International Journal of Environmental Bioremediation & Biodegradation, 2025, Vol. 13, No. 1, 1-11
Available online at http://pubs.sciepub.com/ijebb/13/1/1
Published by Science and Education Publishing
DOI:10.12691/ijebb-13-1-1

Morphological Evaluation of *Chrysopogon zizanioides*: Criterion for the Effectiveness of Phytoremediation of Mine Tailings Under Sahelian Climate

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Received June 14, 2025; Revised July 16, 2025; Accepted July 23, 2025

Abstract Artisanal gold mining generates uncontrolled waste responsible for heavy metal soil contamination metals, threatening both human health and agricultural productivity. Phytoremediation offers a sustainable solution to mitigate these impacts. This study assesses the morphological responses of *Chrysopogon zizanioides* grown in mine tailings under Sahelian climatic conditions. The experiment was conducted in a greenhouse using a randomized complete block design with two treatments: polluted substrates (P) derived from cyanidation residues and non-polluted substrates (NP) from pre-cyanidation washing. Over 18 months of growing in pot, survival rate, tiller production, and biomass growth were monitored. A high tolerance index (TI) was recorded during the first campaign (C1) at 85.7 ± 0.1%, followed by a decrease in C2 (71.2 ± 0.1%) and C3 (70.6 ± 0.1%). An increase in TI was observed in C4 (79.8 ± 0.04%) and C5 (79.1 ± 0.1%). Relative water content (RWC) remained stable in NP pots (64.2%–67.7%), with a peak at C3 (98.3%), while in P substrates it ranged between 59.2% and 69.4%. Specific root length (SRL) showed a decline from C2 onward, indicating a shift in root architecture. Relative growth index (RGI) revealed differentiated growth phases, although no significant differences were observed between NP and P treatments. These morphological responses serve as early indicators of phytoremediation performance under Sahelian conditions, even before further chemical analyses.

Keywords: *Phytoremediation - Mining residues - Morphological parameters - Vetiver - Pollution - Sahelian climate*

Cite This Article: Yamma Rose, Kone Martine, Sawadogo Bienvenue Jocelyne, Maiga Guébré, Yonli Arsène, and Wanko Ngnien Adrien, "Morphological Evaluation of *Chrysopogon zizanioides*: Criterion for the Effectiveness of Phytoremediation of Mine Tailings Under Sahelian Climate." *International Journal of Environmental Bioremediation & Biodegradation*, vol. 13, no. 1 (2025): 1-11. doi: 10.12691/ijebb-13-1-1.

1. Introduction

Mining is a key economic sector in many African countries, including Burkina Faso, which is one of the continent's leading gold producers [1,2,3,4]. This activity generates substantial revenue for the state and is an essential source of income for rural populations facing poverty and climatic hazards [5]. The expansion of the mining sector has resulted in an increase of industrial mines, without curbing the rapid proliferation of artisanal mining (AM). However, while the boom in the mining sector is driving economic development, it also giving raises major and growing environmental concerns. Although it plays an important role in the fight against poverty by injecting cash income into rural areas [6]. The practice of AM is characterised by the uncontrolled use of chemical substances such as mercury (Hg), cyanide (CN), leavy metal and acids leading to the pollution of soil and water resources thus compromising biodiversity and agricultural productivity [7].

The uncontrolled accumulation of mine tailings in the environment leads to massive dispersion of potentially toxic elements (PTEs) such as arsenic (As), zinc (Zn) and iron (Fe), which end up in soils and water resources [8,9,10]. At high concentrations, these contaminants disrupt soil metabolic processes, reduce soil fertility and affect plant growth, potentially causing leaf chlorosis and reduced biomass production [11]. In addition, trace metal elements (TME) accumulate in the food chain through bioaccumulation, threatening human and animal health [12]. Because of their persistence and their toxicity, pollution by TME is now considered to be one of the most worrying environmental problems worldwide [12]. In Burkina Faso, the rehabilitation of soils degraded by mining remains almost non-existent, giving way to continue deterioration of arable land and a reduction in arable land. To reduce the environmental and health impact of AM, innovative and sustainable clean-up strategies are needed. Phytoremediation appears to be an effective and economically viable solution for restoring contaminated soils. This approach, based on the use of hyperaccumulative plants, makes it possible to absorb and stabilise the TME present in the environment, while taking account of the country's socio-economic constraints.

An effective plant for soil phytoremediation must have several key characteristics, including rapid growth, a dense and extensive root system, high biomass production and high tolerance to high concentrations of pollutants [13]. The choice of plant is therefore an essential criterion for effective remediation of contaminants [14]. Species with strong growth and high biomass production are particularly well suited to this approach [15].

Among these *Chrysopogon zizanioides (L.) Roberty*, commonly known as vetiver, stands out for its exceptional physiological properties. It is known for its extremely robust root system, which makes it particularly effective in combating soil erosion [16]. This grass tolerates difficult climatic conditions as well as various heavy metals, making it a species of choice for phytoremediation strategies [17,18,19]. Thanks to its many applications, vetiver is often used in bioengineering to stabilise slopes, treat wastewater and clean up contaminated soil [20].

Morphological and physiological parameters are good indicators of a plant's ability to tolerate heavy metals and nutrient deficiencies [21,22,23]. While the effectiveness of vetiver in remediating contaminated soils has been demonstrated in various climatic contexts, its potential in Sahelian zones, particularly through analysis of its allometric parameters in Burkina Faso, remains poorly documented. In this context, this article aims to assess the morphological response of *C. zizanioides* grown ex situ in mine tailings in a Sahelian climate. The main objective is to analyse the ability of this plant to survive and develop in ex situ mine tailings under Sahelian climatic conditions, through the evaluation of allometric growth parameters. The study also aims to identify early morphological traits likely to reflect the phytoremediation potential of *C. zizanioides* in an arid environment.

2. Material et Methods

2.1. The Sahelian Climate Context

The study was carried out at the Institute for Research in Applied Sciences and Technology (IRSAT) (12°25‘27.8’ ‘N, ;1°29’ 15.17‘’W) in Ouagadougou, Burkina Faso. The experiment was conducted in a greenhouse, exposing the plants to the natural climatic variations of the region throughout the study period. Climatic parameters could not be recorded due to a lack of specific equipment. However, seasonal fluctuations were taken into account based on climate data from the National Meteorological Agency of Burkina Faso over a 30-year period (1992-2022). These data reveal two main seasons: a short rainy season (June to September) and a long dry season (October to May), typical of the Sahelian climate.

The rainy season lasts a maximum of four months, with rainfall ranging from 8.4mm to 368mm, accompanied by moderate temperatures (Tmin = 14.3°C; Tmax = 36.1°C) and high humidity (Hmin = 46%; Hmax = 96%). Sunshine is relatively low (5.1 to 9.1 h/d), with an average wind speed of 2.3 m/s.

The dry season is the longest and is divided into two phases:

- Hot dry season (March to May) with high insolation (>10 h/d), average maximum temperatures reaching 42.1°C, low humidity (Hmin = 6%; Hmax = 28%).
- Cold dry season (November to February, harmattan period): moderate temperatures (Tmax ≈ 39 °C), high direct radiation (6 to 9.9 h/d), with dry northerly winds blowing at an average of 4.4 m/s. This Sahelian climate in the city of Ouagadougou, characterised by high thermal variability, marked water stress and low plant cover, provides a relevant context for assessing the resilience of plants species adapted for phytoremediation such as *C. zizanioides.*

2.2. Description of Experimental Materiel

2.2.1. The Mine Tailings

The mining substrates used for the experiment were collected at Nimbrogo (Nahouri province, Burkina Faso), an active artisanal gold processing area. Two types of tailings were used:

- Unpolluted substrates (NP): derived from sludge recovered after gravimetric washing of the ore, without contact with chemicals (Figure1). These sludges, dehydrated and free of contamination, were transported to IRSAT to be used as controls during the tests.
- Polluted mine tailings (P): collected after treatment by cyanidation. Cyanidation is a process using 800 L of water for 1 kg of cyanide to extract the residual gold. The tailings deposited around the ponds (Figure2) are carried away by rainwater during the rainy season and flow towards surface water points. These tailings pollute soil, surface water and groundwater through run-off or infiltration. The tailings were transported in bags to IRSAT for experimentation. The initial pollutant concentrations and physical characteristics in the tailing are presented in Table 1.

Table 1. Physico-chemical characteristics and average level of Fe, Zn, Hg and As

Matrix	Fe (ppm)	Zn (ppm)	Hg (ppm)	As (ppm)	pH	Organic matter (%)	Electrical conductivity (µS/cm)	Redox (mV)
DL	10	5	0.2	1	*	*	*	*
Environmental quality limit	5	200	0.8	20	*	*	*	*
No polluted soil	29343	340	0,5	5	7,6	4,2	202,9	189
Mine taillings	36965	859	1,1	22	9	2,7	76,9	216

DL: Detection limit
Environmental quality limit: Acceptable limit value according to the Burkina Faso standard of decree
***Not available data**

Figure 1. Ore washing process (Photo credits: Rose Yamma, July 2022)

Figure 2. Cyanidation site of Nimbrogo (Photo credits: Rose Yamma, July 2022)

2.2.2. Plant Material

Some plant species have a high potential for metal accumulation in shoots and roots. The plant material used in this study *is Chrysopogon zizanioides (L.) Roberty*. It is a grass in the family Poaceae, order Poales with the kingdom Plantae and class Liliopsida [24]. This grass was chosen for its many remarkable morphological and physiological characteristics [25,26]. Indeed, *C. Zizanioides* is a perennial rhizome plant that roots deeply up to 3 or 4m. It is sterile, non-invasive, fast-growing capacity, [20,27]. It can survive extreme climatic conditions and tolerate various heavy metals, making it a promising plant for soil and water phytoremediation [17,19]. Its exceptional tolerance to heavy metals has been demonstrated in several studies. The ability of *C. zizanioides* to restore soils contaminated by endosulfan, copper and cadmium was studied in Burkina Faso by Abaga et al., (2021). Similarly, [25] demonstrated the ability of *C. zizanioides* to remediate heavy metals and organic waste. Recent studies [17,24,29,30] showed the effectiveness of *C. zizanioides* in the remediation of soils polluted by mine drainage. The work of Ghosh et al. (2015), which revealed the ability of *C. zizanioides* to remediate fly ash [31].

2.3. Experimental Setup

The experimental set-up consisted of units of planted polluted pots and planted unpolluted pots. Thirty planted pilots were constructed using polypropylene pots 40cm high and 25cm in diameter. This volume was chosen to provide sufficient space for root development facilitating management the system in the greenhouse. Each pot was filled according to a stratification designed to reproduce a filter bed to simulate drainage:

- 5cm of coarse gravel (26-28mm): to ensure effective water drainage.

- 3cm of finer gravel (20-22mm): to ensure a grading transition and stabilise the top layer.
- 7cm of river sand (D90 ≈ 1mm): to filter out fine particles, encourage water infiltration, and limit the vertical migration of pollutants.
- 20cm of soil (cyanide mine tailings or residues from gravimetric washing) at last.

Thus, fifteen pots were filled with 20cm of cyanide mine tailings for the polluted modality (P), and fifteen others with unpolluted tailings (NP) from gravimetric washing, as illustrated by Figure 3. These two types of substrates reflect the real exposure conditions of plant on artisanal mining sites in Burkina Faso. After filling, each pot was supplied with a daily hydraulic load of 4.33mm. The daily hydraulic load was determined considering the average annual rainfall in Ouagadougou (around 768mm/year) and the surface area of the pots. This choice makes it possible to simulate a realistic water supply in a Sahelian climate conditions, by ensuring that humidity is maintained under real stress context. *C. Zizanioides* seedlings (Figure 4) previously propagated in the nursery were mowed at 20cm for the leaves and roots. The *C. Zizanioides* seedlings were transplanted into pots using the rice transplanting method (Figure 5). All the pots were arranged in randomised complete blocks design on a support within a greenhouse (Figure 6), in order to minimize position- related effects.

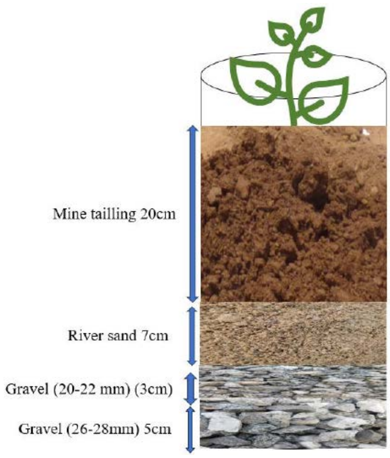


Figure 3. Different layers set

Figure 4. Vetiver plant (2-month-old) before transplanting

Figure 5. Experimental pot just after transplant (at T0)

Figure 6. Experimental pilot (at T12)

2.4. Assessment of Plant Growth

2.4.1. Morphological Monitoring of Plants

Morphological monitoring consisted of measuring the morphological parameters of plant growth, determining the tolerance index, relative water content, specific root length and relative growth index. Plant growth assessment consisted of fortnightly measurements of allometric parameters (number of green leaves, number of new shoots, stem size and circumference dimension) for each modality for 18 months (M1 up to M18).

- Number of green leaves: The principle is to divide the clump into four parts and count each part. The total number of green leaves in each pot on a given date is obtained by adding up the four parts.
- Number of new leaves: the counting of new leaves follows the same principle as that of green leaves, but only new leaf shoots are counted.
- Plant height: a double decameter is used to measure the height of the stem. The measurement is taken from the base of the rhizome to the tip of the terminal leaves. 2 or 3 stems were labelled in each pot for this purpose.
- Plant circumference: all the leaves and stems were

grouped together at the base and the circumference of the plant was measured using a decameter.

2.4.2. Plant Sampling

At the initial time, 30 pots were obtained for experimentation in a growing vase for a period of 18 months (from M1 to M18). Five sampling campaigns (C1, C2, C3, C4 and C5) were carried out at different times T1, T2, T3, T4 and T5, corresponding to 6, 9, 12, 15 and 18 months respectively. Table 2 presents the experimental setup, the sampling plan, as well as the different climatic seasons namely the rainy season, the hot dry season, and the cool dry season covering the entire experimental period.

During each sampling campaign, three pots of each NP and P modality were removed from the batch for plant harvesting. Whole plants were harvested individually (Figure7) from each pot and the biomass was separated from the soil. Roots and leaves were thoroughly cleaned of excess soil, washed with clean water and dried at room temperature in the laboratory. Roots and leaves were measured using a measuring tape (Figure 8). The aerial and root parts were then separated and dried in the shade in the laboratory chamber at room temperature for 48 h. The total fresh weight (FW) of the vetiver leaf and root biomass was obtained by weighing on an analytical balance. The biomass was then oven-dried at 80°C for 48 hours to obtain the dry weight (DW) of the leaf and root biomass using the method of Banerjee et al [24].

These samples were used to determine the tolerance and root efficiency factors of *C. Zizanioides* under experimental conditions. The tolerance index (TI) expressed as a percentage is calculated using formula (A) [32] to assess the ability of *C. Zizanioides* to survive not only in mine tailings, but also under Sahelian climate conditions.

The relative percentage water content (RWC %) was also measured using method (B) of [33]. Specific root length (SRL) was calculated (C) as the ratio of root length to root weight [34].

Table 2. Experimental design

Duration of experiment (T in month)	Non-polluted soil	Mine tailings	Total sampled pots / Campaign numbering	Climatic season				
				CDSn°1	WDSn°1	RSn°1	CDSn°2	WDSn°2
T1 = 6			6 / C1	×	×			
T2 = 9			6 / C2	×	×	×		
T3 = 12			6 / C3	×	×	×		
T4 = 15			6 / C4	×	×	×	×	
T5 = 18			6 / C5	×	×	×	×	×
Total number of pots			30					

CDSn°1 = Cool dry Season during the first year of the experiment
WDSn°1 = Warm dry season during the first year of the experiment
RSn°1 = Rainy Season during the first year of the experiment
CDSn°2 = Cool dry season during the second year of the experiment
WDSn°2 = Warm dry season during the second year of the experiment

Figure 7. Harvesting *C. Zizanioides* from polluted pots at T1

Figure 8. Measurement of *C. Zizanioides* from polluted pots at T1

$$TI\left(\%\right)=\frac{\text{Dry biomass}\left(\text{P}\right)}{\text{Dry biomass}\left(\text{NP}\right)}*100 \qquad (A)$$

$$RWC\left(\%\right)=\frac{\left(FW-DW\right)}{FW}*100 \qquad (B)$$

2.4.3. Plant Growth Index

Periodically, relative growth index (RGI) were calculated by using the relative growth rate (RGR), in order to monitor variation in plant development for each modality and according to each growth parameter. The RGR (D) was determined according to the formula in [34] every fortnight for 18 months. The RGI value (E) is then calculated according to the ratio of the RGR of the polluted modality to the RGR of the unpolluted modality. The uncertainty associated with each RGR is calculated by considering the average value of the entire experimental period for the parameter in question.

$$\text{RGR} = \frac{(\ln(V2)-\ln(V1))}{t2-t1} \qquad (D)$$

$$RGI = \frac{\text{RGR\_P}}{\text{RGR\_NP}} \qquad (E)$$

t1 and t2 are durations of time for each two weeks, with the duration t2 greater than t1; V1 and V2 are the values of the growth parameters considered at t1 and t2 respectively.

2.5. Statistical Analysis

The raw data were processed and the rates calculated using Excel 2016. R software (version 3.3.1) was used to analyse the differences between the modalities and to generate the graphs. The confidence level set at 5% (α = 0.05) means that we accept a margin of error of 5%. In other words, when the p-value is less than 0.05, we consider that there is a significant difference between the P and NP modalities.

3. Results and Discussion

3.1. Results

3.1.1. Tolerance and Water Performance Factors

The evolution of the tolerance index (TI), relative water content (RWC) and specific root length (SRL) of *C. Zizanioides* throughout the experimental period is shown in Table 3.

TIs ranged from 70% to 85%, with an average of 77.28% over the five sampling campaigns. The best survival rate (85.7%) was observed at C1, i.e. during the first six months of experimentation. The lowest tolerance value was 70.6% obtained at C3, corresponding to the twelfth month of experimentation. However, statistically, no significant difference in TI was observed between the different sampling campaigns. This plant species exhibits high tolerance to mine tailings.

Table 3. Average TI, RWC and LRS values for C.Zizanioides

Campaign	TI (ΔTI)	RWC (ΔRWC)		LRS (ΔLRS)	
		NP	P	NP	P
C1	85,7 (0,1)	64,2 (0,8)	62,5 (0,1)	1,6 (0,3)	1,3 (0,04)
C2	71,2(0,1)	66,4 (0,1)	59,2 (0,6)	0,6 (0,23)	1,0 (0,1)
C3	70,6 (0,1)	67,7 (0,9)	66,0 (0,5)	0,5 (0,5)	0,7 (0,2)
C4	79,8 (0,04)	67,0 (0,3)	69,4 (0,5)	0,3 (0,5)	0,4 (0,2)
C5	79,1(0,1)	67,2 (0,2)	68,3 (0,5)	0,3 (0,3)	0,3 (0,2)
Mean value	77 (0,1)	66,5(0,5)	65,1 (0,4)	0,7 (0,3)	0,7 (-0,1)
CV	0,07	0,02	0,06	0,7	0,4

C1, **C2**, **C3**, **C4**, **C5**: from the first sampling campaign to the fifth
CV: Coefficient of Variation

RWC is relatively stable (CV = 2%) and increases over the five campaigns in both modalities NP and P. RWC values for NP pots are between 64% and 67% and from 59% to 69% for P pot. For C1, C2 and C3 campaign and P pots exhibit higher RWC levels compared to P ones. The opposite effect is observed over the last six months at C4 and C5. Although the trend in RWC was reversed at C4 and C5, no significant difference (p-value >0.05) was observed between the sampling campaigns.

The SRL generally showed a downward trend during the experiment. The SRL for the P modality was slightly higher than that for the NP modality, except for C1 and C5. In NP environments, the SRL values decreased from 1.6 in C1 to 0.3 in C5, and from 1.3 in C1 to 0.3 in C5 in P pots.

3.1.2. Relative Growth Rates

The relative growth rates (RGR) of the growth parameters (GL, NL, H, and C) of *C. zizanioides* were monitored throughout the experiment according to the climatic seasons. The results are illustrated in Figures 9 and 10, representing the unpolluted (NP) and polluted (P) modalities respectively. The variation in growth rates in the two experimental contexts is influenced by meteorological factors according to the division of climatic periods.

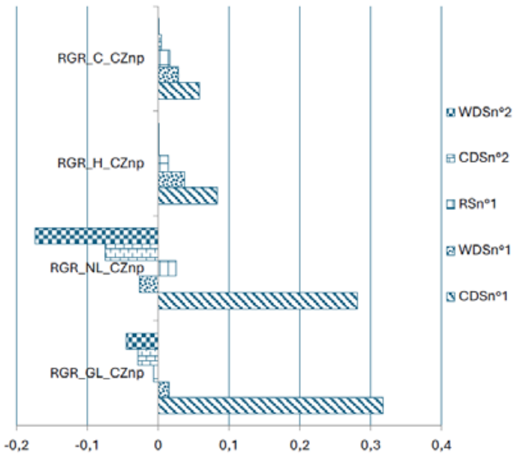


Figure 9. RGR_ NP of morphological parameters by climatic season

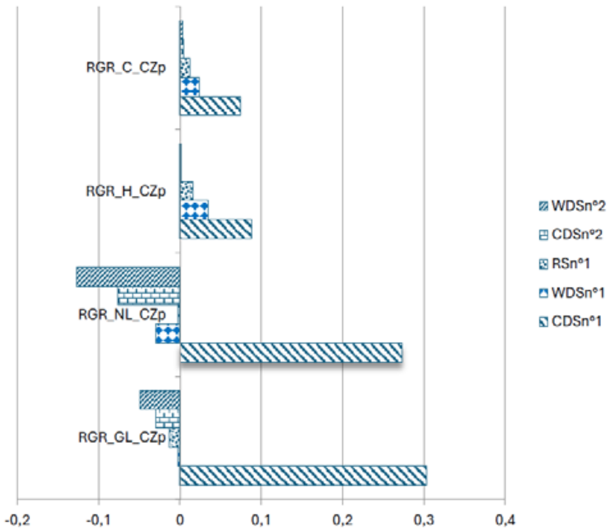


Figure 10. RGR_P of morphological parameters by climatic season

➢ Number of green leaves

Green Leaves development in the NP and P pots shows a similar trend. Green Leaves growth is highest during the first cool and dry season (CDS no. 1) in the NP pots, and the same trend is observed for P pots. The cool and dry season is favourable for green leaves development in both study environments. During this period, sunshine is reduced by residual clouds at the end of the rainy season (RS) and by dust in suspension during the harmattan, which blocks part of the sun's rays. However, the following season, corresponding to the hot dry season, was critical, with RGR decreasing further in both modalities. This decline continued during the rainy season (RS), with almost zero or negative RGR. From WDS n°2 onwards, there was a resumption in the evolution of GL, which nevertheless remained negative until the end of the trials for both modalities. The reduction in RGR suggests a slowdown in green leaf growth. The hot dry season, with the highest Tmax of the year, led to an increase in temperature inside the experimental greenhouse, which induced water stress. The pollution presents in the mine tailings had no significant influence on leaf development. There was no significant difference between the GL development of polluted and unpolluted pots plants.

➢ The number of new leaves

The rate of appearance of new leaves in the NP and P pots is similar to that of the GL pots during the cool dry season, with good performance in terms of new growth. The same trend is observed for the rainy season, although the rate is low compared with the CDS period. In fact, these periods correspond to the season of moderate temperatures, resulting in less stressful weather conditions for the plants, which allows for better adaptation of the plant and a massive increase in the number of new leaves. On the other hand, RGR_NL decreases, with negative values during the hot and dry season, indicating a reduction in new shoots. In the P environment, the increase in new leaves is also dominant in the cold dry season and is reduced during the hot dry season and the rainy season. Thus, the increase in Tmax during these seasons has an influence on the appearance of new leaves. However, no significant difference was observed in the dynamics of the appearance of new shoots in the two modalities.

➢ Plant height and circumference

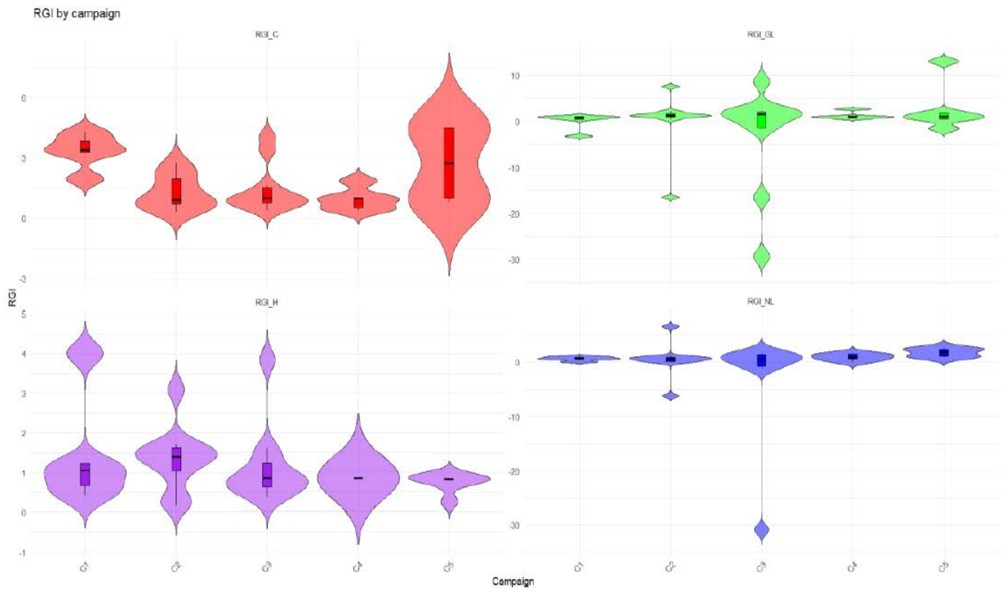
Overall, growth rates in plant height and girth showed a regular and positive dynamic during all seasons of the year in both modalities. Following the example of the GL and NL growth rates, the cold dry season was favourable to growth in height and circumference of *C. zizanioides* in both NP and P pots. On the other hand, from the hot dry season onwards, there was a successive reduction in growth rates, which tended towards zero until the end of the trials for both modalities. Overall, there was no significant difference in plant RGR_H and RGR_C between the NP and P environments during the different seasons covering the experimental period.

3.1.3. The *C. zizanioides* Relative Growth Index

The evolutionary index of morphological parameters monitored throughout the experimental period is shown in Figure 11 by campaign. When the RGI is close to or equal to one, this indicates that there is no significant difference between polluted and unpolluted pots for the parameter in question.

. The RGI_GL varied little during the first two sampling campaigns. The RGI_GL values for C1 and C4 are stable and close to 1, which proves that there is no significant difference in the RGR_GL of the P and NP modalities during these periods. On the other hand, the RGI for campaigns C2 and C5 were variable, with mostly positive values, suggesting that CZ was able to grow in both polluted and unpolluted pots without any significant difference. The RGI_GL of C3 showed a high degree of variability, with predominantly negative values indicating poor growth and a slowdown in the rate of appearance of green leaves. However, there was no significant difference in green leaves between plants in NP and P pots throughout the experimental period.

The evolution of the new shoot growth index (RGI_NL) shows similar trends, with 50% of values close to 1. RGI_NL values show little dispersion in C1. Those for C3 and C4 have a wider distribution around 1, indicating no significant difference between RGR_NL for NP and P, but still reflecting stable growth in the appearance of new shoots during these periods. On the other hand, RGI_NL in C2 and C3 were characterised by heterogeneous growth in new shoots, with negative values predominating in C3. In fact, the negative RGI values reflect a period of reduced growth of new shoots, certainly linked to the high outside temperature and stress due to pollution. Although there was a slowdown in the number of new leaves in C2 and C3, there was no statistically significant difference in the RGI_NL values between the different campaigns or between the modalities.



The violins show the unimodal or multimodal distributions of RGI for the different parameters. Each mode indicates a phase of growth and declines of the RGI around a local maximum

Figure 11. RGI of morphological parameters by campaign

Variability in the height growth index was observed during the experimental period. Overall, the analysis of RGI_H did not show any significant difference between the NP and P pots over the course of the campaigns. In fact, at C1, C2 and C3, not only was there a high density of RGI_H values, but also good plant height growth despite the stressful conditions caused by temperature and pollution. However, a stabilisation in height growth was observed at C4 and more accentuated at the last C5 campaign. At C4, plant height growth was limited and constant, suggesting that the plants had reached maturity, whereas at C5, it was almost zero, reflecting a virtual halt in growth.

The growth index of the clump (RGI_C) at C1 shows rapid growth of *C. zizanioides* with positive values indicating good tolerance of the plants to the experimental conditions. From C2 onwards, the growth index of the circumference is moderate with a gradual decrease until C4. However, at C5, tuft growth increased considerably during the last three months of the experiments. Despite this variability in the evolution of plant circumference, the p-values obtained were all greater than 0.05, indicating that the differences between the campaigns were not statistically significant.

3.2. Discussion

3.2.1. Tolerance, Root Growth and Maintenance of Water Status

Although *C. zizanioides* is widely recognised for its effectiveness in phytoremediation of contaminated soils, particularly for its ability to accumulate heavy metals, studies on its morphological responses under Sahelian climatic conditions remain limited. Data on indicators such as tolerance index (TI), specific root length (SRL) and relative water content (RWC), as well as responses of morphological parameters, are particularly poorly documented in the Sahelian zone. The present study partially fills this gap by providing empirical results to assess the tolerance and adaptability of vetiver growth over an extended period of eighteen months of cultivation under heavy metals and climatic stress conditions.

The high TI levels show that *C. Zizanioides* has a strong capacity to maintain its growth and physiological functions despite the stressful conditions associated with pollution and the high temperatures of the Sahelian climate. The maximum TI observed at C1 suggests a strong capacity of the plant to tolerate mine tailings during the first growth phase. However, the drop in TI at C3 reflects a transitional phase of physiological stress that could be linked to the accumulation of metals and the rise in temperature. However, the absence of significant differences between the campaigns suggests an overall adaptive stability of the species throughout the experiment. According to [25], vetiver's ability to maintain a high TI even in extreme conditions is linked in particular to the depth of its root system, its growth in dense clumps and its low sensitivity to abiotic stresses.

The stability of the RWC between polluted and unpolluted environments indicates that despite the conditions of pollution and high temperatures, *C. Zizanioides* ensures the absorption and transport of water in its organs. This efficient water management is a valuable capacity in a Sahelian context marked by erratic rainfall and often extreme temperatures. Furthermore, the absence of significant difference is consistent with the work of [24] who demonstrated that there is no significant difference (p-value >0.05) between the RWC of vetiver in the control garden and iron mine. This could indicate good water resilience of vetiver.

The initially high SRL (C1) in the NP pots indicates dense and extensive root system development. These results are consistent with the work of [35], who demonstrated that vetiver roots reach 1.80cm after in six months of cultivation. Meanwhile, the reduction in SRL at C2 indicates a slowdown in root growth. This slowdown could be due to the fact that the roots from C2 touch the bottom of the pots and then reorient themselves towards the surface. Indeed, when roots reverse their growth direction upwards, a reduction in their linear elongation is generally observed, accompanied by an increase in their biomass. This response could reflect an adaptive strategy aimed at bypassing the pot walls or maximising access to more humid areas, thus favouring the survival of plant in adverse conditions [36].

3.2.2. Relative Growth Dynamics of Plants

Analysis of the RGRs of the morphological parameters of vetiver (number of green leaves, new leaves, height and circumference) highlights a strong influence of seasonal climatic variations, regardless of the level of substrate pollution. Overall, no statistically significant differences were observed between polluted (P) and unpolluted (NP) environments, suggesting that vetiver is physiologically tolerant to the edaphic conditions of the substrates.

The significant production of biomass in mine tailings reveals that *C. zizanioides* has a capacity to adapt to an environment made hostile by the presence of chemical pollution [37]. The massive evolution of green leaves at the initial period of the trials in both modalities reflects the rapid adaptation of the plant to extreme pollution and climatic variation conditions according to [25]. The first few months of the cold dry season were favourable for the active growth of new leaves thanks to the moderate temperatures and the compost amendment, which stimulated soil fertility and plant growth. Indeed, [38] have shown that compost amendment of 30% to 60% promotes a significant increase in biomass between 15 and 20°C.

This study showed that conversely the hot dry season, with its extreme temperatures, lead to a reduction in RGR_GL, confirming the inhibitor effect of heat stress on plant metabolism. The progressive reduction in the rate at which new shoots appear (RGR_NL) suggests a combined effect of heat stress and pollutants which may have affected leaf production during the hot dry period. When the outside temperature is high, RWC decreases, limiting plant growth. According to the work of [39], heat stress combined with water deficit, leads to a significant reduction in leaf RWC, thus limiting leaf growth. On the other hand, metal stress is responsible for a reduction in circumference growth according to [40], thus inducing a loss of plant biomass [41]. However, in the present study, the absence of a significant difference in biomass evolution between polluted and non-polluted pots suggests that the observed growth reduction cannot be attributed to chemical pollution. The correlation matrix of the RGR values for the monitored parameters, presented in Supplementary Data (SD1), reveals a strong correlation between the polluted and non-polluted treatments. This similarity in parameter evolution confirms that pollution did not significantly affect the plants' growth dynamics. Growth factors therefore appear to be regulated similarly under both conditions, indicating a notable tolerance of the plants to the pollutants present in the substrates. It is thus likely that climatic factors, in particular high temperatures and water deficit, also contributed to limiting biomass production.

3.2.3. Plant Resilience Indicators: Analysis of RGI

During the first six months (C1), which correspond to the relative cool and moderate dry period (harmattan period), the RGI values for all parameters monitored were in general positive and close to 1, reflecting good overall plant growth in both polluted and unpolluted pots. This good growth of the aerial parts of the plants is also supported by the high SRL value, which indicates significant favourable root development. This adaptability is linked to the intrinsic characteristics of the plant, thanks to its extensive and very dense root system [26,42], which allows the plant to establish itself and develop effectively in a polluted environment and under climatic stress conditions [43]. The stability of the RGI during the second C2 campaign is favoured by the drop in outdoor temperatures during the rainy season. Indeed, this rainy period seems to have reduced water stress, promoting root exploration in the pots as well as leaf growth. However, the C3 campaign which correspond to the cold dry season marked a turning point in growth dynamics. The drop in RGI, particularly RGI_GL and RGI_NL, reflects a loss of green leaves and a slowdown in the appearance of new shoots, even after compost amendment. This decline is indicative of climatic stress, which leads to reduced vegetative tissue development. These results are consistent with those reported by [29] concerning mine drainage, which demonstrated the influence of abiotic stress on vetiver growth. In addition, this decline in growth parameters performance of the GL and NL coincides with a decrease in TI (70.6%, the lowest observed throughout the experiment) and LRS indicating a reduction in root exploration. This response could be explained by a reallocation of resources. The roots that reach the bottom of the pots reorient themselves vertically upwards in response to the physical constraint imposed by the limits of the pots. This behaviour is known as root circling, which is not the result of water stress or pollution. It is due, the confinement the roots which limit the natural expansion of the root system [44]. In C4, plant growth in height and circumference was negligible, reflecting a phase of morphological stagnation. This lack of vertical or radial development could also be due to the confinement of the root caused by the limited volume available in the pots. However, the maintenance of a high TI (79.8%) and the stability of the RWC suggest that the plant has adopted a physiological maintenance strategy, enabling it to preserve its vital functions without investing in new morphological structures. Indeed, this type of response is typical of perennial species which subjected to prolonged environmental stress, prioritise long-term survival over active growth [36,45]. Thus, eighteen months after planting (C5), the plants endured all the climatic fluctuations of the city of Ouagadougou.

4. Conclusion

The present study aimed at over 18 months to evaluate the evolution of the morphological parameters of *C. zizanioides* grown under conditions of pollution by mining residues in a Sahelian climate. The criterion used to reveal phytoremediation effectiveness without taking into account chemical analyses was the evolution of morphological parameters during the evolution of the plant. The results highlighted the potential of vetiver to adapt and grow under abiotic stress. During the experiment, variations in the tolerance index, the relative percentage water content and the Specific length of roots revealed that the plant has a high tolerance to mining residues pollution, through the adaptation capacities of roots to manage water availability in Sahelian climate conditions. The evaluation of the various allometric parameters showed that vetiver is resilient to the Sahelian climate, although declines in growth were observed, particularly in the evolution of the number of green leaves and those of new leaves during the hot and dry season. The first half of the experiments were particularly revealing of vetiver's high potential. While the cool and dry season and the rainy season promote good growth dynamics, the hot and dry season induces a reduction in plant growth, even to the point of stalling, in both conditions of polluted pots and unpolluted pots. A striking result of this study is the appearance of root circling, which is characteristic of root confinement in pots, but also indicative of environmental stress increase such as high temperatures. This root behaviour is a response to lack of space associated with heat stress. While the morphological growth of vetiver was not affected at the beginning of the experiment, due probably to the low uptake of pollutants by the plants, subsequent studies demonstrated the ability of this species to maintain stable growth and effectively adapt its root system to mine tailings pollution and a Sahelian climate conditions. This is an early indicator of the plant's performance to ensure phytoremediation in Sahelian climate conditions, especially since the plant is perennial and has a strong and deep root system associated with rapid leaf growth, knowing that among the criteria for choosing a plant for phytoremediation. Especially since *C. Zizanioides* is perennial and has a strong and deep root system associated with rapid leaf growth, knowing that among the criteria for choosing a plant for phytoremediation.

ACKNOWLEDGEMENTS

This experimental study was funded by the National School for Water and the Environment (ENGEES) in Strasbourg. The authors would like to thank ENGEES for its financial support, which enabled the pilots in this study to be carried out.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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