EREM 82/1
Journal of Environmental Research, Engineering and Management
Vol. 82 / No. 1 / 2026
pp. 34–47
10.5755/j01.erem.82.1.36569

A Full Factorial Design Approach to Evaluating the Impact of Hyperthermia on the Phytotoxicity of Fuel Materials

Received 2024/08 | Accepted after revisions 2026/02

https://doi.org/10.5755/j01.erem.82.1.36569

A Full Factorial Design Approach to Evaluating the Impact of Hyperthermia on the Phytotoxicity of Fuel Materials

Larysa Cherniak[1]*, Olexandr Mikhieiev[1], Serhii Kvaterniuk[2], Vasyl Petruk[2], Oleksandr Shtyka[3], Oksana Lapan[1], Valerii Frolov[4]

[1] State University «Kyiv Aviation Institute», Ukraine

[2] Vinnytsia National Technical University, Ukraine

[3] Lodz University of Technology, Poland

[4] National University «Yuri Kondratyuk Poltava Polytechnic», Ukraine

***Corresponding author:** specially@ukr.net

This study investigates the influence of hyperthermia on test plants as a proxy for complex stress factors affecting growth activity under kerosene-induced toxicity. A full factorial experimental design was employed to quantitatively evaluate the non-additive interactions (synergism or antagonism) between thermal seed treatment and soil kerosene content. Morphological parameters, specifically shoot and root length, were monitored over a nine-day period to establish the dynamics of these effects. Based on the empirical data, regression models were developed to assess the impact of these factors on growth characteristics within a petrochemical-polluted soil biotesting framework. The results indicate that at kerosene concentrations equivalent to or below the Allowable Permissible Concentration (APC), pre-sensitization via hyperthermia does not amplify the toxic effect. Conversely, potentiation between the factors was observed only at elevated kerosene concentrations, particularly within ranges previously associated with stimulatory responses in plant bioassays.

Keywords: soil pollution, petrochemicals, aviation kerosene, phytotesting, chemical contamination.

Introduction

Soil contamination by petroleum hydrocarbons represents a pervasive environmental challenge resulting from the transport, storage, and utilization of petroleum products(Janic, 1999). Such anthropogenic pressure degrades the fundamental properties of soil, establishing it as a persistent source of pollution that adversely impacts atmospheric quality, water resources, and trophic chains (Shevchyk-Kostiuk et al., 2022; Brtnický et al., 2029). This issue is particularly acute in vicinities characterized by high technogenic loads, such as fuel storage facilities (Madzhd and Franchuk, 2012), service stations, and maintenance hubs, where petroleum-derived pollutants progressively accumulate (Bogolyubov et al., 2010; Brtnickýet al., 2020). Furthermore, the diversification of vehicle types contributes to distinct pollutant profiles, thereby modulating baseline contamination levels.

Crude oil and its derivatives are classified among the most hazardous soil contaminants due to their inherent recalcitrance and resistance to microbial degradation (de Miguel et al., 1997). Consequently, such contamination threatens soil ecological integrity and inhibits its natural recovery potential. While conventional physicochemical assessment methods are essential, they frequently fail to account for biological interactions or the cumulative effects of complex pollutant mixtures. In contrast, biological monitoring, specifically biotesting, facilitates a comprehensive evaluation of soil ecological status by capturing synergistic and antagonistic interactions between contaminants (Dzhura, 2011, Madzhd et al., 2012). This approach is crucial for evaluating highly stressed environments, notably airport territories (Franchuk et al., 2006).

Prior investigations employing bioanalytical techniques have substantiated the presence of petroleum hydrocarbons in soil systems proximal to aviation infrastructures (Madzhd et al., 2012; Radomska et al., 2020; Cherniak et al., 2020). However, a recurring challenge in interpreting phytotoxicity data is the hormetic effect, where specific concentrations of petroleum products paradoxically stimulate plant growth (Trofimov et al., 2020; Madzhd et al., 2020; Cherniak et al., 2021a). Given that biotesting evaluates the biological response of indicator organisms rather than relying solely on chemical quantification (Dzhura, 2011; Cherniak et al., 2021a), there is a need to enhance the reliability and sensitivity of these assays, particularly in detecting low-level contamination that may otherwise elicit stimulatory responses.

To mitigate these analytical complexities, the present study explores the optimization of bioassay sensitivity by examining the influence of hyperthermia on seed germination and growth within kerosene-contaminated matrices. Hyperthermic treatment serves as a proxy for the multifactorial stressors encountered in situ, potentially refining the accuracy of toxicity assessments (Cherniak et al., 2021b). By utilizing a full factorial experimental design, this research quantitatively evaluates the interaction between thermal pre-treatment and aviation kerosene concentration on plant morphological parameters. The temporal dynamics of these interactions were monitored over a five-to-nine-day interval, aligning with standard biotesting protocols.

The primary objectives of this study were as follows:

1) To evaluate the efficacy of hyperthermic seed pre-treatment in enhancing the sensitivity of plant-based bioassays toward soil contaminated with aviation kerosene, serving as a model petroleum hydrocarbon.

2) To analyze the longitudinal dynamics of the combined influence of hyperthermia and kerosene concentration on the morphological parameters of indicator plants over a 5–9 day observational period.

3) To provide a quantitative assessment of the interaction types (synergism, antagonism, or non-additivity) between the investigated stressors by employing a full factorial experimental design and mathematical modeling.

4) To optimize the diagnostic resolution and precision of phytotoxicity assessments, specifically addressing the confounding effects of growth stimulation (hormesis) at certain pollutant thresholds.

5) To establish a scientifically grounded methodological framework for optimizing soil bioassays under the complex environmental pressures inherent to technogenically transformed landscapes, such as airport infrastructures.

This research addresses an existing methodological gap by offering a scientifically grounded approach to soil monitoring. By integrating the stimulatory effects of low-level petroleum concentrations into the analytical framework, this study enhances the regulatory assessment and environmental management of technogenically impacted landscapes.

Methods

The present study assesses the applicability of phytotoxicity bioassays for monitoring soil systems impacted by aviation kerosene. To evaluate the sensitivity of these biological tools, hyperthermic seed treatment was integrated into the experimental design as a potential sensitizing agent. Morphological parameters were monitored over a nine-day growth cycle to establish the longitudinal dynamics of the response to combined abiotic pressures. Utilizing a mathematical modeling approach based on a full factorial design, the interaction between thermal pre-treatment and kerosene concentration was quantitatively evaluated to discern synergistic or antagonistic patterns. A key focus was placed on mitigating the interpretational challenges posed by growth stimulation at low-level contamination. The study introducesa methodological framework tailored for ecological monitoring in technogenically transformed landscapes, providing enhanced accuracy for environmental risk assessments in aviation-related environments (Ray et al., 2021).

To evaluate the influence of hyperthermic seed pre-treatment on the diagnostic sensitivity of plant-based bioassays toward aviation kerosene (TS-1), lettuce seeds (*Lactuca sativa*) were utilized at a density of 210 seeds per replicate. The sensitization procedure involved immersing the seeds, contained within filter paper envelopes, in a water bath maintained at 60°C for one minute. This specific thermal regime was selected based on established evidence that it maximizes the sensitivity of *Lactuca sativa* to petrochemical constituents while ensuring viable germination rates (Cherniak et al., 2021a; Cherniak et al., 2022; Lapan et al, 2012; Lapanet al., 2020; Madzhd et al., 2012; Mikhieiev et al., 2006). Following a 24-hour dehydration period at room temperature, the seeds were sown in eight experimental units, each containing 200 g of soil. The substrate was artificially contaminated with TS-1 aviation kerosene at concentrations defined as multiples of the approximately permissible concentration (APC = 4 mg/kg), in accordance with environmental monitoring standards (Cherniak et al., 2017; Cherniak et al., 2021b; Madzhd et al., 2016). Each unit was supplemented with 100 ml of distilled water. The initial phase of the study comprised four experimental variants utilizing non-sensitized seeds (lacking heat treatment): a kerosene-free control and three soil samples contaminated with incremental concentrations of the petroleum product.

The experimental design consisted of two distinct blocks. The first block utilized non-sensitized seeds (control group) sown in the following soil variants: a kerosene-free control (1´), and soil contaminated with TS-1 aviation kerosene at concentrations of 1 APC (2´), 10 APC (3´), and 100 APC (4´). The second block comprised identical soil treatments (1–4) but utilized seeds subjected to hyperthermic pre-treatment. Specifically, these included a contamination-free sample (1), and kerosene-impacted samples at 1 APC (2), 10 APC (3), and 100 APC (4).

Following the sowing of the treated seeds, the experimental units were placed inside transparent polyethylene bags to maintain a constant humidity level and transferred to an incubator for germination under dark conditions at a regulated temperature of 22°C. To analyze the combined influence of hyperthermic sensitization and aviation kerosene concentration on the morphological development of the bioindicators, seedling growth was evaluated on the 5th, 7th, and 9th days of the germination period. Morphological parameters,

Fig. 1. *Representative soil samples showing Lactuca sativa seedling development on the fifth day of the experimental period*

specifically root and stem length, were quantified using standard manual measurement techniques in accordance with established protocols (Madzhd et al., 2012; Grodzinskyi et al., 2006) (*Fig. 1*).

The morphological parameters of the bioindicators, which served as the basis for evaluating dual-factor impacts and calculating regression coefficients (DeCoursey, 2003; Walpole et al., 2006), were determined by calculating the mean root and stem length for each experimental unit. Furthermore, these growth parameters were normalized as percentages relative to the corresponding control for each replicate. To quantitatively assess the nature of the interaction between the investigated factors – specifically identifying synergistic, antagonistic, or non-additive effects – a full factorial experimental design and mathematical planning methods were employed. To streamline data recording and statistical processing, factor levels were coded using a binary system, where the upper and lower levels were denoted as "+1" and "−1", respectively. In this framework, the magnitude of the calculated regression coefficient represents the specific contribution of each factor to the total variance of the response function as its level transitions from the lower to the upper boundary.

Utilizing a full factorial design (FFD) for two factors at two levels enables the derivation of a regression model characterized by the following equation (Cherniak et al., 2022; Kvaterniuk et al., 2018):

$$Y = B_0 + B_1 x_1 + B_2 x_2 + B_{12} x_1 x_2, \quad (1)$$

where B_0 – is the coefficient of the regression equation for the test sample; B_1 – is the coefficient of the regression equation for the effect of hyperthermia; B_2 – is the coefficient of the regression equation for the effect of kerosene; B_{12} – is the coefficient of the regression equation for the influence of two factors.

To optimize the diagnostic sensitivity and precision of phytotoxicity bioassays for petroleum-impacted soils, it is necessary to account for potential hormetic effects (growth stimulation) occurring at specific pollutant thresholds. Furthermore, a robust methodological framework is required to enhance the reliability of soil monitoring under the multifactorial abiotic pressures characteristic of technogenically transformed landscapes, such as airport territories. For the practical implementation of the proposed regression model, coefficients were calculated based on experimental data from soil matrices contaminated with aviation kerosene at concentrations of 1, 10, and 100 APC. These calculations were performed for the 5th, 7th, and 9th days of the observation period to capture the temporal dynamics of the biological response.

Implementing a full factorial design (FFD) framework enables the estimation of a total number of effects equal to the number of experimental trials, thereby facilitating the construction of a structured planning matrix. Within the FFD paradigm, beyond the intercept (B_0) and the independent contributions of each factor (quantified by the magnitude and sign of coefficients B_1 and B_2), it is possible to evaluate non-linear relationships within the response function, specifically the interaction effects between variables. In a two-factor experimental model, the interaction coefficient (B_{12}) elucidates how the impact of one variable is modulated by the level of the other, providing a quantitative measure of the non-additivity in their combined action. In the present study, the influence of soil petroleum-derived (factor x_2) was evaluated in conjunction with hyperthermic seed pre-treatment (factor x_1). This approach facilitated the determination of synergistic or antagonistic interactions between these factors, which is critical for refining methodologies aimed at regulating permissible anthropogenic loads on biological systems.

Results and Discussion

The following section details the primary findings of this study and interprets their significance for enhancing the ecological safety of soils impacted by petroleum-derived pollutants. These results are analyzed in direct alignment with the research objectives and evaluated in the context of our previous investigations in the field of soil bioanalysis. Particular emphasis is placed on the broader implications of the findings, including potential explanations for observed inconsistencies in biotesting results at specific pollutant concentrations. Based on the empirical data obtained through the aforementioned methodology – specifically focusing on the growth dynamics of seedling organs – and utilizing a two-factor experimental design matrix, the results have been structured in *Tables 1–3*, corresponding to the respective observation periods.

Table 1. *Experimental design matrix and morphological responses of Lactuca sativa following dual-factor exposure (60°C hyperthermic sensitization and TS-1 aviation kerosene contamination) on the fifth day of observation*

Experiment number	A variant of the experiment	Soil aviation kerosene content relative to the APC					
		1 APC		10 APC		100 APC	
		Yi relative root length (% of control)	Yi relative stem length (% of control)	Yi relative root length (% of control)	Yi relative stem length (% of control)	Yi relative root length (% of control	Yi relative stem length (% of control)
1	t° (1´)	100	100	100	100	100	100
2	Fuel (1 APC)	75	63	75	63	75	63
3	t°+Fuel	73	85	52	85	49	26
4	Test sample	250	12	117	106	83	29

Table 2. *Experimental design matrix and morphological response of Lactuca sativa under dual-factor exposure (60°C hyperthermic sensitization and TS-1 aviation kerosene contamination) on the seventh day of the observation period*

Experiment number	A variant of the experiment	Soil aviation kerosene content relative to the APC					
		1 APC		10 APC		100 APC	
		Yi relative root length (% of control)	Yi relative stem length (% of control)	Yi relative root length (% of control)	Yi relative stem length (% of control)	Yi relative root length (% of control)	Yi relative stem length (% of control)
1	t° (1´)	100	100	100	100	100	100
2	Fuel (1 APC)	75	63	75	63	73	63
3	t°+Fuel	200	249	167	222	100	56
4	Test sample	200	8	29	19	23	19

Table 3. *Experimental design matrix and morphological responses of Lactuca sativa following dual-factor exposure (60°C hyperthermic sensitization and aviation kerosene contamination) on the ninth day of the observation period*

Experiment number	A variant of the experiment	Soil aviation kerosene content relative to the APC					
		1 APC		10 APC		100 APC	
		Yi relative root length (% of control)	Yi relative stem length (% of control)	Yi relative root length (% of control)	Yi relative stem length (% of control)	Yi relative root length (% of control)	Yi relative stem length (% of control)
1	t° (1´)	100	100	100	100	100	100
2	Fuel (1 APC)	75	63	75	63	75	63
3	t°+Fuel	97	115	33	37,5	33	23,5
4	Test sample	120	97	80	115	64	82

To facilitate the practical implementation of *Equation (1)*, regression coefficients were quantified based on the theoretically derived formulas for both root and stem development, as detailed in *Tables 1–3*. These coefficients provide a robust quantitative assessment of the relative contribution of each independent factor to the biological response. Moreover, they establish a comparative framework for evaluating the sensitivity of distinct morphological parameters to varying concentrations of petroleum-derived pollutants. The derived coefficients ensure the robustness of the regression model for predictive applications and provide a systematic basis for refining standardized biotesting procedures:

$$B_0 = \frac{Y_1+Y_2+Y_3+Y_4}{4}, \quad (2)$$

$$B_1 = \frac{-Y_1+Y_2-Y_3+Y_4}{4}, \quad (3)$$

$$B_2 = \frac{-Y_1-Y_2+Y_3+Y_4}{4}, \quad (4)$$

$$B_{12} = \frac{Y_1-Y_2-Y_3+Y_4}{4}, \quad (5)$$

where Y_i – (i=1,2,3,4) is the value of the response function for the selected registered parameter for each separate experiment.

The calculated regression coefficients are defined as follows.

The regression models describing the response function for soil matrices contaminated with 1 APC of aviation kerosene at different stages of the observation period are as follows:

Day 5: $Y = 124.5 + 38x_1 + 37x_2 + 50.5x_1x_2,$ (6)

Day 7: $Y = 86 + 10x_1 - 1.5x_2 + 22.5x_1x_2,$ (7)

Day 9: $Y = 76.75 + 2.25x_1 - 10.75x_2 + 14.75x_1x_2.$ (8)

The regression models describing the response function for soil matrices contaminated with 10 APC of aviation kerosene at different stages of the observation period are as follows:

Day 5: $Y = 143.75 - 6.25x_1 + 56.25x_2 + 6.25x_1x_2,$ (9)

Day 7: $Y = 74.5 - 25.5x_1 - 13x_2 - 13x_1x_2.$ (10)

Day 9: $Y = 74.5 - 25.5x_1 - 13x_2 - 13x_1x_2.$ (11)

The regression models describing the response function for soil matrices contaminated with 100 APC of aviation kerosene at different stages of the observation period are as follows:

Day 5: $Y = 98 - 0.5x_1 + 10.5x_2 + 12x_1x_2,$ (12)

Day 7: $Y = 72 + 5.5x_1 - 15.5x_2 + 18x_1x_2,$ (13)

Day 9: $Y = 68 + 1.5x_1 - 19.5x_2 + 14x_1x_2.$ (14)

Following the estimation of the regression coefficients, the model's goodness-of-fit was validated using Fisher's F-test. The statistical analysis demonstrated that all derived regression equations adequately characterize the investigated biological processes. In all instances, the condition $F \leq F_{crit}$ was satisfied (F = 0.7669 in this study), confirming the model's validity at a significance level of α = 0.05.

The significance of individual regression coefficients was further evaluated using Student's t-test, exemplified here by the data from the fifth day of observation. For the 1 APC variant, all coefficients were found to be statistically significant. However, it was observed that as the petroleum concentration exceeds the 1 APC threshold, the coefficient B_1 loses its statistical significance and may be excluded from the model.

Thus, the final regression models characterizing the development of the biological test system on the fifth day of observation are defined by the following equations:

Day 5: $Y = 124.5 + 38x_1 + 37x_2 + 50.5x_1x_2,$ (15)

Day 7: $Y = 143.75 + 56.25x_2 + 6.25x_1x_2,$ (16)

Day 9: $Y = 98 + 10.5x_2 + 12x_1x_2.$ (17)

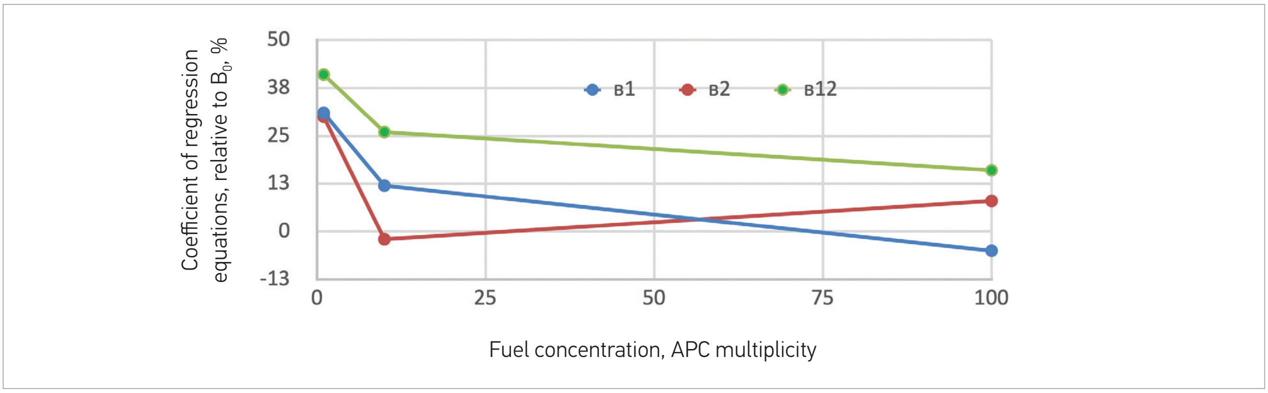
Within these regression models, x_1 and x_2 represent the experimental variables influencing seedling development. The intercept (B_0) reflects the baseline growth response under control conditions, while the coefficients for x_1 and x_2 quantify the magnitude and direction of the independent effects exerted by each factor. Furthermore, the interaction term (x_1x_2) characterizes the synergistic or antagonistic effects arising from the simultaneous application of both factors.

The derived models demonstrate that both individual and combined effects significantly modulate the observed morphological responses. Notably, the high magnitude of the interaction coefficients suggests that the combined action of the investigated factors is a primary determinant of the overall growth dynamics in the bioassays. Consequently, these regression equations serve both descriptive and predictive functions, allowing for the assessment of plant responses across a range of experimental conditions.

Following the aforementioned algorithmic procedure, regression coefficients were calculated to establish the concentration-dependent relationship based on the root elongation of *Lactuca sativa* seedlings. These estimations were performed for seeds subjected to 1-minute hyperthermic pre-treatment at 60°C and subsequently cultivated in soil matrices contaminated with aviation kerosene.

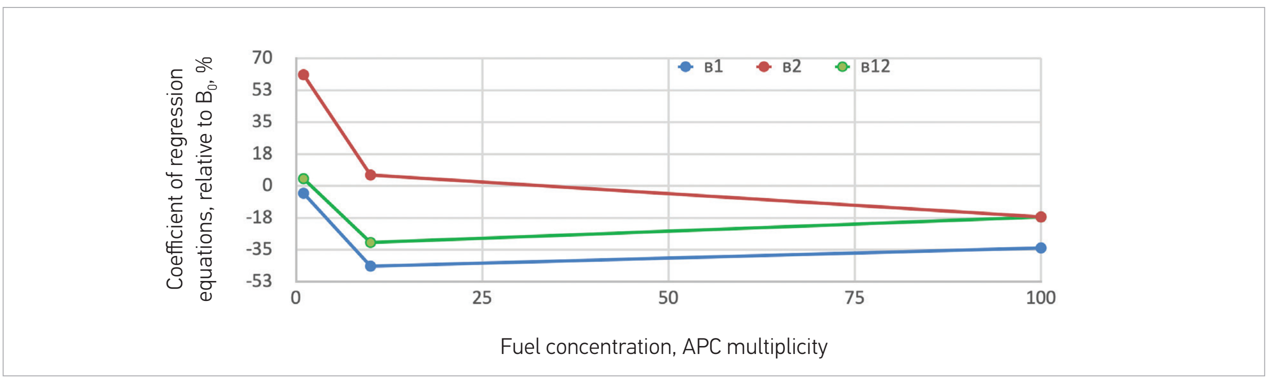
The calculated coefficients are illustrated in *Figs. 2–4*, while the temporal dynamics of these coefficients across varying kerosene concentrations are presented in *Figs. 5–7*.

Fig. 2. *Concentration-dependent dynamics of regression coefficients (normalized to the intercept B_0, %) for root elongation on the fifth day of observation: B_1 – effect of hyperthermic sensitization; B_2 – effect of aviation kerosene contamination; B_{12} – interaction effect between thermal and chemical factors*



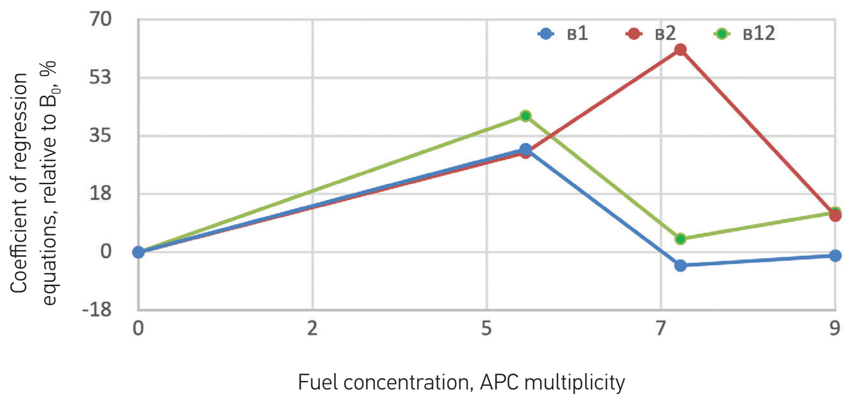
As illustrated in *Fig. 2*, on the fifth day of the experiment, the inhibitory effect of hyperthermia (B_1) on root elongation was restricted to the 100 APC kerosene treatment. Conversely, at lower concentrations, the isolated influence of kerosene was evident, transitioning to a stimulatory effect at 1 APC (B_2). The interaction between factors x_1 and x_2, characterized by the concentration-dependent coefficient B_{12}, remained positive across all kerosene concentrations. These findings suggest that the combined application of these factors amplified their individual positive effects, manifesting as a synergistic interaction.

Fig. 3. *Concentration-dependent dynamics of regression coefficients (normalized to the intercept B_0, %) for root elongation on the seventh day of observation: B_1 – effect of hyperthermic sensitization; B_2 – effect of aviation kerosene contamination; B_{12} – interaction effect between thermal and chemical factors.*



By the seventh day of observation (*Fig. 3*), the influence of x_1 (hyperthermic seed treatment) manifested exclusively as an inhibitory effect. Factor x_2 exhibited a negative impact only at a concentration of 100 APC. The interaction coefficient B_{12} was negative at both 10 and 100 APC, signifying an additional adverse effect resulting from the combined application of these factors, particularly at the highest concentration. This indicates a negative synergism, wherein the simultaneous exposure to both factors intensified their individual toxicity. These results underscore the potential for exacerbated deleterious impacts under stressful environmental conditions.

Fig. 4. *Concentration-dependent dynamics of regression coefficients (normalized to the intercept B_0, %) for root elongation on the ninth day of observation: B_1 – effect of hyperthermic sensitization; B_2 – effect of aviation kerosene contamination; B_{12} – interaction effect between thermal and chemical factors*



By the ninth day of observation (*Fig. 4*), the influence of x_1 on root elongation shifted toward a slightly positive trend, suggesting the onset of regenerative processes. This indicates that the hyperthermal seed treatment, under the specified heating regime, did not induce irreversible physiological damage. Concurrently, root growth was generally stimulated by factor x_2, maintaining a positive effect notably at the 1 APC level. The interaction coefficient (B_{12}) remained positive, significantly mitigating the inhibitory effects associated with x_2 (fuel) exposure.

Fig. 5. *Dynamics of regression coefficients for root length in soil contaminated with petroleum products at 1 APC (compared to B_0, (%)): B_1 – main effect of hyperthermia; B_2 – main effect of kerosene; B_{12} – interaction coefficient of the combined factors*

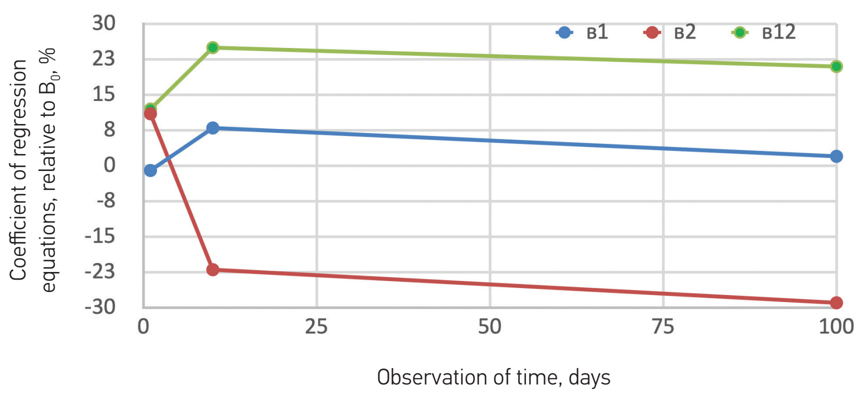


Fig. 6. *Dynamics of regression coefficients for root length in soil contaminated with petroleum products at 10 APC (compared to B_0, (%)): B_1 – main effect of hyperthermia; B_2 – main effect of kerosene; B_{12} – interaction coefficient of the combined factors*

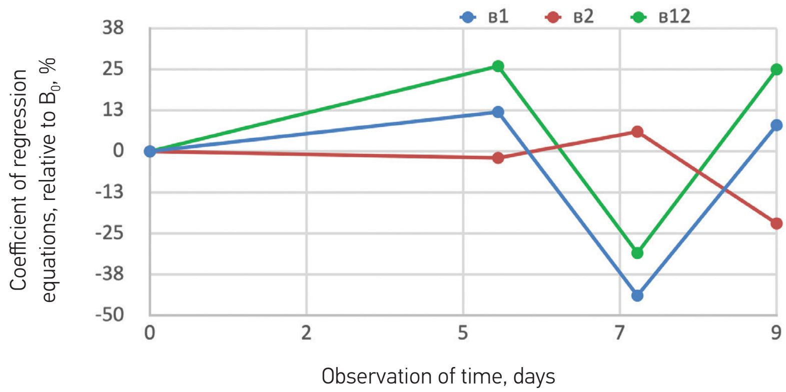
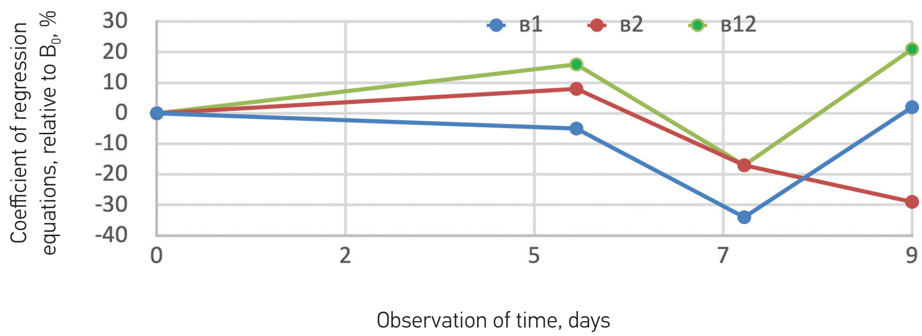


Fig. 7. *Dynamics of regression coefficients for root length in soil contaminated with petroleum products at 100 APC (compared to B_0, (%)): B_1 – main effect of hyperthermia; B_2 – main effect of kerosene; B_{12} – interaction coefficient of the combined factors*



Consequently, it can be inferred that at kerosene concentrations of 1 APC or lower, no additional inhibitory effects occur in pre-sensitized plants, as simulated by hyperthermal seed treatment (x_1). This conclusion is further corroborated by the analysis of factor dynamics (*Fig. 5–7*). An intensification of the x_2 effect was exclusively observed at higher concentrations, specifically within the range of petroleum soil contamination, where stimulatory responses in plant bioassays have been previously documented.

The concentration dependence of regression coefficients for the stem length of lettuce (*Lactuca sativa*) seedlings was derived from seeds subjected to a 5-minute thermal treatment at 60°C and subsequently cultivated in aviation kerosene-contaminated soil. These findings are illustrated in *Fig. 8–10*, while the temporal dynamics of the coefficients across varying kerosene concentrations are presented in *Fig. 11–13*.

As illustrated in *Figs. 8–10*, the impact of hyperthermal treatment (x_1) on seedling stems mirrored the patterns observed in the root systems, with evidence of growth recovery emerging by the ninth day. The transient inhibitory effect on stem elongation on day 5 may be attributed to inter-organ competition for seed-derived nutrients. Under conditions of high metabolic demand, the prioritized stimulation of one organ may result in the reciprocal suppression of another.

Fig. 8. *Concentration dependence of regression coefficients (relative to B_0, %) for seedling stem length on day 5 of observation in petroleum-contaminated soil: B_1 – main effect of hyperthermia; B_2 – main effect of kerosene; B_{12} – interaction coefficient representing the combined influence of both factors*

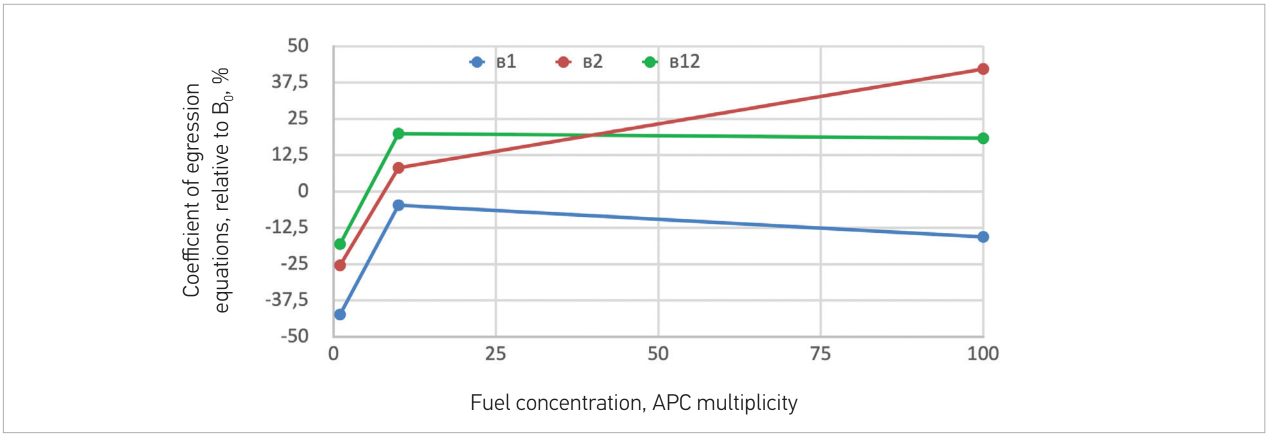


Fig. 9. *Concentration dependence of regression coefficients (relative to B_0, %) for seedling stem length on day 7 of observation in petroleum-contaminated soil: B_1 – main effect of hyperthermia; B_2 – main effect of kerosene; B_{12} – interaction coefficient representing the combined influence of both factors*

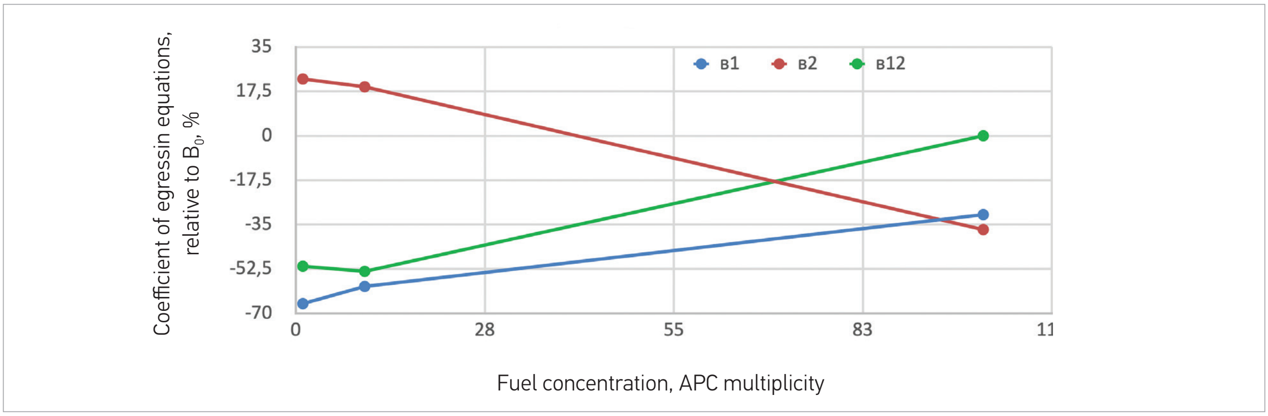


Fig. 10. *Concentration dependence of regression coefficients (relative to B_0, %) for seedling stem length on day 9 of observation in petroleum-contaminated soil: B_1 – main effect of hyperthermia; B_2 – main effect of kerosene; B_{12} – interaction coefficient representing the combined influence of both factors*

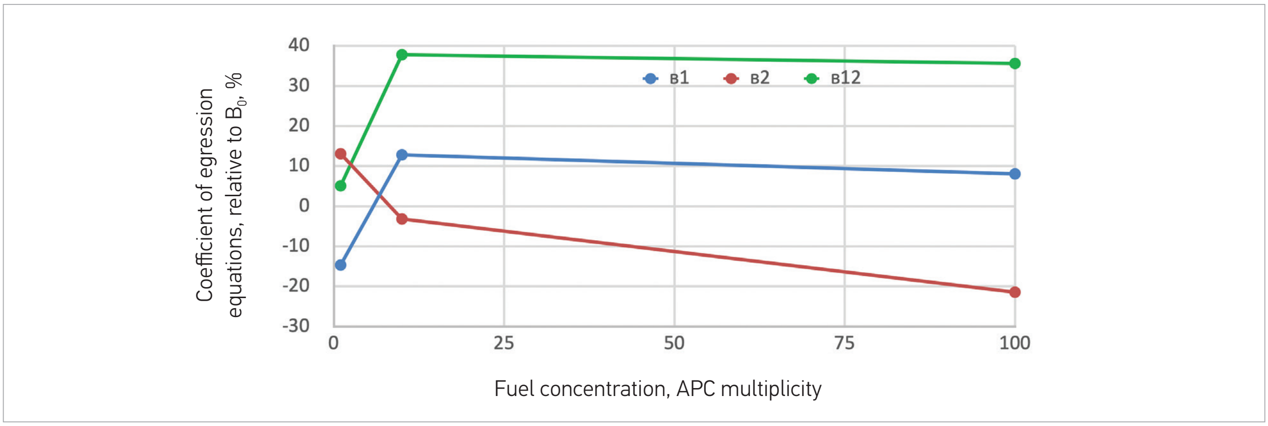
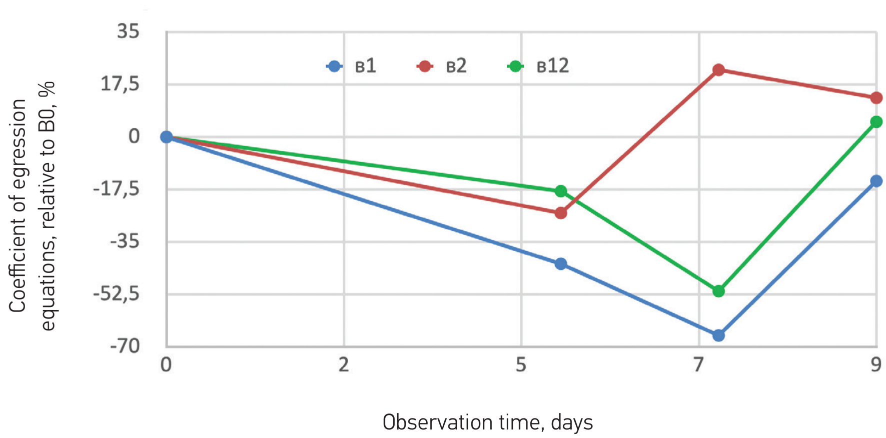


Fig. 11. *Dynamics of regression coefficients for seedling stem length in soil contaminated with petroleum products at 1 APC (relative to B_0, %): B_1 – main effect of hyperthermia; B_2 – main effect of kerosene; B_{12} – interaction coefficient reflecting the combined influence of both factors*



Kerosene contamination (x_2) initially induced a stimulatory response at low concentrations (1 and 10 APC on days 5 and 7), whereas higher exposure levels (10 and 100 APC) exerted a pronounced negative impact. By the later stages of observation (*Figs. 11–13*), seedlings exposed to low concentrations exhibited a return to baseline growth parameters. This phenomenon characterizes a transient hormetic response to the contaminant, where low-dose stimulation precedes potential recovery.

The contribution of non-additivity (coefficient B_{12}) in the reaction of the stem part also changes with the time of observation. Specifically, for 1 APC, a synergistic enhancement of the combined negative impact was observed on days 5 and 7, indicating that the joint effect exceeded the sum of individual factor influences (*Fig. 11*).

Fig. 12. *Dynamics of regression coefficients for seedling stem length in soil contaminated with petroleum products at 10 APC (relative to B_0, %): B_1 – main effect of hyperthermia; B_2 – main effect of kerosene; B_{12} – interaction coefficient reflecting the combined influence of both factors*

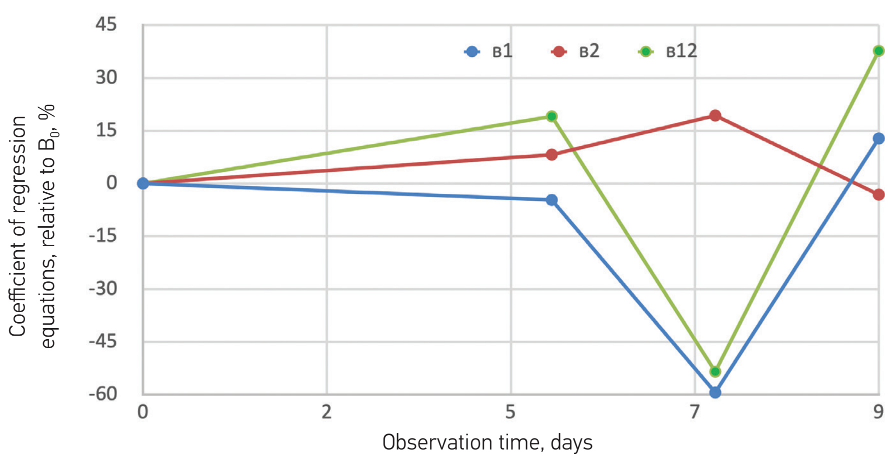
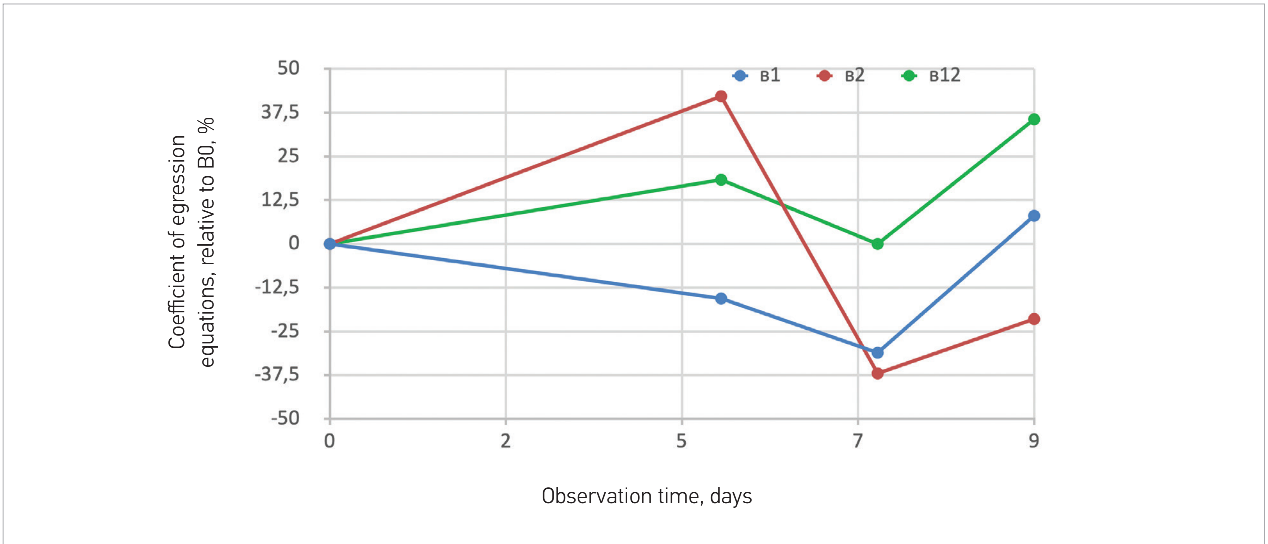


Fig. 13. *Dynamics of regression coefficients for seedling stem length in soil contaminated with petroleum products at 100 APC (relative to B_0, %): B_1 – main effect of hyperthermia; B_2 – main effect of kerosene; B_{12} – interaction coefficient reflecting the combined influence of both factors*



At an exposure level of 10 APCs (*Fig. 12*), an intensified inhibitory effect of x1 was recorded exclusively on the 7th day of observation. In the case of 100 APCs (*Fig. 13*), the fluctuations of the B_{12} coefficient mirrored the dynamics of B_1, albeit maintaining positive values. Consequently, these findings suggest that the duration of soil biotesting under petroleum contamination and hyperthermic seed treatment should be limited to a maximum of 7 days.

Within the scope of this study, the correlation between hyperthermia and biotoxicity is defined through a sensitization mechanism, wherein short-term thermal exposure of seeds (60°C for 1 minute) serves as a diagnostic enhancer that modulates the biological response to chemical contamination by aviation kerosene. At low fuel concentrations not exceeding the APC, hyperthermia does not intensify toxic effects and, in certain instances, may even facilitate temporary growth stimulation. However, as hydrocarbon content increases to levels of 10–100 APC, a negative synergism emerges, whereby thermal treatment radically intensifies the inhibition of growth processes. This interaction is non-additive: hyperthermia acts as a factor that depletes the organism's adaptive resources and alters cell membrane permeability, thereby facilitating the influx of toxic hydrocarbons and provoking more severe oxidative stress. This relationship is most pronounced on the 7th day of observation, when mathematical models (specifically the B_{12} coefficient) demonstrate a systemic transition from hormetic stimulation to intensive inhibition. This allows for the application of hyperthermia as a tool for detecting latent toxicity that remains undetectable by standard bioassay methods under low levels of anthropogenic load.

Conclusion

This study examined the effects of hyperthermia on test plants to simulate the cumulative impact of multiple factors under conditions of kerosene-induced toxicity. The dynamics of these processes were monitored over a period of 5 to 9 days, extending beyond the standard 5-day biotesting protocol to capture delayed physiological responses. To quantify the influence of these factors, a full factorial design was employed to measure stem and root elongation, with the resulting data used to construct predictive regression models.

Experimental results indicated that at kerosene concentrations of 1 APC or lower, no potentiation of the inhibitory effect was observed in pre-sensitized plants (modeled via hyperthermic seed treatment, x_1). Analysis of factor dynamics confirmed that the enhancement of the x_2 effect occurred exclusively at elevated concentrations, specifically at levels previously identified as stimulatory in plant bioassays.

At a concentration of 10 APCs, a significant increase in the negative impact of x_1 was recorded only on the 7th day of observation. Conversely, at 100 APCs, the B_{12} coefficient exhibited synchronous dynamics with B_1, albeit maintaining positive values.

Based on these findings, it is determined that the optimal duration for soil biotesting in petroleum-contaminated environments using hyperthermia-treated seeds should be capped at 7 days. These regression models provide a robust framework for ecological monitoring, enabling the estimation of fuel concentrations based on established phytotoxicity thresholds. Furthermore, the application of hyperthermia to plant seeds is recommended as a standardized stress-simulation technique for future environmental impact assessments of petroleum products.

References

Bogolyubov V. M., Klymenko M. O., Mokin V. B., Bogolyubov V. M. (2010) Monitoryn dovkillya: pidruchnyk [Environmental monitoring: a textbook]. Vinnytsya: VNTU (*in Ukrainian*).

Brtnický M., Pecina V., Baltazár T., Vašinová Galiová M., Baláková L., Bęś A., Radziemska M. (2020) Environmental Impact Assessment of Potentially Toxic Elements in Soils Near the Runway at the International Airport in Central Europe. Sustainability 12(17): 7224. Available at: https://doi.org/10.3390/su12177224

Brtnický M., Pecina V., Hladký J., Radziemska M., Koudelkova Z., Klimanek M., Richtera l., Adamcova D., Elbl J., Vašinová Galiová M., Baláková L., Kynický J., Smolikova V., Houška J., Vaverkova M. D. (2019) Assessment of phytotoxicity, environmental and health risks of historical urban park soils. Chemosphere 220: 678–686. Available at: https://doi.org/10.1016/j.chemosphere.2018.12.188

Cherniak L., Mikhieiev O. M., Madzhd S. M., Hryb A. O. (2020) Vykorystannia system testuvannia roslyn dlia otsinky ekolohichnoho stanu gruntiv na terytorii aeroportu [Use of Plant Test Systems for Assessing the Ecological Condition of Soils within Airport Territory]. Visnyk Kremenchutskoho natsionalnoho universytetu imeni Mykhaila Ostrohradskoho (123) (*in Ukrainian*).

Cherniak L., Mikhyeyev O., Madzhd S., Lapan O., Dmytrukha T., Valentyna P. (2021b) Determination of the Dependence of Plants Growth Characteristics on the Concentration of Petrochemicals in the Soil. Journal of Ecological Engineering 22(2): 226–233. Available at: https://doi.org/10.12911/22998993/131063

Cherniak L. M., Mikhieiev O. M., Madzhd S., Lapan O., Korniienko I., Dmytrukha T. (2021a) The Usage of Plant Test Systems for the Determination of Phytotoxicity of Contaminated with Petroleum Products Soil. Journal of Ecological Engineering 22(6): 66–71. Available at: https://doi.org/10.12911/22998993/137363

Cherniak L. M., Petruk R. V., Mikhieiev O. M., Madzhd S. M., Petruk G. D. (2022) Investigation of the Influence of Hyperthermia and Soil Pollution with the Petrochemicals on Test Objects Using the Method of Mathematical Planning. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 5: 153-157. Available at: https://doi.org/10.33271/nvngu/2022-5/153

Cherniak L., Shtyka O., Bilyk T. (2017) Soil decontamination on airports territories: peculiarities and challengers. In: Proceedings of the International Symposium on Sustainable Aviation, Ukraine, Kyiv, September 10–13: 2017: 77.

de Miguel E., Llamas J. F., Chacon E., Berg T., Larssen S., Royset O., Vadset M. (1997) Origin and Patterns of Distribution of Trace Elements in Street Dust: Unleaded Petrol and Urban Lead. Atmospheric Environment 31(17): 2733–2740. Available at: https://doi.org/10.1016/S1352-2310(97)00101-5

DeCoursey W. J. (2003) Statistics and Probability for Engineering Applications with Microsoft Excel. Amsterdam; Boston: Newnes. xv, 396 p. Available at: https://archive.org/details/statisticsprobab0000deco

Dzhura N. M. (2011) Mozhlyvosti vykorystannia roslynnykh test-system dlia biomonitorynhu naftozabrudnenykh gruntiv. Biolohichni studii [Potential of Plant Test Systems for Biomonitoring of Oil-Contaminated Soils. Biological Studies]. Studia Biologica 5(3) (*in Ukrainian*).

Franchuk H., Antonov A., Madzhd S., Zagorui Ya. (2006) Ekolohichna otsinka vplyvu aviatsiinykh transportnykh protsesiv na yakist komponentiv dovkillia [Environmental assessment of aviation transport processes quality component environment]. Proceedings of National Aviation University 27(1): 184–190. Available at: https://doi.org/10.18372/2306-1472.27.1281 (*in Ukrainian*).

Grodzinskyi D. M., Shilina Yu. V., Kutsokon N. K. et al. (2006) Zastosuvannia roslynnykh test-system dlia otsinky kombinovanoi dii faktoriv riznoi pryrody: metodychni po otsintsi dopustymykh rivniv radionuklidnoho ta khimichnoho zabrudnennia za yikh kombinovanoi dii [The use of plant test systems for the assessment of the combined effect of factors of different nature: Methodological recommendations for the assessment of permissible levels of radionuclide and chemical pollution due to their combined effect]. Fitosotsiotsentr, Kyiv (*in Ukrainian*).

Janic M. (1999) Aviation and externalities: The accomplishments and problems. Transportation Research Part D: Transport and Environment 4(3): 159–180. Available at: https://doi.org/10.1016/S1361-9209(99)00003-6

Kvaterniuk S., Pohrebennyk V., Petruk V., Kvaterniuk O., Kochanek A. (2018) Mathematical modeling of light scattering in natural water environments with phytoplankton particles. In: SGEM2018 Conference Proceedings, Bulgaria, Albena2–8: 2018 18(2.1): 545–552. Available at: https://doi.org/10.5593/sgem2018/2.1/S07.069

Lapan O. V. (2012) Otsinka perekhodu vazhkykh metaliv iz gruntu v roslyny na terytoriiakh, prylehlykh do aviapidpryiemstv [Evaluation of the transition of heavy metals from soil to plants in the territories adjacent to aviation enterprises]. In: Proceedings of XII International Scientific and Practical Conference of Young Scientists and Students "Aviation. Modern Problems of Science", Ukraine, Kyiv 4–5: 2012: 170 (*in Ukrainian*).

Lapan O. V., Mikhyeyev O. M., Madzhd S. M. (2020) Modyfikatsiia sorbtsiinoi zdatnosti roslynnoho komponenta bioplato do 137Cs [Modification of the sorption ability of the plant's component of the bioplato regarding 137Cs]. Nuclear Physics and Atomic Energy 21(2): 172–177. Available at: https://doi.org/10.15407/jnpae2020.02.172 (*in Ukrainian*).

Madzhd S. M., Bovsunovskyy Y., Tagachinska O. (2016) Naukovi metody shcho do kontroliu yakosti gruntiv yak indykatora ekolohichnoi nebezpeky na tekhnohenno navantazhenykh terytoriiakh [Quality control of soils as indicators of environmental hazards of urban areas by scientific method]. Visnyk Kremenchutskoho natsionalnoho universytetu imeni Mykhaila Ostrohradskoho 2(97): 115–121. Available at: https://visnikkrnu.kdu.edu.ua/statti/115_2_2016_1.pdf (*in Ukrainian*).

Madzhd S. M., Cherniak L. M., Mikhieiev O. M. (2020) Vykorystannia Roslyn dlia indykatsii stanu gruntiv tekhnohenno-navantazhenykh terytorii [Use of Plants for Indication of Soil Conditions in Technogenically Loaded Areas]. Visnyk Kremenchutskoho natsionalnoho universytetu imeni Mykhaila Ostrohradskoho 1(120) (*in Ukrainian*).

Madzhd S. M. and Franchuk H. M. (2012) Biologichni metody otsinky ekolohichnoho stanu gruntiv bilia aviapidpryiemstv [Biological methods of assessing the ecological state of soils near airline companies]. Ekologichna bezpeka ta pryrodokorystuvannya [Environmental safety and nature management] 11: 49–52 (*in Ukrainian*).

Madzhd S. M., Franchuk H. M., Hroza V. A. (2012) Statystychnyi analiz toksychnosti snihovoho pokryvu na terytoriiakh poblyzu pidpryiemstv z ekspluatatsii ta remontu aviatsiinoi tekhniky [The statistical analysis of toxicity of snowpack areas near companies of aviation technique operating and repairing]. Science-Based Technologies 15(3): 36–39. Available at: https://doi.org/10.18372/2310-5461.15.5135 (*in Ukrainian*).

Mikhieiev O. M., Hushcha M. I., Shylina Yu. V., Ovsiannikova L. H. (2006) Zastosuvannia roslynnykh test-system dlia otsinky kombinovanoi dii stresoriv riznoi pryrody na ekosystemy [Application of Plant Test Systems for Assessing the Combined Effects of Stressors of Different Nature on Ecosystems] Naukovi pratsi. Ekolohiia 53(40): 56–64 (*in Ukrainian*).

Radomska M. M., Madzhd S. M., Cherniak L. M., Mikhyeyev O. M. (2020) Environmental Pollution in the Airport Impact Area: Case Study of the Boryspil International Airport. Environmental Problems 5(2): 76–82. Available at: https://doi.org/10.23939/ep2020.02.076

Ray S., Khillare P. S., Kim K. H. (2012) The Effect of Aircraft Traffic Emissions on the Soil Surface Contamination Analysis around the International Airport in Delhi, India. Asian Journal of Atmospheric Environment 6(2): 118–126. Available at: https://doi.org/10.5572/ajae.2012.6.2.118

Shevchyk-Kostiuk L. Z., Romaniuk O. I., Oshchapovskyi I. V. (2022) Osoblyvostizabrudnenniagruntivnaftoiu ta naftoproduktamy: ohliad [Peculiarities of soil pollution by oil and petroleum products: a review]. Acta Biologica Ukrainica 1: 32–40. Available at: https://www.researchgate.net/publication/366513369_Osoblivosti_zabrudnenna_gruntiv_naftou_ta_naftoproduktami_oglad (*in Ukrainian*).

Trofimov I., Pavliukh L., Novakivska T., Bondarenko D. (2020) Assessment of Fitotoxic Toxicity of Mixed Aviation Fuels Using of Plant Testers. International Independent Scientific Journal 11: 9–17. Available at: https://www.iis-journal.com/wp-content/uploads/2024/03/IISJ_11.pdf

Walpole R., Meyers R., Meyers S., Ye K. (2006) Probability & Statistics for Engineers & Scientists. Prentice Hall.