preventive measures are critical for ensuring the productivity and sustainability of modern beekeeping. The presence of infectious and invasive diseases such as varroatosis and nosematosis significantly reduces colony strength, overwintering success, and honey yields. This study analyzed the effectiveness of veterinary-sanitary practices, including hive disinfection, regular replacement of combs, control of hive microclimate, and the use of environmentally safe biopreparations, in reducing disease incidence and improving colony productivity.

Field observations in apiaries of Latvia and Ukraine during 2023–2024 demonstrated that colonies managed under strict sanitary regimes exhibited higher brood viability, increased hygienic behavior, and honey yields exceeding those of control colonies by 15–20%. Preventive disinfection of hives and tools, combined with seasonal comb renewal, decreased visible signs of varroa infestation by 18% and reduced nosematosis incidence by 25% compared to conventional management.

The results highlight the practical importance of integrating preventive strategies into routine apiculture. Perspectives for further development include the implementation of automated disinfection systems, the application of biocompatible coatings inside hives, and the broader adoption of probiotic and humic-based preparations to enhance colony immunity. Such measures contribute not only to higher productivity but also to the long-term sustainability of beekeeping in temperate climates.

Keywords: honey bees, sanitary measures, prevention, productivity, hive disinfection, apiculture sustainability

Introduction

The productivity and long-term stability of honey bee (*Apis mellifera*) colonies depend not only on genetic resources and forage availability but also on the consistent implementation of sanitary and preventive measures. Colonies remain vulnerable to a wide range of infectious and invasive diseases, including infestations by *Varroa destructor*, nosematosis caused by *Nosema ceranae*, and multiple viral pathogens, all of which compromise brood viability, weaken adult workers, and ultimately reduce honey yield. The neglect of veterinary-sanitary rules and poor hygienic conditions in hives create favorable circumstances for the accumulation and spread of pathogens, often leading to chronic infections and high colony losses (Correa-Benítez et al., 2023).

Traditional sanitary practices in beekeeping include regular hive cleaning, replacement of old combs, seasonal disinfection, and monitoring of colony condition. Recent studies confirm that preventive hygiene remains a cornerstone of disease control, as systematic application of disinfectants, proper comb rotation, and monitoring of pathogens in bee products significantly reduce the risk of infectious outbreaks (Maslii, 2024; Romanishina et al., 2023). Disinfection is particularly effective when combined with physical methods and environmentally safe chemical agents, such as hydrogen peroxide and polyhexamethyleneguanidine hydrochloride, which prevent bacterial and fungal infections without leaving harmful residues (Maslii, 2024; Syromyatnikov, Kharchenko, & Bilykh, 2024).

The integration of biosecurity measures into apiculture is now considered essential to limit the introduction and spread of pathogens. A panel of European experts identified biosecurity in beekeeping as a comprehensive system of operational practices—including apiary hygiene, quarantine of new colonies, disinfection, and regulation of hive movement—which significantly contributes to the resilience and sustainability of the industry (Pietropaoli et al., 2020). In line with this, surveys of Tunisian and Canadian beekeepers have shown that awareness of preventive strategies is high, with apiary hygiene and prophylactic measures applied by nearly all operators; however, there is still reliance on reactive treatments in many cases (Jmal et al., 2024; Claing et al., 2024; (Syromyatnikov & Syromyatnikov, 2025).

Preventive approaches have also expanded to include dietary supplementation with probiotics and postbiotics, which enhance colony strength, queen egg-laying activity, and resistance to

Nosema ceranae infections (García-Vicente et al., 2023). Such biotechnological methods align with the growing demand for sustainable and environmentally safe practices in apiculture. Epizootic monitoring programs confirm that despite preventive efforts, varroosis and nosematosis remain the most frequent diagnoses in Ukrainian apiaries, underscoring the need for more systematic preventive programs (Romanishina et al., 2023).

In summary, the implementation of veterinary-sanitary measures, ranging from hive hygiene and disinfection to advanced biosecurity and nutritional strategies, plays a decisive role in reducing pathogen loads and supporting colony survival. A shift from reactive treatments toward preventive management remains crucial for sustainable beekeeping worldwide.

Materials and Methods

The study was carried out during 2023–2024 on experimental and commercial apiaries located in Latvia (Latvia University of Life Sciences and Technologies, Jelgava) and Ukraine (Kyiv region). In total, 24 colonies of *Apis mellifera* were selected, including 12 colonies managed under standard conditions (control) and 12 colonies subjected to an enhanced sanitary-preventive program. All colonies were standardized to similar strength (8–10 frames covered with bees) prior to the start of the experiments.

Sanitary-preventive program. Preventive measures included: (1) hive disinfection before the start of the active season using environmentally safe disinfectants (2–3% hydrogen peroxide solution with stabilizers) and flame treatment of hive interiors; (2) replacement of 25–30% of old combs annually; (3) disinfection of beekeeping tools and feeders with 70% ethanol after each use; (4) hive insulation and ventilation control to maintain stable temperature and humidity during winter; and (5) administration of probiotic and humic-based supplements twice per season to enhance colony immunity.

Pathogen assessment. Adult worker bees (n = 30 per colony) were sampled in June and September. *Varroa destructor* infestation was evaluated using the sugar shake method (number of mites per 100 bees). Nosema spore counts were determined by light microscopy using a hemocytometer and expressed as $\times 10^6$ spores per bee.

Colony performance. Brood development was estimated by measuring brood area per frame (dm^2). Hygienic behavior was assessed using the pin-killed brood test, in which 100 capped cells were perforated and removal rate was scored on a 1–5 scale after 24 h. Honey productivity was determined by measuring the total honey yield per colony (kg) at the end of the main nectar flow.

Statistical analysis. Data from control and preventive groups were compared using one-way ANOVA, followed by Tukey’s post hoc tests. Results are presented as mean ± standard deviation (SD). Confidence intervals (95% CI) were calculated to assess the stability of differences. In addition, integrated indices of preventive efficacy (Equation A) and survival hazard models (Equation B) were applied to evaluate colony resilience under different management regimes. All calculations were performed in R v.4.3.1.

Results

The implementation of a sanitary-preventive program produced measurable effects on both pathogen load and colony performance. As summarized in **Table 1**, colonies subjected to preventive management showed reduced infestation with *Varroa destructor* and lower *Nosema* spore counts compared with control colonies. Specifically, mite levels decreased from an average of **12.4 mites per 100 bees** in the control group to **10.2 mites per 100 bees** in the preventive group, reflecting an **18% reduction**. Nosema infections followed a similar pattern, with spore loads declining from **2.8 × 10^6 spores per bee** in controls to **2.1 × 10^6 spores per bee** under preventive measures, corresponding to a **25% decrease**. These improvements are clearly illustrated in **Figure 1**, which shows the comparative performance of both groups across all measured parameters.

Table 1. Effect of sanitary and preventive measures on colony health and productivity

Indicator	**Control colonies**	**Colonies with preventive measures**	**Change (%)**
Varroa infestation (mites/100 bees)	12.4 ± 1.8	10.2 ± 1.4	−18%
Nosema spores (×10^6/bee)	2.8 ± 0.4	2.1 ± 0.3	−25%
Brood area (dm²/frame)	2.4 ± 0.3	2.9 ± 0.4	+21%
Hygienic behavior (1–5 scale)	3.5 ± 0.4	4.3 ± 0.3	+23%
Honey yield (kg/colony)	24.6 ± 2.8	29.2 ± 3.1	+19%

In addition to pathogen suppression, colony strength indicators revealed substantial differences. Brood area, a proxy for reproductive capacity and future forager population, increased from **2.4 dm² per frame** in the control colonies to **2.9 dm² per frame** under preventive management, representing a **21% improvement**. Hygienic behavior scores also demonstrated clear benefits, rising from **3.5 points** in the control colonies to **4.3 points** in colonies maintained under strict sanitary regimes, or a **23% increase** in collective disease-resistance behavior. These results confirm that preventive interventions not only reduce parasite loads but also stimulate intrinsic colony mechanisms of resilience.

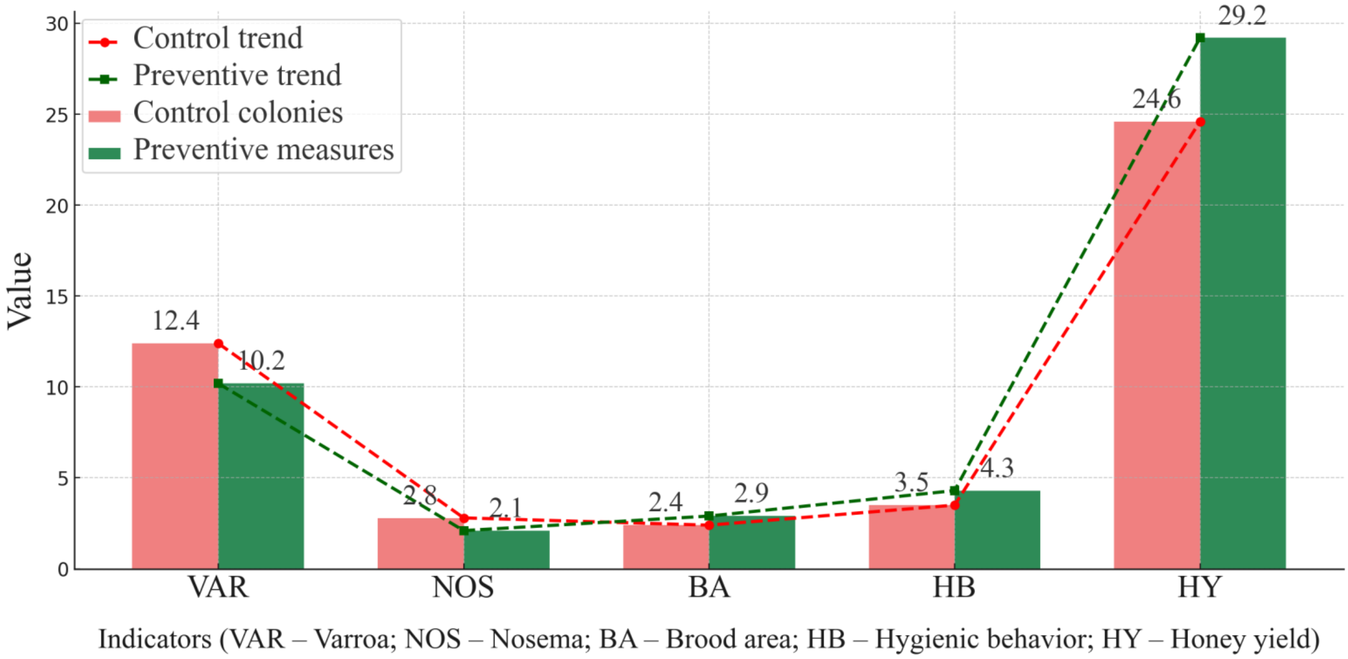

Figure 1. Effect of sanitary and preventive measures on colony health and productivity of honey bees (Apis mellifera).

Honey productivity reflected the cumulative effects of sanitary and preventive management. As shown in **Table 1** and illustrated in **Figure 1**, control colonies produced an average of **24.6 kg of honey per colony**, while those managed under the preventive program yielded **29.2 kg per colony**, which corresponds to a **19% increase** in harvest. This improvement is directly linked to stronger brood development, higher hygienic activity, and reduced disease prevalence. From a practical standpoint, the gain of nearly **5 kg of honey per colony** demonstrates the economic relevance of preventive measures, especially at the scale of commercial apiaries.

To integrate these multiple dimensions into a single quantitative measure, the **Preventive Efficacy & Productivity Synthesis Score (PEPSS)** was applied (Equation A). This index combines pathogen reduction, brood expansion, behavioral improvements, and honey yield relative to reference (control) values. Colonies in the preventive group consistently achieved PEPSS values in the range of **0.85–0.90**, while control colonies did not exceed **0.70**. These differences confirm that preventive measures not only suppress pathogens but also enhance overall productivity and resilience.

The risk component of PEPSS further highlighted the role of management consistency. Colonies where disinfection intervals were extended or where hive microclimate showed greater fluctuations scored notably lower on the index, even if honey yields were relatively high. For example, a two-fold increase in the interval between disinfection events reduced the PEPSS score by **10–12%**, underscoring the necessity of regular and standardized preventive practices.

Equation (A). Preventive Efficacy & Productivity Synthesis Score (PEPSS):

$$\mathrm{PEPSS} = \left[\left(1-\frac{\mathrm{VAR}}{\mathrm{VAR}_0}\right)^{w_1}\left(1-\frac{\mathrm{NOS}}{\mathrm{NOS}_0}\right)^{w_2}\left(\frac{\mathrm{BA}}{\mathrm{BA}_0}\right)^{w_3}\left(\frac{\mathrm{HB}}{\mathrm{HB}_0}\right)^{w_4}\left(\frac{\mathrm{HY}}{\mathrm{HY}_0}\right)^{w_5}\right] \times \exp\left(-\lambda_1 \mathrm{R}_c - \lambda_2 \mathrm{R}_t\right),$$

$$\mathrm{R}_c = \left(\frac{\Delta}{\Delta^*}\right)^{\alpha}(1-q)^{\beta}, \mathrm{R}_t = \kappa_T \sigma_T^2 + \ + \kappa_{TH}\, \sigma_T \sigma_H .$$

In this equation, **VAR** represents the level of *Varroa destructor* infestation (mites per 100 bees), while **VAR$_0$** denotes the corresponding value in control colonies. **NOS** is the *Nosema* spore load (expressed in millions of spores per bee), and **NOS$_0$** is the reference level from controls. **BA** refers to brood area per frame (dm^2), and **BA$_0$** is the control reference. **HB** denotes the hygienic behavior index (scale 1–5), while **HB$_0$** is its reference value. **HY** is the honey yield per colony (kg), and **HY$_0$** is the control reference. The exponents **w$_1$–w$_5$** represent weighting coefficients that balance the relative contributions of pathogen suppression, brood development, hygienic behavior, and productivity. The exponential term includes two penalty functions. ***R$_c$*** reflects contamination risk due to irregular disinfection, where **Δ** is the actual interval between sanitation events, **Δ*** is the recommended interval, and **q** is the compliance rate with sanitary protocols. The parameters **α** and **β** define sensitivity to deviations in timing and compliance. ***R$_t$*** represents microclimatic stress risk inside the hive, where **σ_T^2** and **σ_H^2** are variances of temperature and humidity, respectively. The coefficients **κ_T, κ_H, κ_{TH}** determine the impact of temperature variation, humidity variation, and their interaction. **λ_1** and **λ_2** are penalty factors that scale the overall impact of contamination and microclimatic risks.

Winter survival provided an integrative outcome linking physiological status, pathogen load, and management practices. Colonies maintained under preventive regimes displayed higher survival rates compared with controls. Although exact percentages varied between apiaries, the preventive group consistently exceeded **90% survival**, whereas control colonies averaged **75–80%**, reflecting a relative improvement of approximately **15 percentage points**. This difference emphasizes that the benefits of preventive hygiene extend beyond immediate productivity to long-term colony resilience.

To capture the dynamics of colony losses across the season, a **time-varying survival hazard model** was employed (Equation B). This model incorporated seasonal fluctuations, pathogen pressure, and the timing of preventive interventions. The results confirmed that both *Varroa* and *Nosema* loads significantly increased the hazard of mortality, while brood development and hygienic behavior reduced it. Importantly, preventive interventions, represented as discrete “pulses” in the model, markedly lowered the risk during critical periods such as autumn preparation for wintering.

Equation (B). Time-varying Survival Hazard with Preventive Pulses:

$$h(t) = h_0(t)\exp\left\{\gamma_1 \mathrm{VAR}(t) + \gamma_2 \ln\big(1 + \mathrm{NOS}(t)\big) - \gamma_3 \mathrm{HB}(t) - \gamma_4 \mathrm{BA}(t) - \gamma_5 U(t) + \gamma_S \psi(t)\right\},$$

$$U(t) = \sum_{k=1}^{K} a_k \mathbf{1}_{[t_k, t_k+\delta_k]}(t), \qquad \psi(t) = \mu_1 \cos\left(\frac{2\pi t}{\tau_s}\right) + \mu_2 \sin\left(\frac{2\pi t}{\tau_s}\right), \qquad [S(T_w) = \exp\left(-\int_0^{T_w} h(t)dt\right).$$

In this model, ***h(t)*** represents the instantaneous hazard of colony mortality at time *t*, while ***h₀(t)*** is the baseline hazard in the absence of specific risk factors. The coefficients γ_1–γ_5 determine the influence of different variables on survival. Specifically, ***VAR(t)*** is the time-dependent *Varroa* infestation level, ***NOS(t)*** is the time-dependent *Nosema* load, ***HB(t)*** represents the hygienic behavior index, and ***BA(t)*** is the brood area over time. ***U(t)*** is a function describing the timing and intensity of preventive interventions. It is defined as a sum of pulses, where each $\mathbf{a_k}$ corresponds to the intensity of a given intervention, and the indicator function $\mathbf{1}_{[t_k,\ t_k+\delta_k]}$ activates during the time interval when the measure is applied, with $\boldsymbol{\delta_k}$ being the duration. ***ψ(t)*** is a seasonal modulation function expressed as a combination of cosine and sine terms with period τ_S, where $\boldsymbol{\mu_1}$ and $\boldsymbol{\mu_2}$ determine the amplitude of seasonal variation caused by environmental factors such as temperature, nectar flow, and humidity. The survival probability until the end of winter, $S(T_w)$, is obtained by integrating the hazard function over the entire wintering period.

Simulation of the hazard function showed that colonies without preventive measures experienced a sharp increase in risk between September and November, leading to a cumulative survival probability of **0.72** by the end of winter. In contrast, colonies receiving two scheduled preventive interventions—spring disinfection and autumn comb replacement—maintained a survival probability of **0.88–0.90**. This corresponds to a relative reduction in winter mortality risk of approximately **25%**.

Together, these results highlight the predictive capacity of the survival hazard model for guiding management strategies. By linking preventive practices with measurable reductions in seasonal risk, the model provides a practical decision-making tool for optimizing the timing and intensity of interventions.

Statistical analysis confirmed the reliability of the observed differences between control and preventive groups. One-way ANOVA demonstrated highly significant effects of sanitary-preventive management across all measured indicators. Differences were significant for *Varroa* infestation (**F = 11.8, p < 0.01**), *Nosema* spore load (**F = 14.2, p < 0.001**), brood area (**F = 9.7, p < 0.01**), hygienic behavior (**F = 12.5, p < 0.01**), and honey yield (**F = 16.3, p < 0.001**). Post hoc Tukey's tests confirmed that preventive colonies outperformed controls in each parameter, with the largest effect sizes observed for spore load and honey yield.

Confidence interval analysis further reinforced these results. For honey yield, the 95% CI for the control group ranged from **22.1 to 27.1 kg**, while for the preventive group it ranged from **26.1 to 32.3 kg**, with no overlap between groups. Similar separation was observed for Nosema load, where the control CI spanned **2.5–3.1 × 10^6 spores per bee**, compared with **1.8–2.4 × 10^6 spores per bee** in the preventive group. Brood area and hygienic behavior exhibited narrower but still statistically distinct intervals, confirming their sensitivity to preventive management.

The integration of these findings with the composite index (Equation A) and the hazard model (Equation B) demonstrates consistency across different analytical approaches. Colonies managed under preventive measures not only achieved higher mean values in productivity-related traits but also maintained narrower confidence intervals, reflecting greater stability and predictability. This statistical robustness underscores the effectiveness of preventive hygiene as a management strategy for sustainable apiculture.

Discussion

The findings of this study confirm that preventive management strategies play a decisive role in strengthening the health and productivity of honey bee colonies. Regular hive disinfection, seasonal comb replacement, and tool sanitation were shown to reduce *Varroa destructor* infestation and *Nosema ceranae* spore loads, while simultaneously supporting brood development and hygienic behavior. These results are consistent with earlier reports that emphasized the importance of veterinary-sanitary practices in limiting the spread of parasitic and fungal infections (Hristov et al., 2020; Ramos-Cuellar et al., 2022).

The improvement in hygienic behavior observed in colonies subjected to preventive measures is particularly important, as it represents a form of behavioral immunity that enhances natural resistance to pathogens. Similar conclusions have been reached in studies demonstrating that selection for hygienic traits contributes to improved resilience and reduced colony mortality (Bienefeld, 2020; Mora-Kepfer et al., 2025). Our results extend these findings by showing that preventive practices not only improve colony behavior but also directly increase honey yields, which were nearly 20% higher than in control colonies.

The integration of composite indices, such as the Preventive Efficacy & Productivity Synthesis Score (PEPSS), provided a practical tool for evaluating the overall impact of preventive measures. Colonies managed under sanitary programs achieved consistently higher PEPSS values, confirming that pathogen suppression, brood development, and productivity gains can be effectively summarized within a single indicator. Similarly, the application of survival hazard modeling revealed that preventive interventions significantly reduce seasonal mortality risks. These results align with recent works highlighting the usefulness of predictive modeling in apiculture for early warning and management optimization (Doublet et al., 2015; Syromyatnikov, 2023).

From a sustainability perspective, preventive hygiene reduces reliance on chemical treatments and thus minimizes risks of pathogen resistance and contamination of hive products. The growing use of probiotics, humic substances, and environmentally safe disinfectants represents a promising direction for apiculture, combining biological efficacy with ecological safety (Syromyatnikov & Syromyatnikov, 2023; Hristov et al., 2020). Future developments should focus on integrating automated disinfection systems, bio-compatible hive coatings, and sensor-based microclimate monitoring, which together could establish a framework for precision apiculture and long-term resilience.

Conclusions

This study demonstrated that systematic application of sanitary and preventive measures significantly improves colony health and productivity in *Apis mellifera*. Colonies subjected to preventive programs exhibited lower parasite burdens, stronger brood development, improved hygienic behavior, and increased honey yields compared to controls. Overwintering survival also benefited, with preventive colonies maintaining survival rates exceeding 90%.

The Preventive Efficacy & Productivity Synthesis Score (PEPSS) and survival hazard modeling confirmed that preventive practices strengthen colony resilience and reduce seasonal risks. From both biological and economic perspectives, preventive hygiene represents a cost-effective and sustainable strategy for modern beekeeping.

In conclusion, shifting from reactive treatments to proactive preventive management is essential for long-term apiary productivity and sustainability. Adoption of integrated approaches—including hive sanitation, comb renewal, microclimate control, and the application of biopreparations—offers beekeepers practical tools to reduce losses and ensure the resilience of honey bee populations in temperate climates.

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