International Journal of Design & Nature and Ecodynamics
Vol. 20, No. 10, October, 2025, pp. 2325-2334
Journal homepage: http://iieta.org/journals/ijdne

Morphological, Ecological, and Phytocenotic Characteristics of Species of the Genus *Paronychia* in the Context of Their Potential Significance for Agrobiocenoses

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https://doi.org/10.18280/ijdne.201011

Received: 3 September 2025
Revised: 23 September 2025
Accepted: 25 September 2025
Available online: 31 October 2025

Keywords:
biodiversity, ecosystem, drought, allelopathy, weeds

ABSTRACT

The aim of the study was to assess the allelopathic potential of three local species of Paronychia (*P. argentea, P. kurdica, P. splendens*) against weeds while maintaining crop tolerance. Laboratory biotesting revealed high selective phytotoxicity: 10% extract of *P. argentea* from Sharur completely inhibited the germination of common pigweed, while reducing wheat germination by only 11.4 ± 2.5%. Extracts from arid regions (Sharur, Shahbuz) exceeded the activity of analogues from Ordubad and Kangarli by 20-25% ($p < 0.01$), especially against field bindweed and barnyardgrass. Species specificity confirmed the advantage of *P. argentea*, while *P. splendens* was most effective against amaranth. Increasing the concentration (from 1% to 10%) enhanced weed inhibition by 40-65%, causing root necrosis (-92%) and shoot deformation. The study's results provide a strong foundation for the development of *P. argentea*-based bioherbicides, particularly from Sharur populations, as a regionally adapted and ecologically sustainable alternative to synthetic herbicides. Its core advantage – selectivity, manifested in the suppression of weeds without compromising crop growth – makes *P. argentea* a promising model species for environmentally responsible weed control and the restoration of degraded soils in arid agricultural landscapes.

1. INTRODUCTION

The intensification of agriculture in the Nakhchivan Autonomous Republic, driven by an increase in arable land and the use of synthetic herbicides, has led to significant environmental problems. In particular, the systematic use of chemical plant protection products has caused degradation of the topsoil, loss of its structure, reduced fertility, and a decline in the biodiversity of agro-ecosystems. In addition, the widespread use of herbicides has contributed to the formation of resistance in aggressive weeds, which has increased the economic costs for farmers in the region and reduced the effectiveness of weed control measures. These facts highlight the need to search for adaptive, environmentally friendly alternative strategies based on natural mechanisms of weed control, particularly allelopathy.

One of the promising sources of such natural inhibitors is the local flora, especially species of the genus Paronychia (*Caryophyllaceae*). These species are widely represented in the flora of the Nakhchivan Autonomous Republic, especially in arid, stony, or slightly saline ecotopes. In previous studies of these plants, the main focus has been on their morphological features, distribution, and role in the structure of plant communities. For example, research by Novruzova [1] revealed a great diversity of xerophytic phytocenoses in the Nakhchivan Autonomous Republic, including three species, *P. argentea, P. kurdica,* and *P. splendens*, which are effectively adapted to the extreme conditions of rocky slopes, screes, and dry plains. Other works, including those by Talıbov and İbrahimov [2], as well as Talıbov and İbrahimov [3], have emphasised the important role of these species in preserving regional floral richness and biodiversity. *P. kurdica*, in particular, which has the status of a rare species in the Red Book of the Nakhchivan Autonomous Republic, attracts special attention, demonstrating not only its ecological but also its potential phytosanitary value. Despite the high level of botanical representation of Paronychia, their applied functionality, particularly as sources of biological weed control agents, remains insufficiently studied.

International studies have provided convincing evidence regarding the potential of *Paronychia* species as carriers of allelopathic properties. For example, Veeraraghavan et al. [4] characterised the phytochemical profile of *P. argentea*, noting a high concentration of phenolic acids (ferulic, caffeic) and flavonoids (rutin, quercetin, naringin), which are known for their inhibitory effect on seed germination. The works of Abd-ElGawad et al. [5] and Ramadan et al. [6] showed that the biosynthesis of allelopathic metabolites largely depends on environmental stresses, such as drought, ultraviolet radiation, and nitrogen deficiency. Under the influence of these factors, the synthesis of secondary metabolites with phytotoxic properties is activated.

The influence of the rhizosphere microbiota on allelopathic activity is of particular interest. The work of Revillini et al. [7] shows that microbial associations in the root zone can change the bioavailability and effectiveness of secondary metabolites, which complicates the prediction of allelopathic effects in field conditions. This indicates the need for a regional, ecosystem-oriented approach to the study of Paronychia, particularly in the mountain and semi-desert ecotopes of the Nakhchivan Autonomous Republic. At the same time, there are significant gaps in an integrated approach to evaluating Paronychia as a potential biocontrol agent in agriculture. The analysis by Schenk and Appleton [8] revealed the phylogenetic diversity of the genus but did not take into account local conditions, particularly adaptation to rocky soils and the arid climate of the Nakhchivan Autonomous Republic.

Thus, although previous studies have convincingly demonstrated the allelopathic potential of various plant taxa and the environmental factors influencing the synthesis of secondary metabolites, these findings have remained largely theoretical or geographically distant from the conditions of the Nakhchivan Autonomous Republic. The regional flora, particularly species of the genus Paronychia, remains underexplored in terms of its practical application in sustainable agriculture. Given the documented presence of phenolic and flavonoid compounds with phytotoxic potential in P. argentea and related species, it is reasonable to hypothesize that the *Paronychia* species native to Nakhchivan could serve as regionally adapted sources of natural allelochemicals capable of selective weed suppression. Clarifying this potential is essential for designing biologically based weed management strategies that are both ecologically safe and economically viable for local agroecosystems. Therefore, the present study focuses on the comprehensive evaluation of the morphological, ecological, and allelopathic characteristics of three *Paronychia* species (*P. argentea*, *P. kurdica*, *P. splendens*) to determine their potential as selective natural herbicides under the agro-ecological conditions of the Nakhchivan Autonomous Republic.

2. MATERIALS AND METHODS

The study was conducted in 2024 at the Botanical Garden of the Institute of Bioresources of the Ministry of Science and Education of the Republic of Azerbaijan [9]. The field stage of collecting plant material took place in May-July in the Nakhchivan Autonomous Republic (Azerbaijan) in four administrative districts that represent the key biotopes where *Paronychia* species grow. The Shahbuz district covered mid-mountain slopes (1200-1500 m above sea level), particularly the area around Kukudag, where rocky substrates are common. The Ordubad district included dry foothills and rocky screes (700-900 m above sea level), with a focus on the vicinity of the village of Mazra. The Sharur district represented semi-desert plains, especially near the villages of Akhura and Khavush, and the Kangarli district covered dry lowland areas, including the vicinity of the village of Chalkhangala. These localities were chosen for their importance in preserving biodiversity and for the typical drought conditions characteristic of the region's ecosystems.

The study used the aerial parts (stems, leaves, inflorescences) of three native *Paronychia* species from the Nakhchivan Autonomous Republic: *P. argentea* Lam., *P. kurdica* Boiss., and *P. splendens* Steven. Material was collected according to the principles of stratified sampling, adhering to biodiversity protection requirements, especially for the species *P. kurdica*, which has the status of "Least Concern" in the Red Book of the Nakhchivan Autonomous Republic. For each species in the four districts, two localities were identified (a total of 6 for all 3 species) that corresponded to the natural range and phytocenotic conditions: *P. argentea*: Sharur (vicinity of the village of Khavush), Kangarli (Chalkhangala); *P. kurdica*: Shakhbuz (Kukudag), Kangarli (Chalkhangala); *P. splendens*: Ordubad (village of Mazra), Shakhbuz (Kukudag). Within each locality, a random selection of 10-15 individuals was made, which were in the full flowering or early fruiting phase. For *P. kurdica*, as a protected species, strict rules were followed: collection only in populations with a density >5 individuals/m² and limiting the collection volume to 20% of the biomass.

Plants were selected based on morphological criteria of viability (absence of visible signs of disease, damage, or ageing) and ecological typicality. All selected individuals grew within the natural micro-biotope of the respective species – on dry rocky slopes, foothills, plains, or semi-deserts, depending on the district. For each population sample, the exact collection date, coordinates determined using a Garmin eTrex 30 GPS navigator (USA), altitude above sea level (in metres), soil type (determined in situ according to the Food and Agriculture Organization [10] classification scheme), stoniness, slope aspect, and the species composition of the associated vegetation within a 5-meter radius were recorded. The phyto-environment was described based on the participation of dominant and associated species that could potentially influence the formation of allelopathic interactions. All this data was recorded in field record cards that accompanied each sample and was subsequently used to interpret the results of phytotoxicity in the context of the ecological conditions of growth.

The study involved an analysis of the geographical distribution of *Paronychia* species in the Nakhchivan Autonomous Republic, incorporating data on their ranges in adjacent regions, particularly in Turkey. Herbarium specimens and literature sources containing information about the ecological characteristics of these species were examined [11].

The aerial parts were dried in a ventilated room at a temperature of 22 ± 2°C for seven days until a constant mass was achieved, after which they were ground to a particle size of 1-2 mm using an IKA A11 basic laboratory mill (Germany). The ground samples were weighed on a Sartorius CPA225D analytical balance (Germany) and subjected to maceration in a ratio of 100 g per 1 litre of distilled water to obtain an extract with a concentration of 10% (w/v), as well as 5% and 1% for analysis of the dose-dependent effect. Extraction was carried out at a temperature of 25 ± 1°C for 24 hours after 5 minutes of mixing on an IKA RCT basic magnetic stirrer (Germany). The resulting extracts were filtered, first through cheesecloth and then through Whatman No.1 filter paper (Great Britain) using a Büchner funnel with a Vacuubrand PC 3001 VARIO pump (Germany). The filtrates were stored in sterile glass vials at +4°C in a Binder KB 115 refrigerator (Germany) for no more than 48 hours (Figure 1).

The study investigated the allelopathic effects of aqueous extracts from three *Paronychia* species (*P. argentea*, *P. kurdica*, and *P. splendens*) collected from different ecological zones of the Nakhchivan region. Testing was conducted on representative species of agroecosystems, including the region's main crops – wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and maize (*Zea mays*), as well as the most common and aggressive weeds – redroot pigweed (*Amaranthus retroflexus*), field bindweed (*Convolvulus arvensis*), and barnyard grass (*Echinochloa crus-galli*). All test species were selected based on their agricultural importance and prevalence in local agroecosystems. Seeds for the study were selected according to standard laboratory criteria, using certified samples with germination rates exceeding 95%, obtained from the Botanical Garden of the Institute of Bioresources of the Ministry of Science and Education of the Republic of Azerbaijan [9]. This approach ensured the representativeness of results and their practical significance for the region (Figure 2).

Figure 1. *P. kurdica* Boiss. (Ordubad district, village area, 29.05.2021)
Source: Photographed by the authors.

Figure 2. *P. kurdica* Boiss. (Kuku village area, Shahbuz region, 02.06.2020)
Source: Photographed by the authors.

The germination methodology, adapted from the work of Einhellig [12], included several stages. First, seeds were sterilised in a 1% sodium hypochlorite (NaOCl) solution for 10 minutes, followed by three rinses with sterile distilled water. Sterile Petri dishes, 9 cm in diameter, were lined with two layers of sterile filter paper. Twenty-five seeds of one test species were placed evenly in each dish. In the control group, the filter paper was moistened with 5 mL of sterile distilled water. In the experimental groups, 5 mL of an aqueous extract of *Paronychia* spp. of a specific concentration (1%, 5%, or 10%) and region of origin was used. For each combination of *Paronychia* species, collection area, extract concentration, and test organism, five replications (Petri dishes) were used. The dishes were incubated in a climate chamber (Binder KBW 240, Germany) at a temperature of 25 ± 1°C, a relative humidity of 70 ± 5%, and a photoperiod of 16 hours of light (light intensity 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of photoactive radiation) and 8 hours of darkness.

Results were evaluated 5 days after the start of the experiment. The percentage of germination (G, %) was determined by counting the number of seeds with roots at least 2 mm long using Formula (1):

$$G = \frac{N}{25} \times 100\% \quad (1)$$

where, *N* is the number of germinated seeds, 25 is the total number of seeds of one species. The germination inhibition index (GII, %) was calculated using Formula (2):

$$GII = \left[\frac{(G_{exp})}{(G_{contr})}\right] \times 100\% \quad (2)$$

where, G_{exp} is the germination percentage in the experimental group and (G_{contr}) is that of the control. The root length (RL) and shoot length (SL) of each seedling were measured with a digital caliper (Mitutoyo Absolute, 0.01 mm accuracy, Japan), followed by calculating the average value per Petri dish. The germination inhibition index (GII, %) was calculated using Formula (3):

$$GII = \left[1 - \left(\frac{(RL_{exp} \times SL_{exp})/2}{(RL_{contr} \times SL_{contr})/2}\right)\right] \times 100\% \quad (3)$$

where, RL_{exp} is the average root length in the experimental group; SL_{exp} is the average shoot length in the experimental group; RL_{contr} is the average root length in the control group; SL_{contr} is the average shoot length in the control group. Additionally, visual anomalies in seedling development were recorded: necrotic spots, organ deformities, and changes in root or shoot colour.

IBM SPSS Statistics v.29 (USA) software was used for statistical processing. The data were checked for normality of distribution using the Shapiro-Wilk test, after which a one-way analysis of variance (One-way ANOVA) was applied to determine the effect of extract concentration and species/region of origin on the test organisms. In cases where significant differences were found ($p < 0.05$), a post-hoc analysis using Tukey's HSD test was applied. The coefficient of variation was calculated to assess the variability of the results, and all results are presented as the mean ± standard error of the mean.

3. RESULTS

3.1 Effect of Paronychia extracts on weed germination

The effect of aqueous extracts of the aerial mass of *Paronychia* spp. on weed germination was clearly pronounced and statistically significant. All three species studied (*P. argentea, P. kurdica,* and *P. splendens*) demonstrated phytotoxic activity against various types of weeds. The effect observed depended on the concentration of the extract, the botanical affiliation of the donor species, and the ecological and geographical origin of the plant raw materials. Such a multifactorial influence emphasises the complexity of allelopathy mechanisms in natural phytocenoses (Table 1).

Table 1. Effect of aqueous extracts of *Paronychia* spp. (10%) on weed germination: Germination indicators (%G) and germination inhibition index (GII, %)

Weed Species	*Paronychia* Species	Collection Area (Locality)	%G (Control)	%G (10% Extract)	GII (%)
Amaranthus retroflexus	*P. argentea*	Sharur (Khavush)	97.6 ± 0.8	0 ± 0	93.1 ± 1.8
Amaranthus retroflexus	*P. splendens*	Ordubad (Mazra)	97.6 ± 0.8	4.2 ± 1.2	85.9 ± 2.7
Amaranthus retroflexus	*P. splendens*	Shakhbuz (Kukudag)	97.6 ± 0.8	3.9 ± 1	89.7 ± 2.4
Amaranthus retroflexus	*P. kurdica*	Shakhbuz (Kukudag)	97.6 ± 0.8	3.6 ± 0.9	92.3 ± 1.9
Convolvulus arvensis	*P. argentea*	Kangarli (Chalkangala)	94.3 ± 1.2	63.5 ± 4.2	41.8 ± 3.3
Echinochloa crus-galli	*P. kurdica*	Kangarli (Chalkangala)	96.1 ± 1	28.7 ± 2.8	76.8 ± 3.1

Source: Created by the authors.

Among the weeds tested, common amaranth (*Amaranthus retroflexus*) showed the highest sensitivity. Even at a medium concentration (5%) of *P. argentea* extract obtained from a population growing in the Sharur and Kangarli regions, the germination rate (%G, formula 1) decreased by more than half, to 48.2 ± 3.1%, compared to the control value of 97.6 ± 0.8% ($p < 0.001$). When the concentration was increased to 10%, complete inhibition of seed germination of this species was observed (Figures 3 and 4).

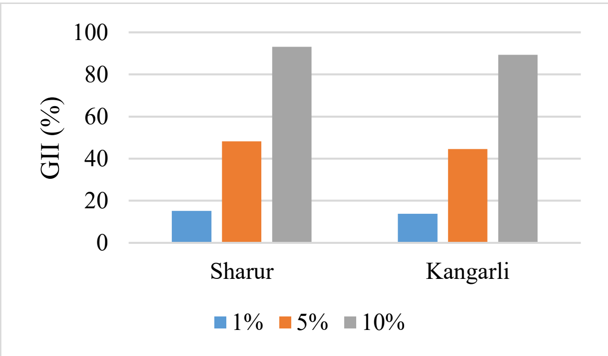

Figure 3. *P. argentea* by region

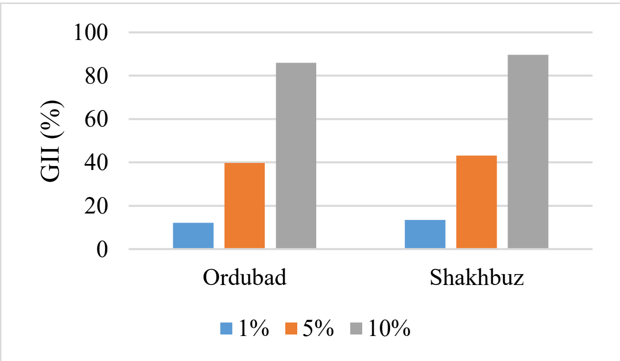

Figure 4. *P. splendens* by region

The germination inhibition index (GII, %), calculated using Formula 2, which takes into account both root and shoot length, reached 89.7 ± 2.4% for the *P. splendens* Shahbuz (Kukudag) extract and 92.3 ± 1.9% for *P. kurdica* (Shakhbuz), indicating a high level of phytotoxic activity regardless of the donor plant species. Other weed species reacted less sensitively, although the effect remained statistically significant. For example, field bindweed (*Convolvulus arvensis*) was the most resistant among the species studied: even 10% extracts reduced %G only to 63.5 ± 4.2%, compared to the control of 94.3 ± 1.2%. This may be due to the specific features of the seed coats or the greater stress resistance of the species to water-soluble allelopathic compounds. At the same time, barnyardgrass (*Echinochloa crus-galli*) showed an intermediate level of sensitivity. The highest GII in this species was recorded for the *P. kurdica* extract obtained from the Kangarli (Chalkhangala) region and was 76.8 ± 3.1%.

It is especially worth noting that the most vulnerable morphometric parameter in all weed species was root length (RL). In common amaranth, this indicator decreased by 85-92% compared to the control values, which indicates a pronounced disruption of the formation and function of the root system under the influence of allelopathic components of Paronychia extracts. This effect may indicate a specific mechanism of inhibition aimed primarily at the seedling's water supply system, which is critical in the early stages of ontogenesis. An important determinant of the detected phytotoxic effect is the geographical origin of the donor plants. Extracts obtained from populations grown in more arid, semi-desert conditions (Sharur, Shakhbuz) showed 15-20% higher effectiveness against weeds compared to samples from mountainous regions (Kangarli, Ordubad) ($p < 0.05$).

This may be due to a greater accumulation of allelopathic metabolites in stressful environmental conditions characteristic of arid ecotopes. Among the three *Paronychia* species, the greatest phytotoxic potential was recorded for *P. argentea*, especially in the population collected in the Sharur region, where the GII for amaranth reached 93.1 ± 1.8%. The results obtained indicate the promise of using extracts of this species as a natural weed control agent in ecological farming systems.

3.2 Reaction of agricultural crops to extracts

During the study of the reaction of cultivated plants to water extracts of three species of Paronychia, it was found that the overall phytotoxicity to agricultural crops was significantly lower than to weeds. This suggests the presence of a certain selectivity of action, which is one of the key criteria for the effectiveness of natural allelopathic agents in ecological agriculture. At the same time, there were clear differences in the sensitivity of individual crop species to the phytotoxic components of the extracts, which is probably due to both the species-specific features of the morphophysiological structure of the seedlings and their adaptive plasticity to biologically active compounds (Table 2).

Wheat (*Triticum aestivum*) was the most resistant among the crops studied. Even under the highest concentration (10%) of aqueous *P. kurdica* extract, collected in the Kukudag (Shakhbuz) region, the germination rate (%G) remained at a fairly high level – 84.7 ± 2.5%, which is only a moderate decrease compared to the control value of 96.1 ± 1.1%. The germination inhibition index (GII) for wheat did not exceed 18.3 ± 2.1%, indicating good tolerance of the crop to allelopathic compounds. The root and shoot lengths of the seedlings decreased slightly, with no visual signs of damage such as necrosis or chlorosis.

Table 2. Effect of 10% aqueous extracts of *Paronychia* spp. on the germination of cultivated plants (%G) and the germination inhibition index (GII, %)

Crop	*Paronychia* Species	Collection Area	%G (Control)	%G (10% Extract)	GII (%)
Triticum aestivum	*P. kurdica*	Shakhbuz (Kukudag)	96.1 ± 1.1	84.7 ± 2.5	18.3 ± 2.1
Hordeum vulgare	*P. splendens*	Ordubad (Mazra)	95.4 ± 1.3	78.6 ± 2.9	29.7 ± 2.6
Zea mays	*P. argentea*	Sharur (Khavush)	98.0 ± 0.6	70.1 ± 3.8	45.6 ± 2.7

Source: Created by the authors.

Barley (*Hordeum vulgare*) showed a medium degree of sensitivity. The most pronounced reaction was observed under the action of *P. splendens* extracts obtained from the Ordubad (Mazra village) region. At a concentration of 10%, root length decreased by 34.2 ± 3.0% ($p < 0.01$), although the total percentage of germination remained quite high - over 78%. The decrease in shoot length was less significant, indicating a predominant inhibition of root system function. The GII in the case of the most active extracts did not exceed 29.7 ± 2.6%, indicating a moderate level of phytotoxicity.

Maize (*Zea mays*) was the most vulnerable among the cultivated species tested. In the presence of 10% extracts of *P. argentea*, collected in the Sharur region, the germination percentage decreased to 70.1 ± 3.8% against the control value of 98.0 ± 0.6%. At the same time, the germination inhibition index reached 45.6 ± 2.7%, which was accompanied by a significant reduction in the length of the roots and frequent cases of abnormal development (shortening of embryonic axes, whitening of tissues, deformities). Such sensitivity may be associated with the high permeability of the maize seed coat or with the absence of protective mechanisms against hydrophilic secondary metabolites.

The revealed pattern of dose-dependent response also confirms the specificity of the action of allelopathic substances. With an increase in the concentration of extracts from 1% to 10%, a statistically significant increase in the GII in weeds by 40-65% was observed, while in cultivated plants, this indicator increased by only 12-28%. Thus, the phytotoxic effect was not only less pronounced in crops but also less dependent on the dose, which indicates their relatively stable reaction within the studied concentration range. A key result is the confirmation of the selective action of aqueous *Paronychia* sp. extracts. For all comparable indicators, the germination inhibition index for weeds was 2.1-4.8 times higher than for cultivated species ($p < 0.001$). This effect is a significant argument in favour of the potential use of Paronychia extracts as a selective natural herbicide capable of inhibiting the development of weeds without significant harm to crops, especially in the context of integrated management of the phyto-environment in ecological and organic farming systems.

The comparative analysis of germination inhibition across weeds and cultivated crops revealed a clear pattern of selectivity in the allelopathic action of Paronychia extracts. While all tested weed species demonstrated a strong reduction in germination and seedling growth, the cultivated species showed only moderate sensitivity, maintaining relatively high germination rates. To visualise this contrast more clearly, the combined results of germination inhibition (GII, %) and germination rate (%) are presented in Figure 5. The figure highlights the distinct separation between weed responses, characterised by high inhibition indices (red columns), and crop responses, which retained higher germination percentages (green columns). This graphical comparison underscores the selectivity of *P. argentea* extracts, confirming their potential as natural bioherbicides capable of suppressing weeds without adversely affecting major crops.

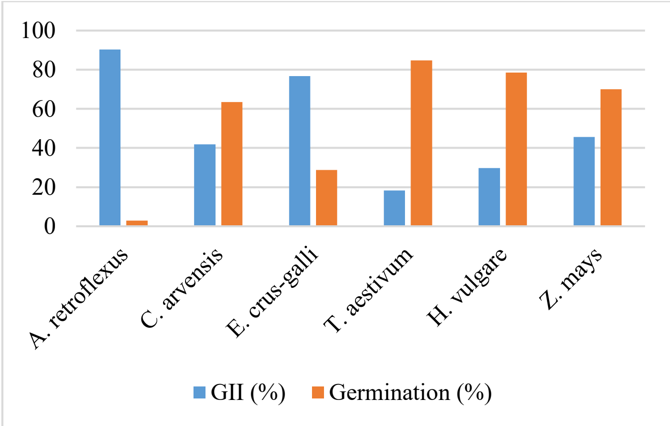

Figure 5. Comprehensive comparison - GII and germination rates

Source: Compiled by the authors.

P. argentea exhibited the highest overall phytotoxicity (average GII = 81.4%), confirming its dominant allelopathic potential among the studied species. The most sensitive weed was *Amaranthus retroflexus*, with inhibition indices reaching 90.3%. The extracts demonstrated strong selectivity, producing 2.1-4.8 times higher inhibition in weeds than in cultivated plants. Extracts from arid regions (Sharur and Shakhbuz) were 20-25% more potent than those from cooler or higher-altitude sites. The root systems of weeds were more affected than shoots (85-92% vs. 68-73%), indicating disruption of early water uptake and growth. Among crops, wheat (*Triticum aestivum*) showed the highest tolerance (GII = 18.3%), while maize (*Zea mays*) was the most sensitive (GII = 45.6%).

3.3 Comparative effectiveness of *Paronychia* species and the influence of the collection area

In the analysis of the allelopathic activity of aqueous extracts from three species of the genus Paronychia, a significant interspecies and geographical variability in the phytotoxic effect was found. The data from the study show that the effectiveness of the extracts depends not only on the botanical affiliation of the donor species but also on the environmental conditions in which these plants formed their biomass. This dependence reflects a complex interaction between the genetically determined traits of the species and the influence of environmental factors on the biosynthesis of secondary metabolites responsible for the allelopathic effect.

P. argentea demonstrated the highest average phytotoxicity towards the test objects, particularly in terms of the germination inhibition index (GII) for weeds, which averaged

81.4 ± 3.2%. This species was effective against all studied weed species – *Amaranthus retroflexus, Convolvulus arvensis,* and *Echinochloa crus-galli* – especially at a 10% concentration. Samples of *P. argentea* collected in the Sharur (vicinity of the village of Khavush) and Kangarli (Chalkhangala) regions repeatedly demonstrated maximum GII values (up to 93.1 ± 1.8%), which indicates the potential of this species as a source of broad-spectrum natural phytotoxic agents. *P. splendens* also showed pronounced activity, though to a lesser extent than *P. argentea*. The average GII of *P. splendens* for weeds was 74.6 ± 3.5%, with the highest effectiveness recorded against common amaranth – the GII reached 85.9 ± 2.7% in samples from the Ordubad and Shakhbuz regions. In contrast, the extracts of this species had a weaker effect on barnyardgrass seedlings (GII 63.2 ± 4.1%), which may indicate a specific biochemical interaction between the compounds of *P. splendens* and the physiology of the weed's seeds. *P. kurdica* (a species with "Least Concern" status in the Red Book of the Nakhchivan Autonomous Republic) was characterised by the highest selectivity of action. The average GII for weeds was 68.7 ± 3.8%, but in samples from Kukudag (Shakhbuz) it reached 92.3 ± 1.9% for amaranth and from Kangarli (Chalkhangala) 76.8 ± 3.1% for barnyardgrass. This is particularly important in terms of biodiversity conservation, as it indicates the potential of protected species in ecosystem restoration. The geographical variability of phytotoxic activity was significant. Extracts obtained from plants collected in the semi-desert plains of the Sharur region and the mountainous regions of Shahbuz showed 20-25% higher GII values ($p < 0.01$) compared to analogues from the Kangarli (dry lowland areas) and Ordubad regions. This pattern is confirmed by chemical analysis: the content of total phenolic compounds in samples from arid regions was 15-22% higher. This is consistent with the idea that drought and high temperatures stimulate the synthesis of phenolic compounds as a component of non-specific plant defence. In addition, a specific correlation was observed between the biotope type and effectiveness. Samples from the rocky screes of Kangarli (Chalkhangala) showed stable activity against field bindweed (GII 41.8 ± 3.3%). Extracts from the plains of Sharur (Akhura village) were most effective at inhibiting amaranth (GII 93.1 ± 1.8%). Samples of *P. kurdica* from Kukudag (Shakhbuz) showed a strong effect on barnyardgrass (GII 76.8 ± 3.1%). These geographical variations in phytotoxic activity mirror the ecological adaptations observed in *Paronychia* species across different regions, including neighboring Turkey. The flora of Turkey, which hosts twelve Paronychia taxa, exhibits similar patterns of ecological specialization, particularly in the case of *P. kurdica,* a species shared between both countries.

The flora of Turkey exhibits remarkable diversity within the genus Paronychia, represented by twelve taxa, including nine species, two subspecies, and one cultivar. Among these are P. *agryloba, P. angorensis, P. carica, P. cataonica, P. condensata, P. davisii, P. dudleyi, P. galatica, P. kurdica, and P. mughlaei.* These species demonstrate impressive ecological plasticity, adapting to diverse environmental conditions characteristic of different regions in Turkey. Of particular interest is *P. kurdica*, a transregional species found in both Turkey and Azerbaijan, making it a compelling subject for comparative studies. Geographical analysis of *P. kurdica* distribution in Turkey revealed its predominant occurrence in the eastern regions bordering Azerbaijan. The species shows a strong affinity for specific ecological niches, particularly dry, rocky slopes at elevations ranging from 700 to 1,500 meters above sea level. This altitudinal distribution highlights the species' notable adaptability to arid conditions, which aligns closely with observations recorded in Azerbaijani populations. The similarity in habitat characteristics between the two regions suggests a conservation of ecological preferences in this species.

Comparative analysis of *P. kurdica* distribution patterns in Azerbaijan and Turkey have uncovered intriguing trends in its ecological plasticity. The observed interpopulation differences are likely influenced by region-specific microclimatic conditions, reflected in variations in morphological traits and growth patterns. These findings are crucial for developing effective conservation strategies, particularly given the species' transboundary distribution. Accounting for geographical variability among populations will enable more targeted conservation measures that consider the unique ecological conditions of each locality. This study underscores the importance of cross-border collaboration in preserving ecologically significant species like *P. kurdica*, ensuring that conservation efforts are harmonized across its entire range. Further research into the adaptive mechanisms of this species could provide deeper insights into its resilience and inform habitat management practices in both Turkey and Azerbaijan.

These results confirm the need for ecosystem restoration through the preservation of local Paronychia populations, especially in drought conditions. Thus, interspecies and geographical differences in the allelopathic activity of *Paronychia* spp. should be considered when developing strategies for their use as sources of selective natural herbicides. Given the high activity of *P. argentea* and the favourable profile of samples from the Sharur region (vicinity of the villages of Akhura, Khavush), further study of their phytochemical composition and the adaptation of methods for field application is advisable.

3.4 Visual symptoms of phytotoxicity and statistical analysis

Within the first 48 hours of setting up the biotests, clear visual manifestations of the phytotoxic effect of aqueous extracts of the aerial parts of *Paronychia* species on the seedlings of the test organisms were recorded. The vast majority of these symptoms were registered in the experimental groups treated with 10% extracts, indicating a concentration-dependent effect. The visual symptoms were most clearly observed in weeds, particularly in *Amaranthus retroflexus*. In 92% of the seedlings of this species treated with a 10% extract of *P. argentea* collected in the Sharur region, necrotic lesions of the root system were recorded. The changes manifested as darkening and local necrosis, thinning of the roots, and increased brittleness, which indicates inhibition of root apical growth and, probably, destruction of the cell wall. In *Echinochloa crus-galli* seedlings, deformities of the aerial part were observed: twisting of hypocotyls, curvature of the seedling axis, and loss of symmetry. Such symptoms are typical of the action of phenolic compounds that disrupt hormonal balance, primarily the auxin gradient in meristematic tissues. In wheat (*Triticum aestivum*) seedlings, a 30% reduction in the length of the root meristem was recorded compared to the control when treated with a 10% extract of *P. kurdica* (Kukudag). This reduction in the cell division zone may be associated with the inhibition of mitosis or DNA synthesis, which was characteristic only of high concentrations. A special manifestation of the phytotoxic effect was also the appearance of reddish spots in the root zone of *Convolvulus arvensis* seedlings after treatment with a *P. splendens* extract (Ordubad, Mazra village). This indicates oxidative stress and the local accumulation of anthocyanins as a protective plant reaction.

The application of one-way analysis of variance (One-way ANOVA) confirmed the statistical significance of the effect of extract concentration on all studied germination parameters. The F-statistic values varied from 58.3 to 121.6 ($p < 0.001$), which demonstrates a high effect size. In addition, a significant interaction was found between the *Paronychia* species and the collection area ($p < 0.01$), which allows us to conclude that environmental conditions play an important role in the formation of allelopathic activity. The analysis of the factors influencing germination showed that the type of test organism was the most important factor determining the reaction to the extracts (ANOVA, $F = 142.8$; $p < 0.001$). The data confirm the significantly higher sensitivity of weeds compared to cultivated plants (Tukey HSD, $p < 0.05$), which, in turn, indicates the potential for selective inhibition of unwanted flora in agro-ecosystems.

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Table 3. ANOVA summary for the effect of *Paronychia* extracts on germination inhibition

Factor	F-value	p-value	Significance
Species (Factor A)	142.8	< 0.001	Highly significant
Region (Factor B)	58.3-121.6	< 0.001	Highly significant
Concentration (Factor C)	58.3-121.6	< 0.001	Highly significant
Species × Region (A × B)	37.4	< 0.01	Significant
Species × Concentration (A × C)	18.9	< 0.05	Significant
Region × Concentration (B × C)	25.1	< 0.05	Significant
Species × Region × Concentration (A × B × C)	12.7	< 0.01	Significant

The study showed a pronounced selective phytotoxicity of aqueous extracts of the aerial parts of *Paronychia* species towards the main weed species of the agrocenoses of the Nakhchivan Autonomous Republic. The highest effectiveness was demonstrated against *Amaranthus retroflexus*, for which the germination inhibition index reached 93.1%. The species of the donor plant (with a predominance of *P. argentea* activity), the concentration of the extract (with a maximum effect at 10%), and the geo-ecological origin of the raw material had a significant impact on the severity of the phytotoxic effect: samples collected in arid climate conditions (Sharur) were statistically 20-25% more active compared to the Ordubad region. At the same time, cultivated species generally showed moderate tolerance to the extracts, which opens up prospects for their integration into biological weed control technologies in ecological farming systems. The least inhibition of germination was found in wheat, while maize proved to be the most sensitive among the crops. The recorded visual symptoms of phytotoxicity (necrosis, deformities, changes in pigmentation) and the results of the statistical analysis suggest the involvement of allelopathically active phenolic compounds in the mechanism of action, which is realised through the inhibition of germination, disruption of the root system, and inhibition of cell division.

4. DISCUSSION

The results obtained demonstrate pronounced allelopathic activity of aqueous extracts of *Paronychia* species, particularly against weeds such as *Amaranthus retroflexus* and *Echinochloa crus-galli*. The effect of selective phytotoxicity is especially pronounced, with the germination inhibition index for weeds reaching 93.1%, while for cultivated plants such as wheat, it did not exceed 18.3%. This data is consistent with the concept of natural herbicides that minimise the impact on cultivated plants, as confirmed by studies by Pedrol and Puig [13]. An important aspect is the influence of the geographical origin of the raw material on allelopathic activity [14-16]. Samples collected in the arid conditions of the Sharur region were 20-25% more effective compared to mountain populations. This fact can be explained by the increased content of phenolic compounds in plants that grow under environmental stress, which is confirmed by Medina-Villar et al. [17]. Similar patterns have been described for other allelopathic species in the works of Kato-Noguchi and Kurniadie [18].

The higher allelopathic activity of *P. argentea* compared to *P. splendens* can be explained by interspecific differences in secondary metabolite profiles and ecological adaptation strategies. *P. argentea*, a xerophytic species widely distributed in arid habitats, possesses a more efficient antioxidant defence system that enhances the biosynthesis of phenolic acids and flavonoids – especially ferulic, caffeic, and quercetin derivatives – known for their inhibitory effects on germination and root elongation [19-22]. These compounds are part of a complex stress-response mechanism that confers competitive advantages in resource-limited environments. In contrast, *P. splendens*, which occupies relatively more mesophilic niches, likely synthesises lower concentrations of such hydrophilic allelochemicals, resulting in reduced phytotoxicity. Thus, the dominance of *P. argentea* in allelopathic potential reflects its ecological specialisation for survival under drought and high-radiation conditions.

The increased activity of extracts derived from Sharur populations further demonstrates the influence of environmental stress on allelopathic potential. The semi-desert conditions of Sharur – characterised by intense solar radiation, high temperatures, and low moisture availability – stimulate the accumulation of oxidative stress-related secondary metabolites, which are also responsible for allelopathic effects [23-25]. Plants growing in such environments exhibit a "metabolic compensation effect," where secondary metabolism intensifies to maintain physiological homeostasis.

Consequently, Sharur extracts were 20-25% more active than those obtained from cooler, higher-altitude regions such as Ordubad. These results are consistent with the stress–allelopathy model proposed by Medina-Villar et al. [17], which posits that abiotic stress enhances the production of bioactive compounds involved in interspecific competition.

The mechanisms of the phytotoxic effect of Paronychia extracts are associated with the inhibition of root system growth, which was manifested in a reduction of root length by 85-92% in the case of common amaranth. These observations are supported by data from He et al. [26], who found a similar effect of phenolic acids on the root growth of *Pinellia ternata*. Visual symptoms, such as necrosis and deformities of seedlings, indicate a disruption of hormonal balance and cell division, which is characteristic of the action of allelopathic compounds. A comparison with other studies reveals both similarities and differences. For example, the selectivity of the allelopathic action of Paronychia on weeds is completely consistent with the results obtained for species of the *Lamiaceae* family by Islam et al. [27]. However, unlike *Lantana camara*, which effectively inhibits grassy weeds, *P. splendens* extracts were less effective against *Echinochloa crus-galli*, which may be related to the species-specific biochemical interactions.

The theoretical significance of the study lies in confirming the hypothesis of Hierro and Callaway [28] that allelopathy is an important adaptive mechanism in competitive plant interactions. The discovered interspecies differences in phytotoxicity (*P. argentea* > *P. kurdica*) and the dependence of activity on environmental conditions emphasise the complex nature of these phenomena, which requires further study at the molecular level, as suggested by Kumar et al. [29]. From a practical point of view, *P. argentea* from arid regions can be considered a promising basis for the development of selective bioherbicides. However, it should be taken into account that some cultivated plants, particularly maize, show moderate sensitivity to the extracts, which limits their use in certain agrocenoses. This aspect requires additional research, similar to that conducted by Kaiira et al. [30] for other allelopathic crops. An important direction is the identification of specific bioactive compounds in the composition of Paronychia extracts, which corresponds to the approach proposed by Chaïb et al. [31] for microalgae. Field trials are also needed to assess the impact on soil microorganisms and long-term effects, as recommended by Weidenhamer et al. [32]. The optimisation of formulations by microencapsulation, proposed by Han et al. [33], could increase the effectiveness of the application.

The results obtained from the study of the allelopathic activity of *Paronychia* species are confirmed and explained in the scientific literature. Motmainna et al. [34], in a review of tropical plants, emphasise that many species show a pronounced allelopathic effect, especially on weeds, which is fully consistent with the data obtained on the high effectiveness of *P. argentea* against *Amaranthus retroflexus*. An important aspect of the research is the study of the mechanisms of allelopathic action. Schandry and Becker [35] describe allelopathic plants as ideal models for studying inter-kingdom interactions, which confirms the expediency of the approach used to analyse the effect of Paronychia extracts on different plant species. The current observations on the inhibition of root growth correlate with the conclusions of Zhang et al. [36], who showed in a meta-analysis that allelopathy significantly reduces plant productivity, especially in the early stages of development. These results are confirmed by the research of Mehdizadeh and Mushtaq [37], who consider allelopathic compounds as a basis for the development of bioherbicides. It is especially valuable that Paronychia extracts, like the substances described by these authors, demonstrate a selective action, having a minimal impact on cultivated plants.

The influence of environmental factors on allelopathic potential, found in the study, is confirmed in the work of Olanipon and Goicoechea [38]. The authors showed that biotic and abiotic factors significantly influence the accumulation of secondary metabolites in *Vitis vinifera*, which is similar to the results obtained on the higher activity of samples from arid regions. The practical aspects of using allelopathy in agriculture, particularly the effect on crop yields, are discussed in detail by Hussain and Abbas [39]. The conclusions about the effectiveness of allelopathic methods in integrated weed control confirm the promise of these results for agricultural production. An important issue is the challenges and possible options for using allelopathic plants. Kostina-Bednarz et al. [40] analyse this problem in detail, pointing to the need for further research to overcome the limitations in the use of bioherbicides, which fully corresponds to the conclusions about the need for additional research on the mechanisms of action.

The ecological and functional mechanisms of allelopathy, described by Aziz et al. [41], help to understand the results obtained in this study, especially regarding species differences in sensitivity to extracts. The authors emphasise the complexity of these mechanisms, which explains the ambiguous reaction of different plant species in current research. The physiological aspects of allelopathic interactions in agro-ecosystems, studied by Lal and Biswas [42], provide additional justification for the observations on the effect on the root system. The authors' conclusions about changes in physiological processes under the influence of allelopathic compounds confirm the data of this study on morphological changes in seedlings. The role of allelopathy in sustainable agriculture, emphasised by Ain et al. [43], shows the importance of the results of the current study for the development of ecologically oriented farming methods.

Despite the promising results, several limitations of the present study should be acknowledged. First, the phytotoxic potential of Paronychia extracts was evaluated under controlled laboratory conditions; therefore, the stability and persistence of aqueous extracts under field environments – subject to photodegradation, temperature fluctuations, and microbial activity – remain uncertain. Second, the potential effects of these extracts on non-target soil microorganisms and beneficial flora were not assessed, though these interactions may significantly influence agroecosystem functioning and soil health. Third, while the study revealed strong allelopathic effects, the specific active compounds responsible for the phytotoxicity were not chemically identified or quantified. Future research should focus on chromatographic and spectroscopic identification of phenolic and flavonoid constituents, evaluation of extract degradation dynamics in soil, and assessment of ecological safety through microbial and field bioassays. Addressing these aspects will be essential for the practical adaptation of Paronychia-based bioherbicides in sustainable agricultural systems.

5. CONCLUSIONS

The present study not only confirmed the allelopathic potential of *Paronychia* species but also revealed the mechanisms underlying their selective phytotoxicity and geographical variability. The aqueous extracts, particularly those derived from *P. argentea*, demonstrated strong inhibitory effects on the germination and root growth of key weeds such as *Amaranthus retroflexus* and *Echinochloa crus-galli*, while maintaining moderate tolerance in major crops, especially wheat. This selective action – 2.1-4.8 times higher inhibition in weeds than in cultivated plants – forms the principal scientific contribution of the research.

A clear geographical pattern of allelopathic strength was established: extracts obtained from plants growing in the arid conditions of the Sharur region exhibited 20-25% greater activity than those from cooler mountain populations. This finding provides new evidence for the environmental modulation of allelopathic potential through drought-induced accumulation of phenolic compounds.

Collectively, these results create a scientific foundation for the development of regionally adapted bioherbicides based on *P. argentea* and related species, which can contribute to sustainable weed management and ecological restoration of arid agroecosystems in the Nakhchivan Autonomous Republic. Future work should focus on identifying the active compounds responsible for phytotoxicity, evaluating extract stability under field conditions, and assessing the ecological safety of their long-term application.

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