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Reducing Herbicide Dependency: Impact of *Murraya koenigii* Leaf Extract on Weed Control and Growth of Wheat (*Triticum aestivum*) and Chickpea (*Cicer arietinum*)

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Abstract: The objective of this study was to determine the effects of *Murraya koenigii* (curry leaf) aqueous extract on the seed germination and growth of two crops and their associated weeds (*Anagallis arvensis*, *Poa annua*, *Lepidium didymum*, and *Vicia sativa*). Wheat (*Triticum aestivum*) and Chickpea (*Cicer arietinum*) seeds were soaked in solutions containing 2, 4, 6, 8, and 10% concentrations of aqueous extracts of *M. koenigii* leaves, while distilled water was used as a control. Higher concentrations of the extract significantly increased the percentage of germination inhibition and decreased the radicle length and plumule length of both crops compared to the control. It was interesting to find that the pot-based experiment had no influence on the shoot length, plant dry mass, chlorophyll, carotenoid, proline, or protein content, stomatal conductance, or photosynthetic and transpiration rate in either crop. Similarly, in comparison to the control, the activity of antioxidant enzymes (peroxidase (PER), superoxide dismutase (SOD), and catalase (CAT)) had no significant influence. Soil physiochemical parameters and weed shoot growth were also investigated. In a Petri plate experiment, 6, 8, and 10% concentrations inhibited germination of both crops. In comparison, in the pot experiment, the growth of both crops was significant at lower concentrations, and 1% aqueous extract of *M. koenigii* was reported to be lethal to weeds without affecting the soil physiochemical properties. Based on the results of this study, it can be inferred that the reduced germination rate of the tested species after treatment with the extract could be attributed to damage caused by the extracts to the membrane system of the seed. This study concluded that an aqueous leaf extract of *M. koenigii* can inhibit the growth of weeds without affecting the germination, growth, photosynthetic, and biochemical properties of *C. arietinum* and *T. aestivum* or the physiochemical properties of soil; thus, it may be a potential candidate for the development of new bioherbicides.

Keywords: allelopathy; biochemical; bioherbicides; chlorophyll; germination; pesticides overuse; weeds

Citation: Vashishth, D.S.; Bachheti, A.; Bachheti, R.K.; Alhag, S.K.; Al-Shuraym, L.A.; Kumar, P.; Husen, A. Reducing Herbicide Dependency: Impact of *Murraya koenigii* Leaf Extract on Weed Control and Growth of Wheat (*Triticum aestivum*) and Chickpea (*Cicer arietinum*). *Agriculture* **2023**, *13*, 1678. https://doi.org/10.3390/agriculture13091678

Academic Editor: Yuan Li

Received: 24 July 2023
Revised: 19 August 2023
Accepted: 23 August 2023
Published: 25 August 2023

1. Introduction

The overuse of hazardous herbicides for weed removal is a major global obstacle to achieving optimal crop productivity. Weeds compete with crops for essential resources such as space, water, soil nutrients, light, and others, leading to yield reductions of up to 34% in major crops [1]. Weed control is an essential factor in crop production, and various weed management strategies are used on arable land around the world. Conventional methods of managing weeds involve manual weeding, mechanical tilling, and the application of chemical herbicides. These approaches help to minimize weed density while increasing agricultural production. Despite the benefits of these approaches in increasing agricultural output, they have some drawbacks. The biggest obstacles in hand weeding are diminishing availability and rising labor costs [2].

Due to increased soil turnover, mechanical weed management disturbs the soil structure and depletes soil fertility. Similarly, the usage of chemical herbicides for weed management has negative effects on soil quality and fertility, the environment, and human and animal health. Because of the difficulties involved with current weed control approaches, it is critical to create sustainable weed management strategies. Throughout history, natural methods have been utilized in traditional agricultural systems to control weeds. Crop rotation and intercropping are two common and effective techniques for managing weeds. In agroecosystems, the production and release of allelochemicals, which are phytotoxic compounds, by plants can influence coexisting species and have a significant impact on weed management. Rain percolating from upper parts can release these allelochemicals into the environment, affecting the growth of other plants [3]. The intercropping of plants or grasses not only covers the agricultural space but also feeds on the nutrients required by crop plants; using aqueous extracts will prove to be the most simple and non-dependent method in the coming era. The effects of allelochemicals include impacts on cell division, plant hormone production, membrane permeability, pollen grain germination, mineral uptake, the opening and closing of stomata, plant pigment and protein synthesis, photosynthesis, photorespiration, nitrogen fixation, and specific enzyme activities [4].

To defend against stress, plants have several Reactive Oxygen Species (ROS) scavenging enzymes, such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (PER), which are activated to strengthen plant resistance to abiotic and biotic stresses [5]. Under stressful conditions such as suboptimal temperature, excessive light, salinity, or pathogen infection, plants produce large quantities of ROS [6]. It is widely acknowledged that stress can impact various aspects of plant biology, including their morphology, physio-chemical processes, and biomolecular processes. As a result, stress can lead to growth inhibition, stomata closure, reduced transpiration, decreased chlorophyll content and photosynthesis inhibition, protein changes, and different responses of antioxidative enzymes [7]. Photosynthesis is necessary for the survival of all life on Earth, as it contributes to oxygen production and the food chain. Transpiration aids in nutrient uptake, water balance, turgor pressure, and plant survival under stress conditions, whereas stomatal conductance is required for gas exchange [8]. However, the use of chemical herbicides affects the nutrient status of soil in the long run, which can cause disruptions in various biochemical processes, such as litter formation, nitrogen fixation [9], or nitrogen cycling, which affects the decomposition and microorganism ecology of soil [10].

M. koenigii is a well-known plant used as a food flavor enhancer all over the world. It is a valued plant due to its distinctive perfume and therapeutic usefulness. Various chemical components have been recovered from every section of this plant. The primary phytochemicals responsible for the distinct and potent aroma are P-gurjunene, P-caryophyllene, P-elemene, and O-phellandrene; additionally, carbazole alkaloids are abundant in the plant [11]. *M. koenigii* has been used for generations in Indian cooking and plays various roles in traditional medicine. *M. koenigii* contains a range of chemical compounds that interact in a complex manner to elicit their pharmacodynamic effects.

The objective of this study is to systematically evaluate the efficacy of an aqueous extract of curry leaves in controlling several common weeds in wheat and chickpea crops, i.e., *A. arvensis*, *L. didymum*, and *P. annua*, *V. sativa*, and to analyze soil physiochemical properties to check the impact of the applied extract on the nutrient status of soil. Moreover, the growth performance and physiological and biochemical parameters of *T. aestivum* and *C. arietinum* crop plants are also examined.

2. Materials and Methods

2.1. Experimental Site

The current study was conducted in Graphic Era Deemed to be University, Clement Town, Dehradun, Uttarakhand (India). The coordinates of the city are 30.318° N and 78.029° E.

2.2. Plant Materials

M. koenigii leaves were used to make an aqueous extract for the study. *M. koenigii* is an aromatic plant found growing wild in forest and residential areas in Uttarakhand. The fresh young green leaves of mature plants were collected from a residential colony of Clement Town, Dehradun. The Systematic Botany Division of Forest Research Institute, Dehradun, identified and authenticated the plants.

2.3. Preparation of Extract

Firstly, the leaves of *M. koenigii* were rinsed with regular water to eliminate dust particles from the surface of the leaves. The leaves were then air dried in the lab before being shredded into small pieces to increase the surface area so that they could be in contact with the solvent, i.e., water. The leaves were then immersed in water in a closed glass vessel to begin the extract preparation. During this 24 h process, the leaves were heated five times every 4 h The boiling procedure was periodic, i.e., the leaves were allowed to boil for 10 min and then left to cool for 4 h. To obtain crude extracts, the extract was filtered using a double layer of muslin cloth and then centrifuged for 20 min at 1000 rpm to eliminate particulate matter. The resulting supernatant was collected and stored at 4 °C for further use [12].

2.4. Petri Plate Experiment and Observation of Seed Germination

The seeds of *C. arietinum* and *T. aestivum* were sterilized by immersing them in a 0.2% sodium hypochlorite solution for 10 min and then rinsed three times with distilled water to prevent any pathogen contamination. Dual layers of filter paper were fixed in Petri plates (radius = 45 mm); then, ten seeds of the recipient species were placed in each Petri plate and treated with 10 mL of the various dilutions (2%, 4%, 6%, 8%, and 10% concentrations) of *M. koenigii* aqueous extract (MKAE). Distilled water was used as a control, and each treatment group had three replicates. The plates were kept at an ambient temperature with a 12 h light/12 h dark cycle. Next, 2 mL of the corresponding extract was added every 48 h to maintain the moisture of the filter paper. The experiment was completed in one week, and the number of germinated seeds was counted from the second to the last day based to determine the germination percentage (Equation (1)) and germination inhibition percentage (Equation (2)). Furthermore, the lengths of the plumule and radicle of the seeds were also recorded, as given in Figure S1 [13].

$$\text{Germination } (\%) = \frac{\text{No. of germinated seeds after given treatment}}{\text{No. of germinated seeds in control}} \quad (1)$$

$$\text{Germination Inhibition } (\%) = 100 - \text{Germination percentage} \quad (2)$$

2.5. Pot Experiments, Growth Conditions, and Experimental Design

Pot experiments were set up in December 2021 and carried out until February 2022 in loamy soil. The overall layout of the experiments is given in Figure 1. The pots were kept under standard weather conditions (10–26 °C temperature; 50–60% relative humidity; 14 h light/10 h dark) that are comparable to normal field conditions in India's chickpea and wheat growing regions. The extract treatments were designed according to the observations recorded during the Petri plate experiment. A total of 3 kg of agricultural soil was filled, and four plants were potted in each pot; the first extract dose was given in soil 2 days before planting plants. The extract treatment was given in five different concentrations, i.e., 1%, 2%, 3%, 4%, and 5% (weight/volume). Distilled water was used as a control; each treatment group had three replicates. A total of two doses of the corresponding extract were given. The number of recipient species plants (*C. arietinum*, *T. aestivum*, *A. arvensis*, *P. annua*, *L. didymum*, and *V. sativa*) that died was counted, as depicted in Figures S2–S4 [13].

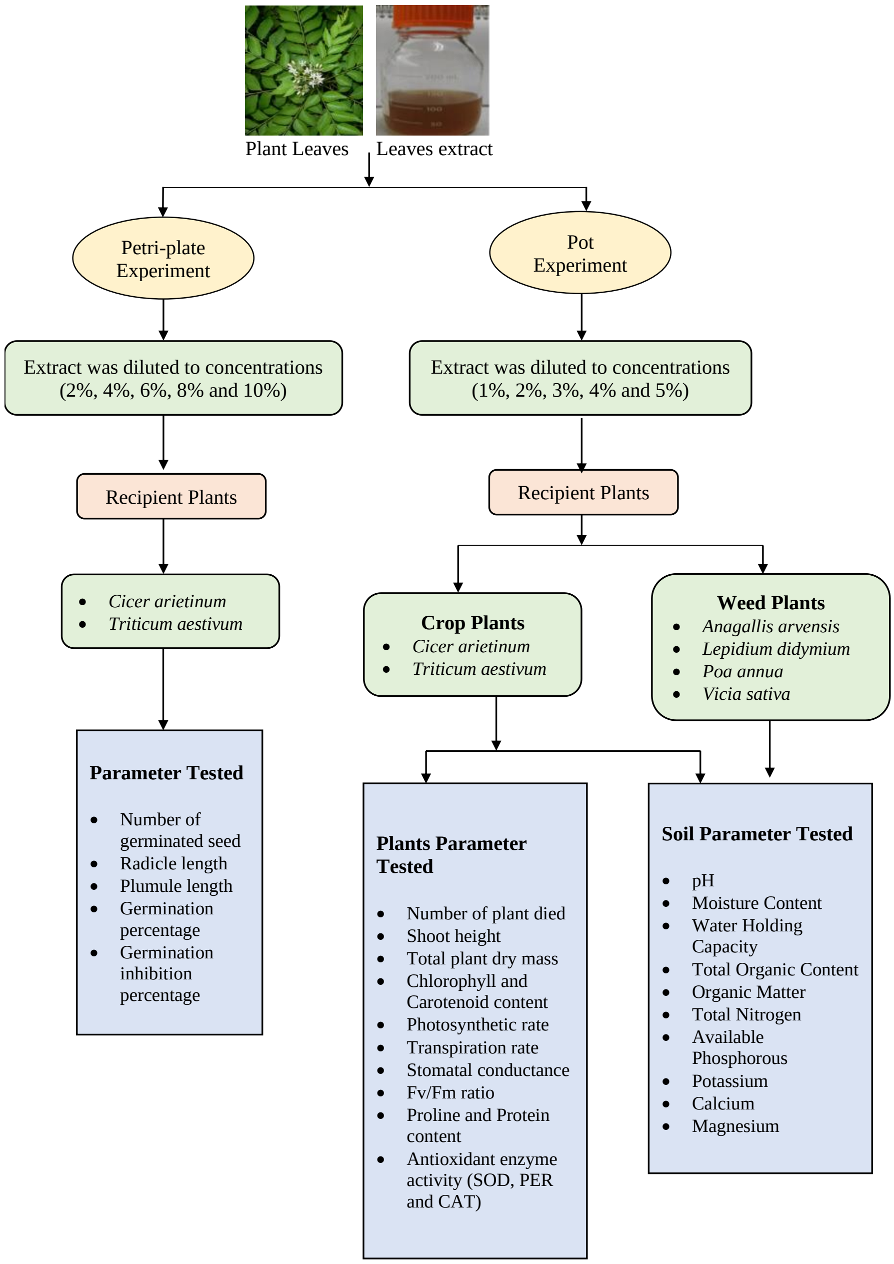

Figure 1. The layout of the experimental design adopted in this study.

2.6. Photosynthetic Parameter Measurements

To quantify photosynthetic pigments, the method of Arnon [14] was used. The chlorophyll content, fresh and dry weight of the root, and shoots of crop recipient species were calculated. Shoots were separated from the roots at the cotyledonary node, then dried at 65 °C for 48 h, and weighed. Next, 250 mg of leaves was grated in 10 mL of 80% acetone using a pestle and mortar. The paste was centrifuged at 3000 RPM for 5 min, then transferred to a 25 mL volumetric flask, and the volume was made up using acetone. The samples were analyzed on a spectrophotometer (Labtronics instrument LT-2800, Labtronics Panchkula, India) at 663 nm, at 645 nm for chlorophyll A (Equation (3)) and B (Equation (4)), at 652 nm for total chlorophyll (Equation (5)), and at 470 nm for carotenoids (Equation (6)) [14].

$$\text{Chlorophyll A (mg/g)} = 12.7\ (\text{A at } 663) - 2.69\ (\text{A at } 645) \times \frac{\text{V}}{1000 \times \text{W}} \tag{3}$$

$$\text{Chlorophyll B (mg/g)} = 22.9\ (\text{A at } 645) - 4.69\ (\text{A at } 663) \times \frac{\text{V}}{1000 \times \text{W}} \tag{4}$$

$$\text{Total Chlorophyll (mg/g)} = \frac{\text{A at } 652}{34.5} \times \frac{1000 \times \text{V}}{1000 \times \text{W}} \tag{5}$$

$$\text{Carotenoid (mg/g)} = \frac{1000\ (\text{A at } 470) - 1.8 \times \text{Chl. A} - 85.02 \times \text{Chl. B})}{198} \tag{6}$$

where A is the absorbance on the spectrophotometer, V is the final volume of supernatant, and W is the fresh weight of the sample.

The Li 6400 photosynthetic system (Li-Cor, Inc., Lincoln, NE, USA) was used to measure the net photosynthetic rate (Pn), stomatal conductance (gs), and transpiration rate (E). Fully grown and developed leaves from each replication were examined between 10 a.m.–12 p.m. under a photosynthetic flux density of 1000 μmol m^{-2} s^{-1}, provided by a LED light source. The leaf chamber had an air humidity of about 60%, a CO_2 concentration of 370–380 μmol mol^{-1}, an ambient air temperature of 26–28 °C, and a flow rate of 500 μmol s^{-1} [15]. Chlorophyll fluorescence measurements were taken in the morning between 10–11 a.m. using a portable Hansatech Plant Efficiency Analyzer (Hansatech, King's Lynn, UK). Before the measurements, the leaves were darkened for 20 min using leaf clips. Fluorescence was stimulated by red (actinic) radiation with a peak wavelength of 650 nm, emitted by light-emitting diodes. The irradiance was set to 2000 μmol m^{-2} s^{-1}. The maximum quantum yield of photosystem II was estimated by the ratio Fv/Fm = (Fm − Fo)/Fm [15].

2.7. Determination of Biochemical Parameters

2.7.1. Proline

The Bates method [16] was used for the proline assay. To begin, 0.2 g of leaves was homogenized with 4 mL of 3% sulphosalicylic acid solution; then, 2 mL of the resulting solution was combined with reactive ninhydrin (2 mL) in acetic acid (2 mL) and incubated in boiling water for 1 h. After completion of the reaction, the samples were immediately placed in an ice box. Once the samples had reached ambient temperature, they were allowed to settle. The samples were then mixed with 4 mL of toluene, and the resulting solution was vigorously shaken. An ultraviolet-visible spectrophotometer (Perkin Elmer Lambda 25) was used to calculate absorbance at 520 nm using the colored complex. Finally, the proline content (Equation (7)) was estimated in mol/gram of fresh weight (FW) using the given equation [17].

$$\text{Proline} = \frac{\text{Absorbance of sample} \times \text{K value} \times \text{dilution factor}}{\text{Weight of sample} \times 100} \tag{7}$$

2.7.2. Soluble Protein

The content of protein was measured from leaves using the method of Lowry [18]. This experiment is based on the hydrolysis of proteins, which release amino acids, resulting in the formation of colored complexes with the Fulvin reagent. The concentration of protein in each sample was determined using a standard curve of bovine serum albumin, and the protein content was calculated in mg/g DW (dry weight) [17]. Finally, the absorption of the samples at 660 nm was estimated using a spectrophotometer (Perkin Elmer Lambda 25).

2.7.3. Antioxidant Enzyme Assay

Leaf material from each sample (500 mg) was homogenized in an extraction buffer containing 0.5% Triton X-100 [$C_{14}H_{22}O(C_2H_4O)_n$] and 1% polyvinylpyrrolidone [$(C_6H_9NO)_n$] in 100 mM potassium phosphate buffer (pH 7.0). The crude extraction was prepared utilizing a chilled mortar and pestle. The supernatant was used for enzymatic assays after centrifuging the homogenate at 15,000 rpm for 20 min at 4 °C. A cold-temperature enzyme extract for superoxide dismutase (SOD) was then prepared. Firstly, the measured amount of leaf sample (1 g) was chilled in liquid nitrogen to prevent proteolytic activity. The chilled sample was ground with 10 mL of extraction buffer (0.1 M phosphate buffer, pH 7.5, including 0.5 mM EDTA and 1 mM ascorbic acid). The mixture was passed through the multilayer cheesecloth, and the resulting filtrate was centrifuged for 20 min at 15,000 rpm at 4 °C. The supernatant obtained after centrifugation was used as an enzyme [19]. The activity of SOD was assessed by measuring the reduction of optical density of nitroblue tetrazolium dye by the enzyme [20]. The reaction was started by adding 2 mM of riboflavin to the tubes and then placing them under two 15 W fluorescent lamps for 15 min. The reaction mixture used in this experiment consisted of 13 mM methionine, 25 mM nitroblue tetrazolium chloride, 0.1 mM EDTA, 50 mM phosphate buffer (pH 7.8), 50 mM sodium carbonate, and 0.1 mL of an enzyme extract. As a control, a complete reaction mixture without enzymes but producing the maximal color was used. The reaction was halted by turning off the light and leaving the tubes in the dark. The optical density was measured at 560 nm using a Perkin Elmer UV/VIS spectrophotometer Lamda 25, and one unit of enzyme activity was defined as the amount of enzyme that caused a 50% decrease in absorbance compared to tubes that did not contain an enzyme [15]. A non-irradiated complete reaction mixture was used as a control. PER activity was calculated with guaiacol as the substrate, as Husen [21] illustrated. The assay mixture contained 0.1 M phosphate buffer with a pH of 6.1, 4 mM guaiacol, 3 mM H_2O_2, and 0.4 mL crude enzyme extract, with a total volume of 1.2 mL. Enzyme activity was measured by recording the optical density (OD) at 420 nm using a spectrophotometer (Perkin Elmer Lambda 25), and the results were expressed as µmoles H_2O_2 destroyed per minute per milligram of protein [15]. Chandlee and Scandalios' [22] method was used to measure the catalase enzyme activity (CAT). In an ice box, a mixture of 2.5 mL of 50 mmol L^{-1} potassium phosphate and 0.3 mL of 3% H_2O_2 was prepared; then, 2.0 mL of enzyme extract was immediately added to the mixture. The absorbance variation curve at 240 nm was determined for 3–4 min. The change in absorbance was used to calculate the enzyme activity, which was expressed as mg/protein/min [17].

2.8. HPTLC Analysis of Allelopathic Compounds

HPTLC was used to obtain more detailed information on the chemical components present in the extract of *Murraya koenigii*. The extract was qualitatively analyzed for various phytoconstituents using TLC (thin layer chromatography) G-60 F254 silica gel (Merck, Rahway, NJ, USA) plates as stationary phase and a mobile phase consisting of a mixture of toluene, ethyl acetate, methanol, and formic acid. A Biostep AS-30 applicator and a filling syringe (AS-30) were used for application. HPTLC plates precoated with G-60 F254 silica gel were used for fingerprinting to obtain better separation of the compounds present (quercetin, kaempferol, and benzoic acid) in the extract. The plates were washed with methanol before use to remove any impurities that may have been picked up during laboratory storage. The fingerprint of each extract was obtained by scanning the chromatographic plate at 254 nm. Next, 1 mL of *M. koenigii* dried extract was precisely measured and dissolved in 100 mL of methanol. The analysis was performed at a constant temperature (22 ± 1 °C) and humidity (47 ± 1%) [23]. The compounds were identified by comparing the peak (retention time) of each sample with the peak of the standard compound (i.e., pure compound) [24].

2.9. Physiochemical Analysis of Soil

Soil samples were taken from the donor's extract-treated weed pots at the termination of the experiment. All soil samples were taken randomly from three points in each pot, mixed uniformly, and kept inside zipper plastic bags. After removing fine roots, stones, and plant organic residue by hand, each soil sample was air-dried at ambient temperature. Following that, samples were pulverized, strained through a 2 mm mesh sieve, and homogeneously blended for additional soil physicochemical analysis. The potentials of hydrogen ions (pH), water holding capacity (WHC), soil texture, nitrogen (N), phosphorus (P), potassium (K), organic carbon (OC), organic matter (OM), calcium (Ca), and magnesium (Mg) of all soil samples were determined. The pH was determined using a digital meter (Labtronics instrument LT-49) [25]. A hydrometer was used to measure soil texture [26], while the WHC was estimated by the gravimetric method [27]. Total nitrogen was calculated by the Kjeldhal method, as described in [28]. A UV-vis spectrophotometer (Labtronics instrument LT-2800, Labtronics, Panchkula, India) was used to calculate the phosphorus concentration [29]. A Systronics flame photometer-128 was used to measure potassium [30]. The calcium, magnesium, organic carbon, and organic matter contents were measured using an atomic absorption spectrophotometer (Analyst-800) [31,32]. The standard ranges of the physiochemical parameters of soil, as described by Krishi Vigyan Kendra (KVK) (Delhi, India), for good agricultural soil are mentioned in Table 1.

Table 1. The standard ranges of the physiochemical parameters of soil, as described by Krishi Vigyan Kendra.

Parameters	Standard Range
pH	6.5–8.2
Organic Carbon	0.5–0.75%
Total Nitrogen	240–480 kg/ha
Available Phosphorus	28–56 kg/ha
Available Potassium	140–280 kg/ha
Calcium	3.36–6.72 kg/ha
Magnesium	2.24–4.48 kg/ha

2.10. Statistical Analysis

A statistical analysis of the experimental data was performed using the Analysis of Variance (ANOVA). The level of significance was taken as 0.05. The null hypothesis was rejected if the *p*-value of the test statistic (F) was less than or equal to 0.05. The Tukey's post hoc test was used for pair-wise comparisons whenever the null hypothesis was rejected.

3. Results and Discussion

3.1. Seed Germination

Different concentrations of *M. koenigii* aqueous extract (MAKE) significantly ($p \leq 0.05$) affected the germination percentage (GP) of *C. arietinum* and *T. aestivum*. In the case of *C. arietinum*, the germination percentage was moderate at 2% and 4% concentrations of extract, i.e., around 60–70%, but it started decreasing with increasing the concentration of extract, from 50% at 6% to 0–10% at 8% and 10% concentrations. In *T. aestivum*, the germination percentage was found to be 90–100% at a 2% concentration of extract, whereas it was observed to be 10–20% at 4% and 6% concentrations, and 0% at 8% and 10% concentrations. The values of germination percentage in *C. arietinum* and *T. aestivum* pure culture were close to 100% at the control level (Table 2).

The application of *M. koenigii* extracts showed that at 2% and 4% concentrations, the plumule and radicle lengths of both crops were similar to those of the control. In comparison, they were very low at 6%, 8%, and 10% concentrations. This implies that higher concentrations of extract slowed plant growth, which is unacceptable for crop yield. We also determined that the germination inhibition percentages (GIPs) of *C. arietinum* and *T. aestivum* were significantly influenced ($p \leq 0.01$) by the apparent allelopathic action of the MAKE concentrations (Table 2). GIP was not obtained in the controls. The minimum inhibition was recorded at a 2% concentration, while the maximum was at 8% and 10%.

Table 2. The number of germinated seeds, germination percentage, germination inhibition percentage, and radicle and plumule length in two important crop plants (*C. arietinum* and *T. aestivum*) under control and treated situations. Under treated conditions, different concentrations of *M. koenigii* aqueous extract (MKAE) were used at different temperatures in the Petri dish experiment.

Parameters	Plant Name	Treatments					
		Control	2%	4%	6%	8%	10%
Germinated seeds	*C. arietinum*	10.00 ^{a}	9.33 ^{ab}	7.67 ^{c}	5.00 ^{d}	0.33 ^{e}	0.67 ^{f}
	T. aestivum	10.00 ^{a}	10.00 ^{a}	2.00 ^{b}	0.67 ^{d}	0.00 ^{e}	0.00 ^{e}
Germination (%)	*C. arietinum*	100.00 ^{a}	93.30 ^{ab}	76.70 ^{c}	50.00 ^{d}	3.30 ^{e}	6.70 ^{f}
	T. aestivum	100.00 ^{a}	100.00 ^{a}	20.00 ^{b}	6.70 ^{c}	0.00 ^{e}	0.00 ^{e}
Germination Inhibition (%)	*C. arietinum*	0.00 ^{a}	0.00 ^{a}	23.30 ^{b}	50.00 ^{c}	96.70 ^{d}	93.30 ^{e}
	T. aestivum	0.00 ^{a}	0.00 ^{a}	80.00 ^{b}	93.30 ^{c}	100.00 ^{cd}	100.00 ^{cd}
Radicle length (cm)	*C. arietinum*	17.53 ^{a}	5.50 ^{b}	5.27 ^{bc}	4.20 ^{d}	0.67 ^{e}	1.23 ^{f}
	T. aestivum	11.13 ^{a}	6.73 ^{b}	4.30 ^{c}	0.10 ^{d}	NG	NG
Plumule length (cm)	*C. arietinum*	2.00 ^{a}	0.90 ^{b}	0.57 ^{c}	0.37 ^{cd}	0.10 ^{e}	0.07 ^{ef}
	T. aestivum	11.70 ^{a}	9.40 ^{b}	7.83 ^{c}	NG	NG	NG

Differences between the mean of each row superscripted by the same letter were not statistically significant ($p \leq 0.05$). NG—No growth.

Although the allelochemicals were shown either to be stimulatory or inhibitory in the first tranche of experiments, i.e., Petri plate experiments (PPEs), the results revealed that higher concentrations (6%, 8%, and 10%) of aqueous extracts significantly inhibited the germination of both crops, i.e., *C. arietinum* and *T. aestivum*. Lawan et al. [33], Vashishth et al. [34] and Khattak et al. [35] have also reported similar findings. The allelochemicals found in aqueous extracts of *Jatropha curcas* were found to be stimulatory to wheat at lower concentrations, while at higher concentrations, the extracts were either inhibitory or did not affect wheat plant growth compared with the control. This could have been because the biological activity of allelochemicals is concentration dependent [36]; however, these findings are contrary to those of Bora et al. [37], whose study reported the allelopathic effect of *Acacia auriculiformis* leaf extracts on the seed germination of certain crops. Eyini et al. [38] reported the allelopathic impact of *Bambusa arundinacea* on *Arachis hypogaea* and concluded that the aqueous extracts of weeds hindered the germination of crop seeds. Higher concentrations of the *Acacia auriculiformis* extract cause significant reductions in the root length of *Brassica juncea*, *C. arietinum*, *Phaseolus mungo*, *Raphanus sativus*, and *Vigna unguiculata* [39]. Kruse et al. [40] reported unfavorable results, as the germination rate and growth of *Triticum durum* were retarded due to the toxic effects of the phenolic compounds present in leachates (from the leaf, root, and litter) of *Populus nigra* at high concentrations (75 g/L). The findings of Hachani et al. [41] suggested that *Populus nigra* extracts, on the other hand, were more phyto-inhibitory than *Casuarina glauca* extracts. This could have been due to the high concentration of polyphenols found in all *Populus nigra* extracts. This helps to explain the allelopathic effects of chemical substances released by *C. glauca* and *P. nigra* on *T. durum* germination and early seedling growth.

3.2. Cash Crop Growth and Physiological Parameters

The shoot lengths of *C. arietinum* ranged from 19.68 cm to 20.20 cm, including the control specimens. Table 3 shows that at 1% concentration, the shoot length was better than under the control conditions, while in *T. aestivum*, it ranged from 14.67 to 15.30 cm, including in the control specimens. The total plant dry mass ranged from 0.6 to 1.2 gm for both crops, including in the control specimens, and both these parameters, as estimated for plant morphological growth, were not significantly ($p \leq 0.05$) affected by the application of extract. A comparison of means revealed that there was no significant difference in chlorophyll a (Chl a) and chlorophyll b (Chl b) levels between the control and MAKE-treated plant leaves.

Table 3. Shoot height, dry mass, photosynthetic pigments (Chlorophyll a, b, total chlorophyll, and carotenoids), net photosynthetic rate (Pn), stomatal conductance (gs), transpiration rate, and chlorophyll fluorescence (Fv/Fm) in two important crop plants (*C. arietinum* and *T. aestivum*) under control and treated conditions.

Parameters	Plant Name	Treatments					
		Control	1%	2%	3%	4%	5%
Shoot length (cm)	*C. arietinum*	20.00 ^{a}	20.20 ^{ab}	19.63 ^{c}	20.17 ^{bd}	19.68 ^{ce}	19.93 ^{cef}
	T. aestivum	15.30 ^{a}	14.70 ^{b}	14.73 ^{bc}	14.67 ^{d}	14.90 ^{e}	15.00 ^{f}
Total plant dry mass (gm)	*C. arietinum*	1.1 ^{a}	1.0 ^{ab}	0.9 ^{bc}	0.7 ^{d}	0.6 ^{de}	0.7 ^{d}
	T. aestivum	1.2 ^{a}	1.1 ^{ab}	1.1 ^{ab}	0.9 ^{c}	0.6 ^{d}	0.7 ^{e}
Chl a (mg g^{-1} FW)	*C. arietinum*	6.766 ^{a}	6.748 ^{ab}	6.749 ^{abc}	6.668 ^{d}	6.631 ^{e}	6.614 ^{ef}
	T. aestivum	1.810 ^{a}	1.616 ^{b}	1.571 ^{c}	1.522 ^{d}	1.497 ^{e}	1.508 ^{ef}
Chl b (mg g^{-1} FW)	*C. arietinum*	3.526 ^{a}	3.883 ^{b}	3.773 ^{c}	3.737 ^{d}	3.641 ^{e}	3.582 ^{f}
	T. aestivum	5.071 ^{a}	6.304 ^{b}	5.970 ^{c}	5.966 ^{cd}	5.975 ^{cde}	5.884 ^{f}
Total Chl (mg g^{-1} FW)	*C. arietinum*	18.493 ^{a}	19.739 ^{b}	19.681 ^{c}	19.565 ^{d}	19.333 ^{e}	19.188 ^{e}
	T. aestivum	7.652 ^{a}	8.725 ^{b}	7.913 ^{c}	7.130 ^{d}	6.754 ^{e}	6.638 ^{ae}
Car (mg g^{-1} FW)	*C. arietinum*	2.116 ^{a}	1.968 ^{b}	2.010 ^{c}	1.996 ^{d}	2.033 ^{ce}	2.048 ^{ef}
	T. aestivum	1.458 ^{a}	2.127 ^{b}	2.172 ^{bc}	2.224 ^{d}	2.277 ^{e}	2.311 ^{e}
Pn (µmol m^{-2} s^{-1})	*C. arietinum*	30.00 ^{a}	29.98 ^{ab}	29.98 ^{ab}	29.97 ^{abc}	29.95 ^{bcd}	29.94 ^{de}
	T. aestivum	18.02 ^{a}	18.03 ^{ab}	18.02 ^{a}	18.00 ^{c}	17.99 ^{cd}	17.97 ^{e}
gs (mol m^{-2} s^{-1})	*C. arietinum*	0.25 ^{a}	0.24 ^{ab}	0.22 ^{bc}	0.22 ^{bc}	0.21 ^{cd}	0.20 ^{de}
	T. aestivum	0.28 ^{a}	0.27 ^{ab}	0.27 ^{ab}	0.25 ^{c}	0.24 ^{cd}	0.21 ^{e}
E (mmol m^{-2} s^{-1})	*C. arietinum*	5.72 ^{a}	5.71 ^{ab}	5.69 ^{bc}	5.68 ^{cd}	5.68 ^{cd}	5.65 ^{e}
	T. aestivum	4.93 ^{a}	4.92 ^{ab}	4.89 ^{c}	4.87 ^{cd}	4.85 ^{de}	4.81 ^{f}
Fv/Fm	*C. arietinum*	0.789 ^{a}	0.789 ^{a}	0.788 ^{ab}	0.787 ^{abc}	0.788 ^{ab}	0.786 ^{bcd}
	T. aestivum	0.820 ^{a}	0.821 ^{ab}	0.820 ^{a}	0.818 ^{ac}	0.817 ^{cd}	0.817 ^{cd}

NG—No growth. Differences between the mean of each row superscripted by the same letter were not statistically significant ($p \leq 0.05$).

After examining the total chlorophyll data, it was found that stress conditions significantly impacted the content. However, there was no significant difference between the control and MAKE-treated specimens. Similar results were observed for carotenoids, photosynthetic rate (Pn), stomatal conductance (gs), and transpiration rate (Table 3). The Fv/Fm ratio is a suitable indicator for evaluating PSII in plants exposed to environmental stress [17]. The Fv/Fm test is intended to allow as much light energy as possible to enter the fluorescence pathway. A saturating light source reduces the maximum number of reaction centers [42]. The Fv/Fm ratio typically decreases as plant stress increases, because fewer open reaction centers become available. Similar to other physiological parameters, no difference was noticed statistically in the Fv/Fm ratio of control and treated crop plants (Table 3).

The increased proline levels in response to environmental stress indicate a plant's stress response. The accumulation of proline in plant cells under stress conditions serves as a protective mechanism, shielding from toxicity, as reported by Rahbarian et al. [43]. Proline also plays a significant role in osmoregulation, membrane stability, detoxification, cytosol pH adjustment, and the maintenance of cell enzyme structure [44]. As no significant difference was reported in the means comparison of control and MKAE-treated plants, it can be concluded that plants were not facing any kind of stress condition. A comparison of mean data on leaf protein content showed that there was no significant effect on either cash crop at lower concentrations of MKAE treatments (Table 4).

Table 4. Contents of proline and soluble protein in two important crop plants (*C. arietinum* and *T. aestivum*) under control and treated conditions.

Biochemical Features	Plant Name	Treatments					
		Control	1%	2%	3%	4%	5%
Proline (mg g^{-1} FW)	*C. arietinum*	1.08 ^{a}	1.09 ^{ab}	1.07 ^{abc}	1.05 ^{cd}	1.02 ^{de}	1.01 ^{ef}
	T. aestivum	1.17 ^{a}	1.17 ^{a}	1.16 ^{ab}	1.15 ^{abc}	1.13 ^{cd}	1.12 ^{cde}
Soluble Protein (mg g^{-1} DW)	*C. arietinum*	56.24 ^{a}	56.24 ^{a}	56.23 ^{a}	56.21 ^{ab}	56.20 ^{abc}	56.19 ^{abcd}
	T. aestivum	48.45 ^{ab}	48.48 ^{a}	47.47 ^{bc}	46.79 ^{de}	47.17 ^{cd}	46.72 ^{def}

Differences between the mean of each row superscripted by the same letter were not statistically significant ($p \leq 0.05$).

There was no significant difference observed in superoxidase dismutase activity (SOD) for control and MKAE-treated plants. SOD constitutes the first line of defense against reactive oxygen species (ROS). A mean data comparison showed that there was no significant difference observed in the activity of PER (Peroxidase) and CAT (Catalase) between all MKAE concentrations tested and the control groups. PER catalyzes peroxide reduction and generates ROS. Under water stress conditions, plants produce reactive oxygen species (ROS) that can act as secondary messengers in signal transduction pathways at low concentrations [45]. However, high concentrations of ROS can cause damage to the membrane, photosystems (PSI and PSII), photosynthetic pigments, and enzymes [43]. Chloroplasts and mitochondria are the main sites for electron transfer cycles in plant cells and are particularly vulnerable to ROS production [46]. CAT is responsible for preventing the accumulation of cellular organelles and protecting these organelles and tissue from destruction by peroxide, as several metabolic reactions continuously synthesize peroxide [45] (Table 5).

Table 5. Antioxidant enzyme activities in two important crop plants (*C. arietinum* and *T. aestivum*) under control and treated conditions.

Biochemical Features	Plant Name	Treatments					
		Control	1%	2%	3%	4%	5%
SOD (Uμg^{-1} protein)	*C. arietinum*	1.03 ^{a}	1.02 ^{ab}	1.02 ^{ab}	1.00 ^{abc}	1.00 ^{abc}	1.00 ^{abc}
	T. aestivum	2.56 ^{a}	2.51 ^{ab}	2.50 ^{ab}	2.48 ^{bc}	2.47 ^{bc}	2.45 ^{cd}
PER (Uμg^{-1} protein)	*C. arietinum*	0.374 ^{a}	0.373 ^{ab}	0.373 ^{ab}	0.371 ^{abc}	0.369 ^{cd}	0.368 ^{de}
	T. aestivum	0.22 ^{a}	0.20 ^{ab}	0.19 ^{bc}	0.18 ^{cd}	0.15 ^{e}	0.15 ^{e}
CAT (Uμg^{-1} protein)	*C. arietinum*	0.308 ^{a}	0.308 ^{a}	0.307 ^{ab}	0.304 ^{bc}	0.302 ^{cd}	0.300 ^{de}
	T. aestivum	0.28 ^{a}	0.28 ^{a}	0.27 ^{ab}	0.26 ^{abc}	0.23 ^{cd}	0.22 ^{cde}

Differences between the mean of each row superscripted by the same letter were not statistically significant ($p \leq 0.05$).

3.3. Number of Weed Plants Died

No effect of the first dose on *A. arvensis* plants was observed after fifteen days, as they were green, fresh, and healthy at all aqueous extract concentrations. All the weed plants followed the same trend after the first treatment dose. The average plant height of *A. arvensis* ranged between 14.67 and 15.33 cm (compared to the plant height of the control, i.e., 14.93 cm), 0.80 cm to 1.33 cm (control 1.60 cm) for *L. didymum*, 8.70 cm to 9.73 cm including the control for *P. annua*, and between 9.73 cm and 10.00 cm, compared to the control value of 10.27 cm, for *V. sativa*. Seven days after the second dose, all *A. arvensis* plants died at 1%, while flowers and leaves started drooping at 2, 3, 4, and 5%. Approximately

50% of plants died at 2%, 25% at 3% and 4%, and a few plants died at 5% treatment concentration, whereas all of the control plants were green and healthy with flowers. One week after the second treatment dose, the plants of *L. didymum* began to droop at 1% and 2%, but not at 3%, 4%, or 5%. After a fortnight, about 50% of plants died at 1%, and a few plants died at 2% and 3% concentrations, whereas all of the control plants were green and healthy. The second dose did not affect the treatments at 4% and 5% concentrations. In the case of *P. annua*, the mean heights ranged from 9.40 to 10.30 cm (including the control), and budding started in all of the plants after the second dose of treatment. None of the plants drooped or died, which indicated that the second dose had no visual effect. One week after the second dose of treatment, the plants of *V. sativa* started drooping at 1, 2, 3, and 4% concentrations. No significant impact was seen at 5% concentration, while after a fortnight, all the plants died at 1, 2, and 3% and a few at 4% and 5%, while under control conditions, all plants were green and healthy (Figure 2). Hence, it can be concluded that the inhibition percentage (IP) is zero under control conditions and at all concentrations of *P. annua*. The IP of *A. arvensis* was 100% at 1% treatment, 50% at 2%, and too low to be measured at 3%, 4%, and 5%. In the case of *L. didymum*, the IP was 50% at 1% and 2%, 25% at 3%, and zero at 4% and 5% treatments, whereas in *V. sativa*, the IP was 100% at 1, 2, and 3%, 50% at 4% and very low at 5% treatment (Figure 2). When the concentration of an herbicide increases but its herbicidal action decreases, it is known as the herbicide "dilution effect". This phenomenon appears to contradict the basic idea that larger quantities of a chemical should have a greater influence. However, various scientific concepts, like antagonistic effect [47,48], selectivity and non-target effects [49,50], and physiological responses [51,52], can assist in understanding why this happens.

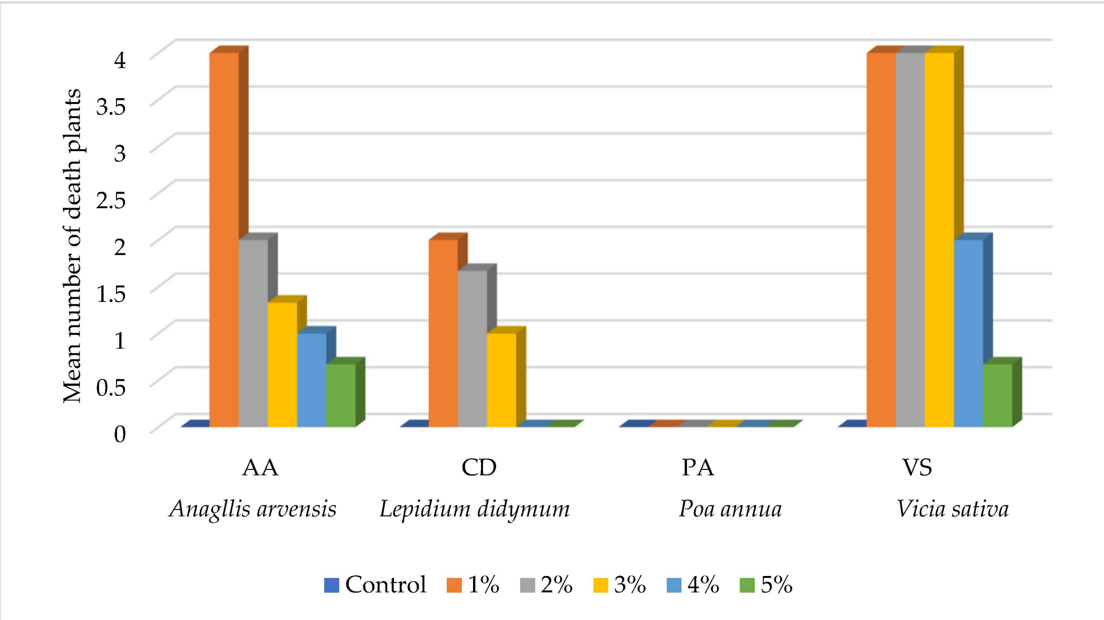

Figure 2. Mean number of weed death plants following treatment with *M. koenigii* aqueous extract.

Several studies have reported that the germination and growth of cash crops are significantly inhibited by various plant extracts or leachates, with some exceptions. It is therefore important to determine the donor plant extract concentration at which it supports the growth of recipient crop plants and inhibits the growth of recipient weed plants, as such findings are more likely to fulfill the above-mentioned requirements to make a bioherbicide. Bansal [53] found similar results to the current study, reporting that extracts from *Lantana camara* inhibited the seed germination and seedling growth of various weed species, including *Echinochloa colonum*, *Digitaria sanguinalis*, *Panicum psilopodium*, and *Commelina benghalensis*, which are common weeds associated with rice. However, there was no significant effect on the seed germination of rice. Water extracts of sorghum with sunflower and sorghum, sunflower, and mulberry were combined and used as an herbicide to control various weed species such as wild oats, little seed canary grass, labsquarters, and swine cress in wheat. The extracts were sprayed at different concentrations (12, 15, 18, and 21 L/ha) at two different growth stages of wheat (40 and 55 days after sowing). The study also included a control treatment, where synthetic herbicide (Affinity 50 WP) and a weekly check were used for comparison. Applying an increasing dose of water extract (12–21 L/ha) in all treatment combinations resulted in a significant reduction in total weed density and dry biomass production of narrow and broad-leaved weeds. Applying a mixture of sorghum, sunflower, and mulberry water extracts at 18 L/ha 40 + 55 days after sowing resulted in an 87.14% decrease in total weed dry matter and a 19.5% increase in wheat grain yield. However, it was found that applying sorghum + sunflower water extracts at 12 L/ha 40 + 55 days after sowing was more cost-effective than the other treatments [54].

3.4. HPTLC Analysis of Allelopathic Phytochemicals

An HPTLC analysis of the extracts revealed the presence of quercetin, benzoic acid, and kaempferol compounds (Figure 3). The outcomes from our HPTLC analysis contributed to our comprehension of the allelopathic capabilities of *M. koenigii* and offer scientific proof of its viability as a natural herbicide for eco-friendly weed management. The detection of allelopathic components such as benzoic acid (1.95%), kaempferol (3.28%), and quercetin (2.92%) additionally reinforced the idea that utilizing allelochemicals holds promise for ecologically sound and efficient weed management. This approach lessens the need to use synthetic herbicides, encouraging more sustainable agricultural methods. Various researchers have reported allelopathic activity against various plant species in these compounds. Compared to the control, quercetin significantly inhibited the radicle growth of *Pasteuria ramosa* seedlings [55]. Additionally, at 0.06 mM, p-hydroxybenzoic acid inhibited *Anabaena flosaquae* and *Chlorella pyrenoidosa* growth [56] and the activity of kaempferol was also reported by Cid-Ortega and Monroy-Rivera [57] and Li et al. [58].

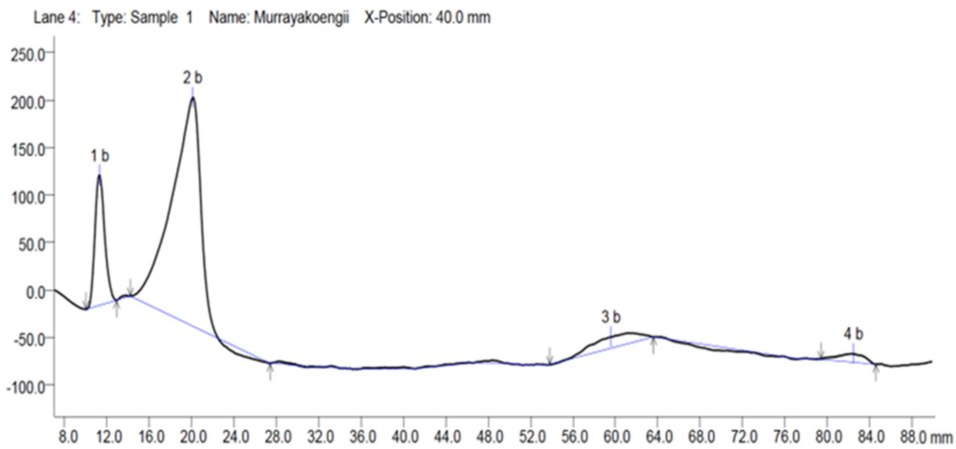

Figure 3. HPTLC analysis graph of *M. koenigii* aqueous extract. (Arrow represents major peak 1b: benzoic acid, 2b: kaempferol, 3b: quercetin).

3.5. Physiochemical Parameters of Soil

The pH of the soil ranged from 7.23 to 7.37 in *A. arvensis* pots, 7.20 to 7.33 in *L. didymum* pots, 7.20 to 7.37 in *P. annua* pots, and 7.23 to 7.37 in *V. sativa* pots (Figure S5a). The moisture content in the soil of *A. arvensis* pots was 16.87–17.20%, 16.97–17.23% in the soil of *L. didymum* pots, 16.93–17.17% in the soil of *P. annua* pots, and 17.03–17.20% in the soil of *V. sativa* pots (Figure S5b). The water holding capacity ranged from 46.29 to 46.42 in *A. arvensis* pots, 47.23 to 47.33 in *L. didymum* pots, 47.27 to 47.41 in *P. annua* pots, and 46.36 to 46.52 in *V. sativa* pots (Table 6) (Figure S5c). The pH of the control soil was recorded as 7.20 for *A. arvensis*, 7.22 for *L. didymum*, 7.21 for *P. annua*, and 7.24 for *V. sativa*. Meanwhile, the moisture content and WHC of the control were 17.12% and 46.40% for *A. arvensis*, 17.08% and 46.39% for *L. didymum*, 17.13% and 46.35% for *P. annua*, and 17.18% and 46.31% for *V. sativa.* All of the parameters were within KVK's standard ranges. This means that the statistical analysis did not find a significant difference between the treatments and the control group.

Table 6. Impact of *M. koenigii* extract on the physical parameters of loam soil.

Plant Name	Type of Plant	Treatment	pH	Moisture Content (%)	Water Holding Capacity (%)
C. arietinum	Crop	Control	7.38 ± 0.07	17.10 ± 0.26	46.39 ± 0.04
	Crop	1%	7.23 ± 0.03	17.23 ± 0.22	47.34 ± 0.08
	Crop	2%	7.40 ± 0.06	17.20 ± 0.17	47.46 ± 0.04
	Crop	3%	7.40 ± 0.10	17.27 ± 0.15	47.32 ± 0.11
	Crop	4%	7.20 ± 0.06	16.87 ± 0.27	47.35 ± 0.08
	Crop	5%	7.27 ± 0.09	17.10 ± 0.15	47.36 ± 0.01
T. aestivum	Crop	Control	7.32 ± 0.07	17.10 ± 0.26	46.40 ± 0.04
	Crop	1%	7.30 ± 0.12	17.23 ± 0.22	46.38 ± 0.07
	Crop	2%	7.23 ± 0.07	16.93 ± 0.28	46.47 ± 0.05
	Crop	3%	7.33 ± 0.07	16.93 ± 0.24	46.28 ± 0.07
	Crop	4%	7.27 ± 0.03	16.97 ± 0.23	46.28 ± 0.02
	Crop	5%	7.33 ± 0.03	17.17 ± 0.20	46.39 ± 0.08
A. arvensis	Weed	Control	7.20 ± 0.07	17.12 ± 0.26	46.40 ± 0.04
	Weed	1%	7.27 ± 0.12	16.87 ± 0.22	46.29 ± 0.02
	Weed	2%	7.33 ± 0.03	16.87 ± 0.18	46.38 ± 0.11
	Weed	3%	7.37 ± 0.07	17.20 ± 0.21	46.33 ± 0.09
	Weed	4%	7.23 ± 0.07	17.03 ± 0.20	46.41 ± 0.08
	Weed	5%	7.30 ± 0.06	16.90 ± 0.25	46.42 ± 0.12
L. didymum	Weed	Control	7.22 ± 0.07	17.08 ± 0.26	46.39 ± 0.04
	Weed	1%	7.20 ± 0.06	17.23 ± 0.15	47.32 ± 0.02
	Weed	2%	7.20 ± 0.06	17.10 ± 0.20	47.33 ± 0.06
	Weed	3%	7.33 ± 0.03	17.07 ± 0.20	47.29 ± 0.07
	Weed	4%	7.30 ± 0.12	17.17 ± 0.09	47.33 ± 0.07
	Weed	5%	7.27 ± 0.09	16.97 ± 0.27	47.23 ± 0.04
P. annua	Weed	Control	7.21 ± 0.07	17.13 ± 0.26	46.35 ± 0.04
	Weed	1%	7.37 ± 0.03	17.07 ± 0.22	47.41 ± 0.07
	Weed	2%	7.27 ± 0.12	17.00 ± 0.15	47.27 ± 0.06
	Weed	3%	7.20 ± 0.06	17.10 ± 0.21	47.36 ± 0.06
	Weed	4%	7.23 ± 0.07	17.17 ± 0.28	47.31 ± 0.05
	Weed	5%	7.30 ± 0.06	16.93 ± 0.19	47.36 ± 0.10
V. sativa	Weed	Control	7.24 ± 0.07	17.18 ± 0.26	46.31 ± 0.04
	Weed	1%	7.27 ± 0.09	17.07 ± 0.15	46.41 ± 0.01
	Weed	2%	7.33 ± 0.09	17.03 ± 0.20	46.36 ± 0.03
	Weed	3%	7.23 ± 0.07	17.13 ± 0.27	46.52 ± 0.01
	Weed	4%	7.30 ± 0.06	17.07 ± 0.17	46.41 ± 0.08
	Weed	5%	7.37 ± 0.07	17.20 ± 0.21	46.43 ± 0.09

Total organic carbon and organic matter were found to constitute 0.51–0.52% (Figure S5d) and 0.88–0.89% (Figure S5e) in all pots, respectively. In the *A. arvensis* pots, total nitrogen ranged from 324.05 to 342.87 kg/ha, 319.87–330.33 kg/ha in pots of *L. didymum*, 326.14–340.78 kg/ha in *P. annua* pots, and 328.23–340.78 kg/ha in *V. sativa* pots (Figure S5f). The available phosphorus ranged from 43.49 to 45.55 kg/ha in *A. arvensis pots*, 42.75 to 44.80 kg/ha in *L. didymum* pots, 44.24 to 46.85 kg/ha in *P. annua* pots, and 42.56 to 44.80 kg/ha in *V. sativa* pots (Figure S5g). The potassium content was found to be 171.81–172.63 kg/ha in *A. arvensis* pots, 171.81–172.63 kg/ha in *L. didymum* pots, 171.51–172.55 kg/ha in *P. annua* pots, and 172.03–172.44 kg/ha in *V. sativa* pots (Figure S5h). The calcium and magnesium contents ranged from 5.79 to 6.53 kg/ha and 2.24–3.03 kg/ha in *A. arvensis* pots, 6.46–6.72 kg/ha and 2.32–2.81 kg/ha in *L. didymum* pots, 6.03–6.73 and 2.27–3.33 kg/ha in *P. annua* pots, and 6.24–6.62 kg/ha (Figure S5i) and 2.42–3.03 kg/ha (Figure S5j) in *V. sativa* pots, respectively (Table 7). The results of our analysis showed that there was no statistically significant difference between all treatments and the control. Additionally, all the parameters were found to be within the ranges prescribed by Krishi Vigyan Kendra.

Table 7. Impact of *M. koenigii* extract on the chemical parameters of soil.

Plant Name	Type of Plant	Treatment	TOC (%)	OM (%)	TN (kg/ha)	AP (kg/ha)	K (kg/ha)	Ca (kg/ha)	Mg (kg/ha)
C. arietinum	Crop	Control	0.52 ± 0.00	0.88 ± 0.00	332.24 ± 9.11	42.32 ± 0.37	172.26 ± 0.36	6.52 ± 0.00	2.96 ± 0.00
	Crop	1%	0.51 ± 0.00	0.89 ± 0.00	340.78 ± 4.18	45.17 ± 0.19	172.55 ± 0.38	6.05 ± 0.00	2.69 ± 0.00
	Crop	2%	0.51 ± 0.00	0.88 ± 0.00	328.23 ± 2.09	44.24 ± 0.86	172.14 ± 0.45	6.81 ± 0.00	2.02 ± 0.00
	Crop	3%	0.51 ± 0.00	0.89 ± 0.00	326.14 ± 9.58	46.11 ± 0.19	172.18 ± 0.21	6.27 ± 0.00	2.99 ± 0.00
	Crop	4%	0.51 ± 0.00	0.88 ± 0.00	326.14 ± 9.58	45.55 ± 1.78	172.33 ± 0.13	6.83 ± 0.00	2.09 ± 0.00
	Crop	5%	0.52 ± 0.00	0.89 ± 0.00	332.42 ± 7.24	47.04 ± 0.32	172.33 ± 0.21	6.03 ± 0.00	2.84 ± 0.00
T. aestivum	Crop	Control	0.52 ± 0.00	0.89 ± 0.00	334.60 ± 9.11	43.38 ± 0.37	171.52 ± 0.36	6.53 ± 0.00	2.28 ± 0.00
	Crop	1%	0.52 ± 0.00	0.89 ± 0.00	334.51 ± 4.18	45.36 ± 1.71	172.82 ± 0.13	6.33 ± 0.00	2.09 ± 0.00
	Crop	2%	0.52 ± 0.00	0.89 ± 0.00	324.05 ± 4.18	44.43 ± 1.04	171.88 ± 0.25	6.23 ± 0.00	2.84 ± 0.00
	Crop	3%	0.51 ± 0.00	0.89 ± 0.00	334.51 ± 5.53	46.85 ± 0.37	171.92 ± 0.17	6.71 ± 0.00	2.94 ± 0.00
	Crop	4%	0.51 ± 0.00	0.89 ± 0.00	332.42 ± 9.58	42.19 ± 0.19	172.29 ± 0.10	6.47 ± 0.00	2.06 ± 0.00
	Crop	5%	0.51 ± 0.00	0.89 ± 0.00	328.23 ± 9.11	45.73 ± 0.67	171.77 ± 0.26	6.07 ± 0.00	3.48 ± 0.00
A. arvensis	Weed	Control	0.52 ± 0.00	0.89 ± 0.00	336.60 ± 9.11	43.31 ± 0.37	172.22 ± 0.36	6.53 ± 0.00	2.96 ± 0.00
	Weed	1%	0.51 ± 0.00	0.89 ± 0.00	324.05 ± 4.18	43.49 ± 0.19	171.81 ± 0.17	6.41 ± 0.00	2.66 ± 0.00
	Weed	2%	0.52 ± 0.00	0.89 ± 0.00	326.14 ± 10.86	45.55 ± 0.67	172.63 ± 0.31	6.54 ± 0.00	2.24 ± 0.00
	Weed	3%	0.51 ± 0.00	0.89 ± 0.00	342.87 ± 2.09	44.80 ± 1.41	172.63 ± 0.16	5.79 ± 0.00	2.62 ± 0.00
	Weed	4%	0.52 ± 0.00	0.89 ± 0.00	328.23 ± 11.64	44.61 ± 0.67	172.03 ± 0.30	6.53 ± 0.00	2.99 ± 0.00
	Weed	5%	0.52 ± 0.00	0.89 ± 0.00	324.05 ± 8.36	45.36 ± 1.71	172.07 ± 0.10	6.28 ± 0.00	3.03 ± 0.00
L. didymum	Weed	Control	0.51 ± 0.00	0.88 ± 0.00	335.20 ± 9.11	42.11 ± 0.37	171.12 ± 0.36	6.64 ± 0.00	2.66 ± 0.00
	Weed	1%	0.51 ± 0.00	0.89 ± 0.00	319.87 ± 7.24	42.75 ± 0.19	172.33 ± 0.44	6.72 ± 0.00	2.32 ± 0.00
	Weed	2%	0.51 ± 0.00	0.89 ± 0.00	326.14 ± 3.62	43.68 ± 0.32	171.96 ± 0.26	6.59 ± 0.00	2.62 ± 0.00
	Weed	3%	0.51 ± 0.00	0.89 ± 0.00	330.33 ± 8.36	44.80 ± 0.86	171.81 ± 0.17	6.46 ± 0.00	2.59 ± 0.00
	Weed	4%	0.51 ± 0.00	0.88 ± 0.00	319.87 ± 7.24	44.43 ± 1.04	172.22 ± 0.42	6.69 ± 0.00	2.81 ± 0.00
	Weed	5%	0.51 ± 0.00	0.88 ± 0.00	326.14 ± 13.06	42.93 ± 0.49	172.63 ± 0.23	6.57 ± 0.00	2.51 ± 0.00
P. annua	Weed	Control	0.52 ± 0.00	0.89 ± 0.00	332.71 ± 9.11	44.11 ± 0.37	172.63 ± 0.36	6.43 ± 0.00	2.74 ± 0.00
	Weed	1%	0.52 ± 0.00	0.89 ± 0.00	330.33 ± 9.11	46.85 ± 0.19	171.92 ± 0.20	6.03 ± 0.00	2.27 ± 0.00
	Weed	2%	0.52 ± 0.00	0.89 ± 0.00	332.42 ± 3.62	44.24 ± 0.32	172.55 ± 0.43	6.44 ± 0.00	2.47 ± 0.00
	Weed	3%	0.51 ± 0.00	0.88 ± 0.00	326.14 ± 3.62	46.29 ± 1.04	171.92 ± 0.20	6.77 ± 0.00	2.54 ± 0.00
	Weed	4%	0.51 ± 0.00	0.89 ± 0.00	328.23 ± 5.53	44.61 ± 1.31	172.26 ± 0.19	6.52 ± 0.00	2.89 ± 0.00
	Weed	5%	0.51 ± 0.00	0.89 ± 0.00	340.78 ± 5.53	44.61 ± 0.67	171.51 ±0.10	6.68 ± 0.00	3.33 ± 0.00
V. sativa	Weed	Control	0.51 ± 0.00	0.88 ± 0.00	338.38 ± 9.11	43.62 ± 0.37	171.54 ± 0.36	6.62 ± 0.00	2.78 ± 0.00
	Weed	1%	0.51 ± 0.00	0.89 ± 0.00	330.33 ± 7.54	44.80 ± 0.97	172.03 ± 0.17	6.53 ± 0.00	2.96 ± 0.00
	Weed	2%	0.52 ± 0.00	0.89 ± 0.00	340.78 ± 5.53	45.55 ± 0.67	172.44 ± 0.37	6.24 ± 0.00	2.54 ± 0.00
	Weed	3%	0.51 ± 0.00	0.89 ± 0.00	328.23 ± 8.36	44.24 ± 0.97	172.33 ± 0.38	6.60 ± 0.00	2.42 ± 0.00
	Weed	4%	0.52 ± 0.00	0.89 ± 0.00	334.51 ± 11.06	42.56 ± 0.32	172.07 ± 0.27	6.35 ± 0.00	2.89 ± 0.00
	Weed	5%	0.51 ± 0.00	0.89 ± 0.00	330.33 ± 4.18	43.68 ± 1.17	172.07 ± 0.37	6.32 ± 0.00	3.03 ± 0.00

TOC: total organic carbon, OM: organic matter, TN: total nitrogen, AP: available phosphorous, K: potassium, Ca: calcium, Mg: magnesium.

The ideal pH range for plant growth is 5.5–6.5, because this allows for optimal availability of nutrients [59]. Additionally, most soil microbes also thrive in this pH range, because plants grow well in this range and produce more root exudates that can serve as a carbon source for the survival and proliferation of microbes [59]. Total organic carbon influences many soil characteristics, including color, nutrient holding capacity (cation and anion exchange capacity), nutrient turnover, and stability, influencing water relations, aeration, and workability [60]. Singh et al. [61] detected pHs in a range of 8.5–9.0, organic carbon contents in a range of 0.9–2.5 (%), nitrogen contents in a range of 0.11–0.22 (g/kg), phosphorus contents in a range of 0.42–13 (g/kg), potassium contents in a range of 0.19–3.9 (g/kg), and calcium contents in a range of 0.64–1.65 (g/kg) in the soil of a botanical garden and an agricultural field. Their findings were close to those of the present study.

4. Conclusions

Wheat is an important crop that is grown worldwide. Still, it suffers from heavy weed infestations, which can result in the loss of 20–40% of a crop's production [62]. Weed problems in wheat vary by region due to differences in agroclimatic conditions and management practices. Similarly, chickpea is one of the most important pulse crops worldwide, but it has low productivity, of which weeds are a major cause. Weeds reduce crop yield by 24–63% on average [63]. Chickpea is a poor weed competitor due to its slow initial growth and vegetative cover. The present study demonstrated that a 1% concentration of *M. koenigii* aqueous extract could kill *A. arvensis*, *L. didymum*, and *V. sativa* without significantly affecting the germination, growth or photosynthetic and biochemical properties of cash crops (*C. arietinum* and *T. aestivum*) or the physiochemical properties of soil. These findings show that curry leaf extract treatment has a remarkable species-specific sensitivity in terms of seed germination and plant development and that crops are more resistant than weeds. A good understanding of the intricacies of the curry leaf weed–crop interactions can facilitate the development of bioherbicides to suppress weeds.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture13091678/s1, Figure S1. *C. arietinum* and *T. aestivum* seeds treated with *M. koenigii* aqueous extract (MKAE); Figure S2: *T. aestivum* and *C. arietinum* plants treated *M. koenigii* aqueous extract (MKAE); Figure S3: *A. arvensis* and *L. didymum* plants treated with *M. koenigii* aqueous extract (MAKE); Figure S4: *P. annua* and *V. sativa* plants treated with *M. koenigii* aqueous extract (MKAE); Figure S5: Graph showing impact of *M. koenigii* aqueous extract on physiochemical parameters of soil (AA—*A. arvensis*, LD—*L. didymium*, PA—*P. annua* and VS—*V. sativa*).

Author Contributions: Conceptualization, D.S.V. and A.B.; Data curation, R.K.B., S.K.A., L.A.A.-S., P.K. and A.H.; Formal analysis, D.S.V.; Funding acquisition, S.K.A. and L.A.A.-S.; Investigation, D.S.V.; Methodology, D.S.V., A.B. and R.K.B.; Project administration, S.K.A. and L.A.A.-S.; Resources, A.B.; Software, L.A.A.-S., P.K. and A.H.; Supervision, A.B.; Validation, R.K.B., S.K.A., P.K. and A.H.; Visualization, R.K.B., P.K. and A.H.; Writing—original draft, D.S.V.; Writing—review & editing, A.B., R.K.B., S.K.A., L.A.A.-S., P.K. and A.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research publication was funded by Princess Nourah bint Abdulrahman University Researchers Supporting Project number (PNURSP2023R365), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia. This research publication was funded by the Deanship of Scientific Research at King Khalid University through Large Groups Project under grant number (R.G.P.2/77/44).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The infrastructural support provided by the Head of the Department of Environmental Science, Graphic Era (Deemed to be University), Dehradun, India is gratefully acknowledged. Deepti Singh Vashishth wishes to thank Ashish Kumar Arya and Rinky Yadav for their support. The authors extend their appreciation to Princess Nourah bint Abdulrahman University Researchers Supporting Project number (PNURSP2023R365), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia. The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through Large Groups Project under grant number (R.G.P.2/77/44). All individuals included in this section have consented to the acknowledgement.

Conflicts of Interest: The authors declare no conflict of interest.

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