

Synergistic Effects of Geological Materials on the Growth and Metabolic Parameters of *Zea mays* L. Grown in Sandy Soil

Alaa S. Mahmoud

Assiut University

Kotb A. Farghali

Assiut University

Mohamed A. Moneim

Assiut University

Abdalla M. El Ayyat

Assiut University

Ezzat A. Ahmed

Assiut University

Suzan A. Tammam

susan@aun.edu.eg

Assiut University

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Abstract

Background

Sandy soils in arid and semi-arid regions suffer from low fertility and poor water retention, limiting crop yields. This study tested four low-cost geological materials from Egypt's Western Desert (Upper Cretaceous Quseir and Duwi formations): brick red siltstone (M), green siltstone (H), Ca-bentonite-rich black shale (B), and glauconite (G). This work aimed to investigate the applied singly and in binary, triple, and quaternary combinations (2% w/w) to sandy soil, their effects on *Zea mays* L. seedling growth were assessed across fifteen treatments and a control, in triplicate, two weeks after germination. XRD/XRF confirmed illite-dominant siltstones, Ca-bentonite-rich black shale, and glauconite minerals. The concentrations of major oxides, including SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , Na_2O , K_2O , and MgO , in the studied sediments were determined using XRF analysis.

Results

The GM mixture produced the greatest shoot length (23.4 cm), while B, G, GH, and GHM treatments enhanced root length by 1.77–2.3-fold relative to control. GH, GHM, and the quaternary mixture increased shoot fresh weight (up to 1.66-fold), and GHM gave the highest root fresh weight ratio (2.11-fold). Chlorophyll *a* peaked under BG (2.12 mg g⁻¹ F. Wt.), while soluble protein content was highest in shoots under BH (12.3 mg g⁻¹) and in roots under H (9.25 mg g⁻¹). BM and BH treatments maximized soluble sugar accumulation (9.9 and 10.8 mg g⁻¹, respectively), and BG produced the greatest Na⁺ accumulation in both shoots and roots (6.8 and 9.9 mg g⁻¹), accompanied by elevated K⁺ (1.7–2.7 mg g⁻¹) under H and its binary mixtures. Correlation analysis linked free amino acid metabolism closely to ionic balance and osmotic adjustment across treatments.

Conclusion

Overall, bentonite and glauconite, particularly combined with green siltstone, most effectively enhanced growth, photosynthetic pigments, and osmolyte accumulation, highlighting their promise as sustainable, slow-release amendments for improving crop productivity in nutrient-poor sandy soils. Moreover, the markedly increased in K⁺ content of shoots promotes photosynthesis efficiency, whereas the increased Na⁺ content in roots played an important role in osmotic adjustment whichever facilitated water and mineral uptakes in plants growing under arid and semi-arid conditions.

Introduction

Excessive use of artificial fertilizers causes soil salinization and pollution. While natural fertilizers such as glauconite and bentonite are eco-friendly, low cost and abundant in the warm deserts. Globally, the sandy soil is poor in their fertility and low water retention. Hence, the applying of geological materials to sandy soil enhancing soil fertility increases cation exchange capacity and improved the essential nutrients constituents, ultimately plant productivity.

Natural fertilizers are slow-release components, reduce nutrient leaching from the soil and provide long term plant growth [1]. The addition of these geologic materials promotes the morphological traits of plants such as length, fresh weight & leaf area [2–3]. Furthermore, the addition of natural superabsorbent materials to sandy soils improved the plant growth and chlorophyll contents which is an indicator of photosynthetic efficiency [4–5].

Application of geological materials provided plants by essential macro- and micro- nutrients which supports metabolic activities as constituent of enzymes and improve growth and stress tolerance of plants [6]. These nutrients play a crucial role in the construction of plant vital molecules such as carbohydrates, proteins, amino acids and enzymes. Soluble carbohydrates and amino acids are soluble compatible osmolytes that act as osmotic protectors and reduce the osmotic potential of cell [7] which are helpful for plants exposed to adverse environmental conditions. Moreover, the osmotic pool provided by Na and K elements which are abundant in geological materials participate in the osmotic adjustment of xerophytes and indirectly through increasing water-soluble metabolites [8].

The supplying slow -release elements of natural geological materials is a sustainable approach to ameliorate crop productivity. Thus, the present investigation is an attempt to understand the synergetic effect of different geological materials on the growth performance and physiological parameters in *Zea mays* L. seedlings. The study includes the effect of each brick red siltstone (M), green siltstone (H), black shade (Ca- bentonite B) and glauconite (G) and their binary, triple and quaternary mixture as additive materials to fine sandy soils. The evaluation of the obtained data was done using analysis of variance (F test) and degree of correlation between different parameters under different treatments.

Materials and methods

The Upper Cretaceous geological materials exposed along the Kharga–Dakhla stretch at the Western Desert of Egypt were used in the present study. For clarity, these sediments are abbreviated as follows: the brick red siltstone of the Mut Member (M), approximately 30 m thick; the green siltstone of the Hindaw Member (H), about 6 m thick; the Ca-bentonite-rich black shale (B), approximately 12 m thick; and glauconite of the Duwi Formation (G), approximately 2 m thick (Fig. 1).

1. (a) The brick red siltstone (M) of the Mut Member of Quseir Formation at Teneida area.
2. (b) Green siltstone (H) of Hindaw Member of Quseir Formation at Abu Tartur area.
3. (c) black shale (B) and glauconite (G) of the Duwi Formation at Abu Tartur area. after Hassan [9].

The mineralogical composition of the studied sediments was investigated by using X-ray diffraction (XRD) and the elemental analysis was determined by using X-ray fluorescence (XRF).

Experimental seeds of *Zea mays* L. var. *everta* Sturt (cultivated plants) were used for experimentation. The seeds of *Zea mays* were supplied by the Crop Science Department, Faculty of Agriculture, Assiut University, Assiut, Egypt. The mature seeds were germinated in plastic pots containing 1000 g of air-dry sandy soil (Fine texture). This sandy soil was collected from Kharga Oasis in the western Egyptian desert. The pots containing sandy soil were treated with the addition of natural geological materials. The chosen geological materials were: B. red siltstone (M), green siltstone (H), black shale (Ca-bentonite, B) and glauconite (G). Certain amounts (2% of the soil weight) of geological materials (B, G, H, binary, triple and quaternary mixtures) were added to each pot incubated. *Zea mays* seeds in addition to control (15 treatments + Control). Three replicates were assigned at random to each treatment level. Soil was irrigated with distilled water reaching field capacity (20% of soil weight).

Under natural laboratory conditions, the experiment was carried out, where the air temperature was 35 – 24°C during the day and night, respectively, relative humidity of the air was 35–40% with daily artificial and natural illumination. Seeds germination was carried out in plastic pots, and plumule emergences took place after 2– days.

At the end of the experiment, the growth parameters of healthy seedling (Two weeks ago) of the investigated plants were detected. These parameters included fresh weight & length of shoot and root, as well as length and weight treatment/control ratio.

Determination of chlorophyll characteristics:

Chlorophyll (a) and chlorophyll (b) were extracted from fresh leaves of *Z. mays* using 85% acetone, the calculation of chlorophyll content (mg. g⁻¹ fresh weight), total chlorophyll (a + b) and chl. a /b ratio and quantified according to Lichtenthaler [10].

Preparation of plant extracts for analysis:

Seedlings of investigated species were washed with distilled water and dried thoroughly with filter paper (Whitman No.1). Excised parts (shoots and roots) were freshly weight (0.5 g) and homogenized in 10 ml of ice-cold distilled water, followed by centrifugation at 7000 rpm for 15 min. The supernatant was transferred to a glass bottle, and extracts were kept in freeze until assays of ions and metabolites.

Determination of soluble nitrogen metabolites:

Free amino acids (A.A.) and soluble proteins (S.P.) were determined according to producers described by Lee and Takahashi [11], Lowry et al, [12] respectively. By using spectrophotometer UNICAM model UV-Vi's spectrometry (Made in England), the content of each metabolite in different parts of experimental plants has been expressed in mg. g⁻¹ fresh weight.

Determination of total soluble sugars (SS)

In the extracts of both shoots and roots of investigated plants, the total soluble sugars were determined according to Dubois et al [13].

Analysis of Na and K ions:

Sodium (Na⁺) and potassium (K⁺) ions were determined using Carl Zeiss flame photometer was applied and the calculation was done according to Williams and Twine [14].

Statistical analysis:

The data obtained from the results had been statistically evaluated by analysis of variance (One way), and simple linear correlation coefficient (r.) between different plant parameters according to Ostle [15]. The statistical analysis was conducted using the SPSS program [16].

Results

Mineralogy and geochemistry:

The X-ray diffraction (XRD) patterns for the brick red and green siltstones (Fig. 2a, b) display a dominant peak at 8.44° (2θ), indicating that illite is the primary clay mineral. The Ca-bentonite-rich black shale exhibits a high smectite content (up to 85%), consistent with Williams et al. [17], and is characterized by a basal reflection at ~ 5.8° (2θ) (Fig. 2c). For the glauconite, XRD analysis (Fig. 2d) evolved glauconite as the dominant mineral phase.

The chemical compositions of the studied sediments were quantified via X-ray fluorescence (XRF) analysis, with full datasets compiled in Table 1. High concentrations of K₂O, Fe₂O₃, and MgO in the brick red and green siltstones reflect the presence of illite and dolomite, alongside iron-bearing clay minerals and iron oxides. For the Ca-bentonite-rich black shale, the major components are SiO₂ (57.60 wt. %), Al₂O₃ (16.93 wt. %), and Fe₂O₃ (6.33 wt. %). These silica and alumina levels confirm smectite dominance, whereas the elevated iron is driven by pyrite. Lastly, the glauconite sample features 5.92 wt. % K₂O, signifying a slightly evolved maturity stage according to Odin and Matter [18]. The complete chemical compositions of the brick red siltstone, green siltstone, black shale (Ca-bentonite-rich), and glauconite samples are presented in Table 1.

Table 1
Chemical analysis of the applied sediments

Sample	SiO ₂ %	Al ₂ O ₃ %	CaO%	Na ₂ O%	K ₂ O%	Fe ₂ O ₃ %	MgO%
Brick red siltstone (M)	52.06	14.26	2.32	1.45	3	8.28	4.53
Green siltstone (H)	52.61	21.68	0.45	0.35	4.28	6.74	1.14
Ca-bentonite rich (B)	57.60	16.93	1.3	0.09	1.13	6.33	2.19
Glauconite (G)	51.05	5.92	1.46	0.15	5.66	21.73	2.87

The symbols displayed were previously defined in the preceding text.

Effect of geological materials on Zea mays characteristics

1-Growth parameters:

a-Shoot and root length

The effect of different geological materials on the shoot and root length of *Zea mays* plants was illustrated in Fig. 3a. It was noticed that the shoot length was slightly responded to by the addition of geological materials, where a maximum shoot length (23.4 cm) was observed with GM mixture. Conversely, the geological materials supplied to sandy soil exhibited an increase in the root length, especially with B, G, GH and GHM treatments (13.3–17.9 cm). This is indicated by the length treatment/control ratio which tended to 1.77–2.3 (Fig. 3c), whereas the low ratio (0.73) was observed under H treatment. Commonly, the amended geological materials were greatly affected on the root length nor the shoot length.

b-Shoot and root weight

Apparently, the addition of GH materials to sandy soil produced a high fresh weight of shoot followed by GHM and quaternary mixture which indicated by the ratio of shoot fresh weight treatment/control (High value was 1.66). The low ratio (0.77) was found with H and BH materials. In the case of root fresh weight, the high value was observed in the presence of GHM materials, and the low value was detected with supplied BM. The treatment /control ratio of fresh weight indicated that GHM materials had the highest value (2.11) and the lowest value (0.82) existed with BM and BGH treatments (Fig. 3b, d).

c-The water content (WC)

The applying geological materials exhibited an increase on the WC in both shoots and roots of *Z. mays* (Fig. 4). The roots gained a high amount of WC particularly with the triple mixture. The lowest WC in shoot and root of *Z. mays* parts was shown with H and G amendments, respectively. This implied that the addition of investigated materials helpful in soil water retention ultimately increased WC of incubated plants.

d-Chlorophyll parameters (Chl.)

The addition of M, BG, GH and BHM materials stimulated Chl. *a* content of *Z. mays* plants which tended to a maximum ($2.12 \text{ mg g}^{-1} \text{ F. Wt.}$) with BG treatment (Fig. 5). While the Chl. *b* content was markedly increased in the presence of single and quaternary geological materials. Apparently, the total Chl. content stimulated with applying M, BG and BHM amendments. Adversely, the Chl. *a/b* ratios produced a high value by applying the binary and triple mixture materials.

e-Water soluble metabolites:

1-Nitrogen metabolites

a-Free amino acids (A.A.)

The changes in A.A. contents in *Z. mays* parts were variable under different treatments of geological materials (Fig. 6a). It was noticed that the addition of H materials to sandy soil stimulated the A.A. of both shoots and roots. The same results were observed with mixtures except in the case of GH treatment. Conversely, the GHM, GBM and quaternary mixtures had a negative effect on the A. A. content of roots.

b-Total soluble proteins (S.P)

The supplied H and binary BG, BH and BM mixtures had a boosting effect on the S.P. content of both shoots and roots of *Z. mays* (Fig. 6b). A highest S.P. content was observed in shoots ($12.3 \text{ mg. g}^{-1} \text{ F.Wt.}$) with BH treatment, whereas the S.P. content of roots tended to a maximum ($9.25 \text{ mg. g}^{-1} \text{ F.Wt.}$) under H treatment. Generally, the rest of the additive geological materials to sandy soil had adverse effect on the S.P. of both *Z. mays* parts.

2-Total soluble sugars (S.S.)

The presence of different geological materials investigated exhibited an increase in S.S. content of *Z. mays* organs, exceptionally, G, H, GH, and GM treatments had a negative effect (Fig. 6c). In general, S.S. of roots was relatively high compared to that of shoots. Among the treatments, BM and BH produced the highest S.S. content in both shoots and roots (9.9 and $10.8 \text{ mg. g}^{-1} \text{ F.Wt.}$, respectively).

Na⁺ and K⁺ contents:

At different treatments the roots gained a high Na⁺ content than that of the shoots (Fig. 7a). It was noticed that the maximum Na⁺ content in both shoot and root (6.8 and $9.9 \text{ mg. g}^{-1} \text{ F.Wt.}$, respectively) was attributed to the presence of BG materials. While the applied M and BGH mixture in the sandy soil had adverse effect on the Na content of *Z. mays* roots (Minimum value was $2.9 \text{ mg. g}^{-1} \text{ F.Wt.}$).

Conversely, to Na content, the shoots gained a high K content compared to that in roots. The H and binary mixtures (1.7 – $2.7 \text{ mg. g}^{-1} \text{ F.Wt.}$) stimulated the K content of shoots (Fig. 7b). The same was true in the case of K⁺ in roots at different treatments except with application of B and M materials.

Statistical evaluation:

From the ANOVA (Table 2), the effects of different geological materials investigated on the morphological and physiological parameters of *Z. mays* were significant and highly significant. Exceptionally, the F value of Chl. *a*, amino acids and soluble sugars of roots were non-significant under the effects of amended geological materials. Correlation between different parameters of *Z. mays* investigated at various treatments was shown in Tables (3,4 and 5).

Table 2
F values for the effect of geological materials on different parameters investigated of *Zea mays* plants (df = 15)

Morphological parameters	F	Metabolites parameters	F	Chlorophyll parameters	F	Ion parameters	F
Shoot L.	4.41**	Shoot proteins	10.45**	Chl a.	1.685	Shoot Na	16.34**
Root L.	11.86**	Root proteins	4.79**	Chl b.	6.74**	Root Na	7.92**
Shoot /Root ratio L.	4.53**	Shoot amino acid	2.23*	Total chlorophyll	2.17*	Shoot K	7.82**
Shoot Wt.	33.76**	Root amino acid	1.918	Chl a/b ratio	5.71**	Root K	8.27**
Root Wt.	55.23**	Shoot sugar	2.82**				
Shoot /Root ratio Wt.	10.99**	Root sugar	1.800				
**Significant at 0.01 level * Significant at 0.05 level - Non-significant							

Table 3
Correlation coefficient (r.) between morphological parameters (shoot length SL, root length RL, shoot weight SWt, root weight RWt) and ions (Na & K of shoot and root) in *Zea mays* at different geological materials.

Parameters	SL&RL	SL&SW	RL&RW	SW&RW	Shoot Na		Root Na		Shoot K		Root K	
G. materials					S.L.	SWt.	RL.	RWt	SL	SWt	RL	RWt
Control	-	*	-	*	-	-	..	-	..	..	..	-
B	-	-	-	-	-	-	-	..	-	-	..	-
G	..	-	-	-	..	-	-	-	..	-	-	-
H	-	-	..	-	*	**	-	-	-	-	..	-
M	-	..	-	-	-	-	-	-	-	-	-	-
BG	-	-	-	-	*	-	-	*	-	*	-	..
BH	-	-	-	..	-	..	-	-	-	-	-	..
BM	-	-	-	**	-	-	-	..	..	-	-	..
GH	-	-	-	**	..	-	-	-	-	-	..	-
GM	-	-	-	**	-	-	-	**	-	..	..	-
HM	-	**	..	-	-	-	-	-	**	**	-	-
BGH	-	-	**	-	-	-	**	**	-	-	*	**
BHM	*	..	-	-	-	-	-	**	-	-	-	-
GHM	-	-	-	-	-	..	*	*	-	-	-	-
GBM	-	-	-	*	-	**	-	**	..	-	..	-
BGHM	-	-	-	-	-	-	-	**	-	-	-	-
**Significant at 0.01 level * Significant at 0.05 level - Non-significant												

The applying of some geological materials to sandy soils exerted a significant correlation between the parameters of *Z. mays* investigated. In the case of morphological characters, the shoots wt. was positively correlated root wt. with the addition of B or G materials mixed with both H and M materials. The Na content of roots was positively correlated with root wt. and vice versa with K content at different treatments. The same was true in the case of Na and K content of shoot with shoot Wt. with applying BGH materials, the root length was positively correlated with both ion contents. In contrast the presence of G materials exerted a negative correlation between Na of shoot and shoot length, whereas the H and BG materials had adverse effects. While HG materials had a negative correlation between different parameters of shoots.

A wide correlation between metabolites investigated in *Z. mays* and applying various geological materials (single& mixtures). In the B and BGH treatments the A.A. was positively correlated with S.P., S.S. and total Chl. contents of shoots (Table 4). In roots the same was recorded with M materials, whereas A.A. had a negative correlation with S.P. and S.S. in the presence of BH materials. The same correlation was observed between A.A. and S.S. in shoot under BH, BM and GH treatments. The correlations between S.P. and S.S. in *Z. mays* organs was few compared to that A.A. This means that the addition of geological materials to plants incubated in sandy soils played a crucial role in the free amino acid's metabolism of *Z. mays*.

Table 4
Correlation coefficient (r.) between metabolites (amino acids A A, soluble protein S P, and Soluble sugars S S) and total chlorophyll in *Zea mays* at different geological materials.

Parameters	A A & S P		A A & S S		S P & S S		A A & Chl.	S P & Chl.	S S & Chl.
G. materials	Shoot	Root	Shoot	Root	Shoot	Root			
Control	-	-	-	-	**	-	**	-	-
B	**	-	-	-	**	*	-	-	-
G	-	-	-	_*	-	-	**	-	-
H	_*	-	-	_*	-	-	-	-	-
M	_*	**	-	**	-	**	-	-	-
BG	-	**	*	-	-	-	_*	-	_*
BH	_*	_*	_*	_*	-	-	-	-	-
BM	-	-	_*	-	-	-	_*	-	-
GH	-	-	_*	-	-	-	-	-	-
GM	-	-	-	**	-	-	**	-	-
HM	-	-	-	-	-	-	-	-	-
BGH	**	_*	*	-	*	-	**	**	-
BHM	-	-	-	-	-	-	-	-	**
GHM	_*	-	-	-	-	-	_*	**	-
GBM	-	-	-	-	_*	-	-	-	-
BGHM	-	-	**	-	-	-	_*	-	_*
**Significant at 0.01 level * Significant at 0.05 level - Non-significant									

The recorded correlations between metabolites with Na and K was variable with the application of geological materials (Table 5). The BH treatment exerted a positive correlation between K and A.A. contents of both shoots and roots. Whereas same element was negatively correlated with S.S. The significant positive correlation existed between Na content and total Chl. with applying H and its mixtures with the rest materials. The same correlation was found between the total Chl. and K content with BG and BGM materials. In roots, K content had a positive correlation with A.A. under BH, BM treatments, as well as with Na content. While the quaternary mixture exerted a positive correlation between Na content and S.S. of the same part. In contrast, Na content was negatively correlated with total S.P. of shoot under H, BH and GBM treatments.

Table 5

Correlation coefficient (r.) between ions Na & K in shoot and root with metabolites (amino acids A.A., soluble protein S.P., and Soluble sugars S.S. (and with total chlorophyll in *Zea mays* at different geological materials

Parameters	K&A A		K&S P		K& S S		Na & A A		Na & S P		Na & S S		K &Chl.	Na &Chl.
G. materials	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Shoot
Control	-	-	-	*	-	-	-	-	..**	*	..*	-	-	-
B	..**	-	..**	*	..**	**	**	-	**	*	**	-	-	-
G	-	-	-	-	-	-	-	-	-	-	-	..**	*	-
H	-	-	-	..**	*	-	-	-	..*	-	-	-	-	*
M	-	-	-	-	-	-	-	-	-	-	**	-	-	-
BG	-	-	*	-	-	-	-	-	-	-	-	-	*	-
BH	**	*	-	-	..**	..**	-	-	-	-	-	-	-	**
BM	-	*	..*	-	-	*	-	**	-	-	-	-	-	-
GH	-	-	-	-	-	..*	-	..**	..*	-	-	-	..**	-
GM	-	-	-	-	-	-	*	-	-	-	-	-	-	*
HM	-	-	..**	-	-	-	-	-	-	-	-	-	-	**
BGH	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BHM	-	-	-	-	-	-	-	-	-	-	-	-	..**	-
GHM	-	-	-	..**	-	-	-	-	-	-	-	-	-	-
GBM	-	-	-	-	-	*	-	-	..**	..**	**	-	*	-
BGHM	-	-	-	-	-	-	-	-	-	-	-	*	-	*
**Significant at 0.01 level * Significant at 0.05 level - Non-significant														

Discussion

Introducing the natural materials to sandy soils occupied warm deserts make it suitable as an alternative fertilizer. The additive materials not only as single, but also as mixtures helpful for increasing the cation exchange capacity and soil fertility. Accordingly, the present results refer to the synergy of geologic materials in stimulation of *Z. mays* root length with GHM mixtures as well as with single B and G treatments. While the shoot length was slightly affected by the amended substances which indicated by the treatment / control ratio of root and shoot lengths. This was agreement with Zhang et al., [19], and Farghali and Tammam.[5] in the case of bentonite application. Similarly, the synergistic effects of natural materials on the fresh weight of both *Z. mays* organs existed under GH, GHM, and quaternary treatments in addition to single materials. This means that addition of appropriate amounts of natural fertilizers could be a promising approach for improving sandy soils and biomass of plant organs [20].

The amendment of geological materials facilitates the water availability and nutrients for plant growth [21]. Both organs of *Z. mays* gained a high-water content under different treatments investigated compared to control. Therefore, the natural fine materials increase retention of soil and support plant water content and growth [22–23].

The natural fertilizers contain several essential elements such as Mg, K, and Fe...etc. which play a crucial role in plant metabolism, photosynthesis and respiration. In this respect Fe has functions including chlorophyll biosynthesis and maintenance of chloroplast structure [24]. While Mg is associated with construction of chlorophyll molecules, and K greatly improves chlorophyll content and efficiency [25]. Apparently, the investigations M, BG and BHM had a boosting effect on the chlorophyll *a* and total chlorophyll contents. Further, chlorophyll *b* was stimulated by additive single and quaternary mixture materials. In general, the suppressed total chlorophyll content of *Z. mays* plants was compensated by the chlorophyll *a/b* ratio at different treatments. This implied that the synergetic effect between some geological materials was recommended considering the improvement of chlorophylls of plants cultivated in sandy soils.

Some elements play an essential role in planting enzymatic activities and assimilate. Geological materials enrich minerals which sustain sandy soil fertility and the main role in metabolic compounds, thereby enhancing plant productivity [26]. The effect of B with H, G and M mixtures stimulated the soluble protein contents in both shoot and root of *Z. mays*. The same was true in the case of H and M materials with proteins in shoot and root, respectively. This indicated that bentonite and green siltstone singly or in combination with the rest binary mixtures enhance the proteins, ultimately enzymatic activities in *Z. mays* investigated and water bound partially depends on a colloidal property of S.P [5]. While the brick red siltstone materials had a deleterious effect on the soluble protein contents of both organs.

The accumulation of free amino acids can act as osmolytes to protect enzymes and is helpful in sustainable viscos properties of cytoplasm [27]. Thereby, the obtained data pointed to the stimulation of A.A. in shoots with applying binary mixtures HM and BG as well as GBM & quaternary mixture. Likewise, The A.A. contents of roots were enhanced under H, BM, HM & BHM materials. This indicated that silicate mineral materials had a boosting effect on the free amino acids of roots and improved stress resistance [28]. Adversely, the low levels of A.A. in both *Z. mays* organs under glauconite treatment (single or in mixture) might be attributed to the toxic effect of excessive Fe. Commonly, the roots gained a higher amount of A.A. than those of the shoots, whereas the shoots had superiorities in the soluble protein contents.

The increased root ability to uptake water and nutrients from the soil depends on the root osmolality attributed partially to the soluble sugar's contents, particularly under drought conditions [29]. Apparently, the roots had considerable S.S. contents than the shoots at different treatments. The applying of bentonite and green siltstone in single or in combination with glauconite and red siltstone materials enhanced the S.S. content in both *Z. mays* organs. While the glauconite and red siltstone singly had a suppressive effect on S.S. content of both shoots and roots might be due to increase in the respiration rate and breakdown of S.S. in both organs. Thereby, sugars play pivotal roles in osmoregulation and chelating abilities to bind Na^+ to starch granules, K^+ accumulation to maintain a lower Na/ K ratio in tissue [30].

The root uptake and transport of elements to shoots occurs against the concentration gradient and as an energy requiring translocation process [31]. The increased Na^+ inhibits the uptake of nutrients such as K^+ by interfering with transporters in the root plasma membrane [32]. The presented data revealed that the shoots of *Z. mays* accumulate K^+ more than that of the roots and vice versa with Na^+ . This means that the mechanisms of osmotic adjustments in some plants depend on the accumulation K^+ and /or sharing with Na^+ ions [33]. Noticeably, the bentonite and glauconite mixture enhanced the Na contents in both shoots and roots organs. Similarly, the applying GHM and GBM triple had a boosting effect in shoots and roots, respectively. While the red siltstone had adverse effect on Na^+ of both organs. In the case of K^+ , the binary mixtures HM and BM had considerable content in both shoots and roots, respectively. The same effect of green siltstone application on K^+ in both *Z. mays* organs. Therefore, ions accumulation might be one of the most effective strategies for plant adaptations to arid and semi-arid environments [8].

Statistical data (F test) indicated that the application of used geological materials had a highly significant effect on morphological, metabolic and mineral constituents of both shoots and roots. This implied that the additions of natural fertilizers were beneficial for raising the level of elements such as K, Mg, Fe etc. in soil which promote biochemical activities and improved the plant growth. In some cases, these natural materials had adverse effects that might be due to toxicity and/or antagonism of mineral in incubated sandy soil [34].

The data obtained emphasized that geological materials had a significant effect on the correlations between different parameters of investigated *Z. mays* organs. The improvement of shoot and root growth was indicated by the positive correlation between shoot weight and root weight with applying mixtures of bentonite or glauconite with H and M materials. Likewise, the applied BGH materials promote the root length and weight which indicated by a positive correlation with both Na^+ and K^+ contents in root. While the shoot length stimulation was attributed to low Na^+ levels under BGH treatment. Moreover, Ca & Mg participates in many metabolic activities and shares the same charging trend with K^+ [35].

The total chlorophyll was significantly correlated with different metabolic compounds, especially A.A., Therefore, the presence of siltstone substances enhances enzyme activities by inducing systematic resistances in plants ultimately reducing ROS which reflect the positive effects of silicate minerals materials in plant growth [28]. This indicated that natural fertilizers improve photosynthetic efficiency and assimilate production of *Z. mays*. The correlations of both soluble proteins and soluble sugars were few compared to that of free amino acids which implied that the amended geological materials played a crucial role in the A.A. metabolism in shoot and roots of investigated plants. There was strong correlation between ions and metabolites. Those ions like Na^+ cause imbalance and oxidation stress in plants [36]. With bentonite application, Na^+ had a positive correlation with different metabolic compounds, and vice versa in the case of K^+ . Under GBM application, soluble proteins were negatively correlated with Na^+ in both shoots and roots, whereas soluble sugars had a positive correlation with Na^+ . Likewise, the total chlorophyll positively correlated with Na^+ with the application of H and different mixtures of geological materials. With BH amendment, the K^+ had a positive correlation with A.A. and negative correlation with soluble sugars, of both

Z. mays organs. This means that ions play important roles in metabolic synthesis and physiological processes, through ionic balance and interaction of ions with metabolic compounds in plant leaves [37, 35].

Conclusion

The present study demonstrated that the geological materials investigated such as brick-red siltstone (M), green siltstone (H), black shale rich in Ca-bentonite (B), and glauconite (G) had significant effects on various growth and physiological parameters of *Zea mays* plants. These materials release their nutrients gradually over an extended period, also influenced the relationships among morphological characteristics, metabolite contents, and Na⁺ and K⁺ concentrations in shoots and roots. Furthermore, free amino acids showed significant correlations with both Na⁺ and K⁺, highlighting their crucial role as osmolytes in enzyme protection and in enhancing plant tolerance to adverse environmental conditions. Overall, bentonite and glauconite, whether applied individually or in combination with the other geological materials, primarily improved plant growth performance and increased the concentrations of water-soluble metabolites in *Z. mays*, thereby potentially enhancing plant productivity. Noticeably, the brick red siltstone singly had a suppressive effect on most metabolic parameters investigated. Moreover, the marked increase in K⁺ content in the shoots may promote photosynthetic efficiency. In contrast, the elevated Na⁺ content in the roots appears to play an important role in osmotic adjustment, thereby facilitating water and mineral uptake in plants growing under arid and semi-arid conditions.

Abbreviations

Z. mays
Zea mays L.
(M)
brick red siltstone
(H)
green siltstone
(B)
Ca-bentonite-rich black shale
(G)
glauconite
XRD
X-ray diffraction
XRF
X-ray fluorescence
Chl. *a*
chlorophyll (*a*)
Chl. *b*
chlorophyll (*b*)
Chl. *a/b*
chlorophyll *a/b* ratio
(*r*)
simple linear correlation coefficient
S Wt.
shoot weight
R Wt.
root weight
S Wt./R Wt. ratio
shoot weight/ root weight ratio
S.L.
shoot length
R.L.
root length
S.L./ R.L
shoot length/ root length ratio
A.A.

free amino acids
S. P.
total soluble proteins
S.S.
total soluble sugars
WC
water content
F.Wt.
fresh weight

Declarations

Ethics approval and consent to participate

This study uses plant materials and does not utilize transgenic technology, either involve endangered or protected species. We complied with all relevant institutional, national and international guidelines and the appropriate permissions were obtained from the Faculty of Science, Assiut University, Egypt, for obtaining *Zea* seeds. This study was supported by Department of Botany & Microbiology, and Department of Geology, Faculty of Science, Assiut University, including handling this plant, geological materials and processing the experiment.

Consent for publication

Not applicable. The authors confirm that the manuscript has been read and approved by all authors. The authors declare that this manuscript has not been published and is not under consideration for publication elsewhere. All methods were carried out in accordance with relevant guidelines and regulations.

Competing interests

There was no conflict of interest from the authors.

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Author Contribution

All authors reviewed the manuscript

Data availability

All the data are in the published article.

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Figures

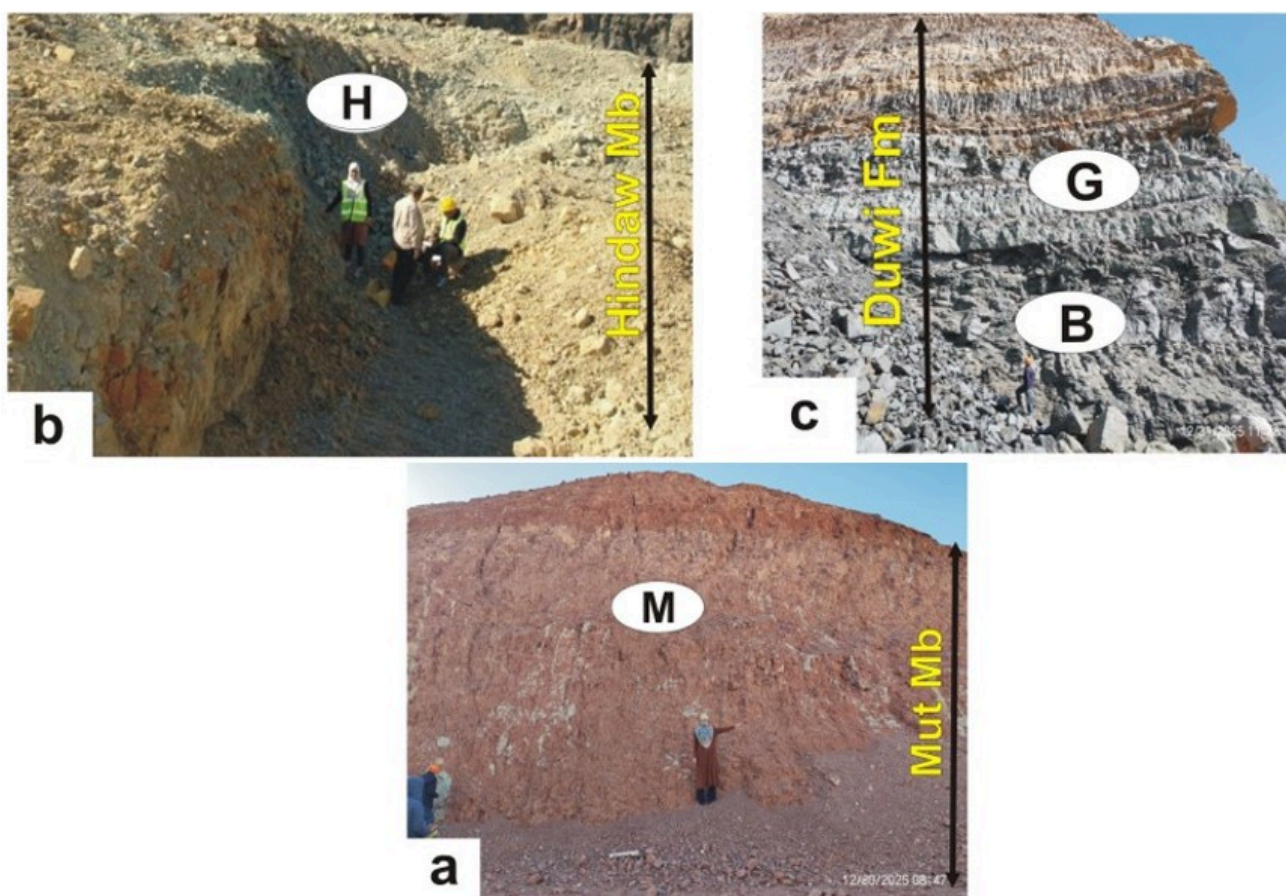


Figure 1

Field photographs showing:

- (a) The brick red siltstone (M) of the Mut Member of Quseir Formation at Teneida area.
- (b) Green siltstone (H) of the Hindaw Member of Quseir Formation at Abu Tartur area.
- (c) black shale (B) and glauconite (G) of the Duwi Formation at Abu Tartur area. after Hassan [9].

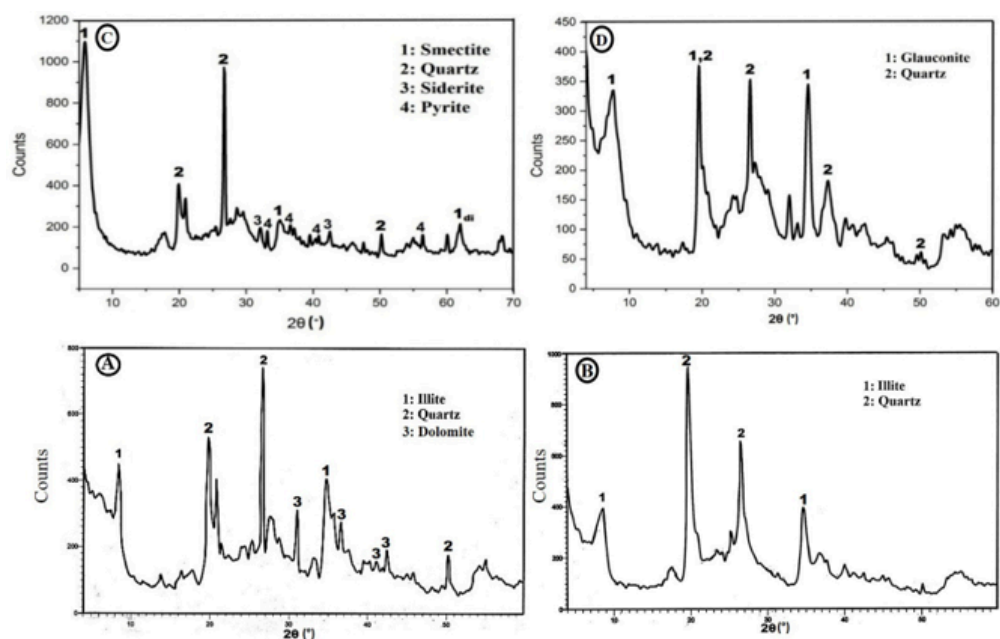


Figure 2

X-ray diffraction patterns of brick red siltstones (A), green siltstone (B), black shale (C) and glauconite (D)

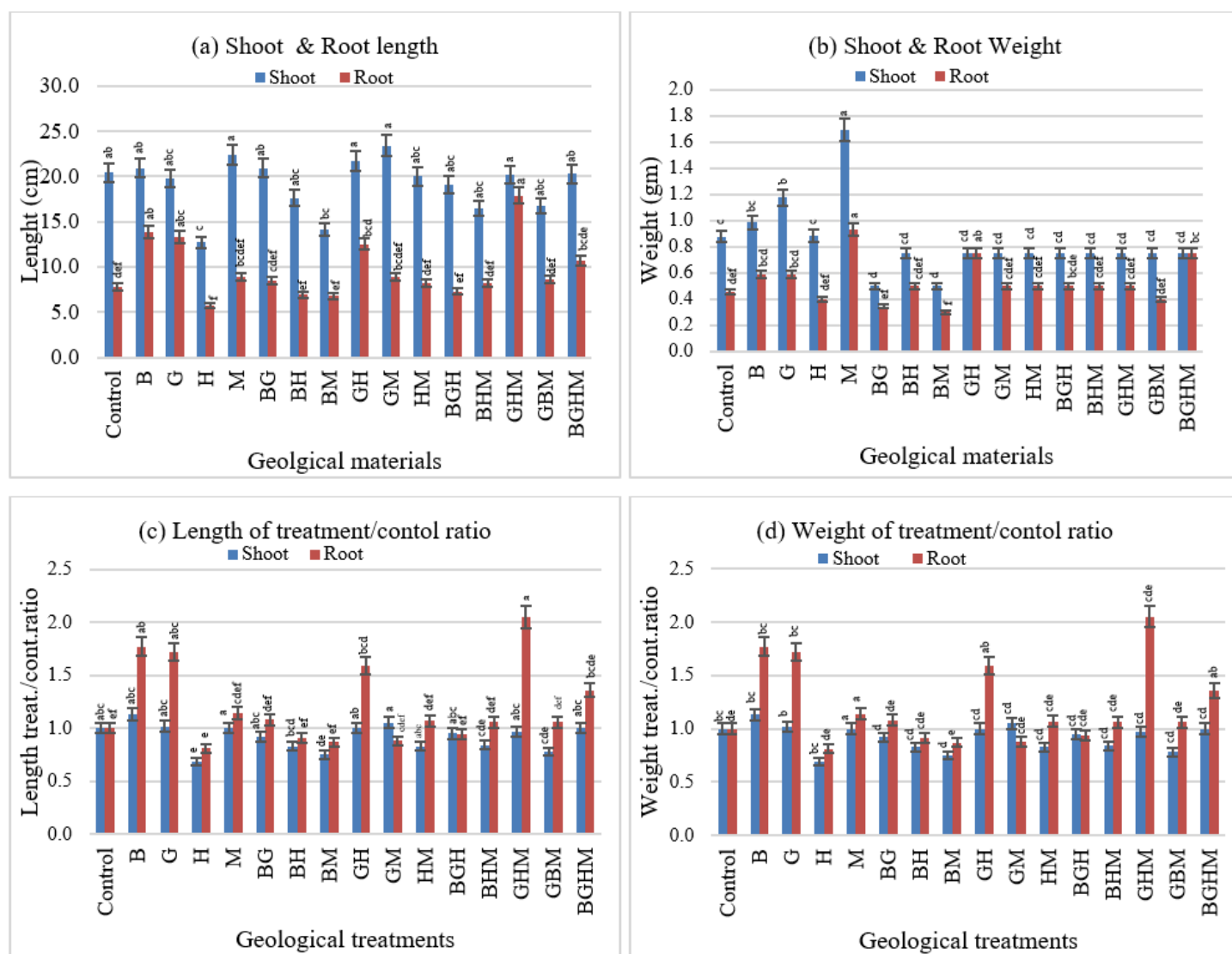


Figure 3

Average values of (a) shoot and root length (cm) & (b) shoot and root weight (g) & (c) length treatment/control ratio & (d) weight treatment /control ratio of *Zea mays* L. under different geological materials [values having similar symbols (a, b, c, ... geological materials (indicate no significant difference according to the Tukey test)].

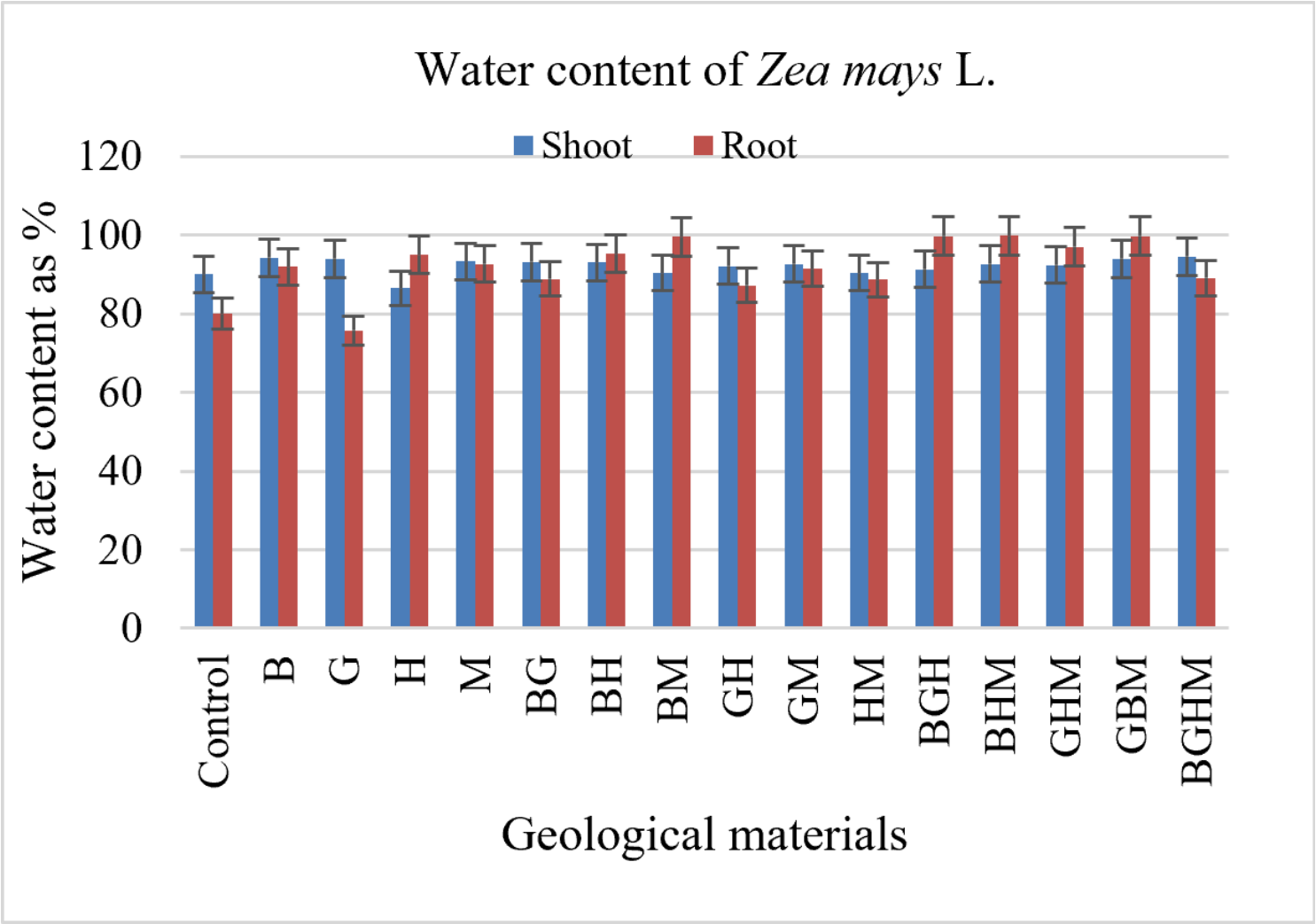


Figure 4

The average values of shoot & root water content of *Zea mays* L. under different geological materials.

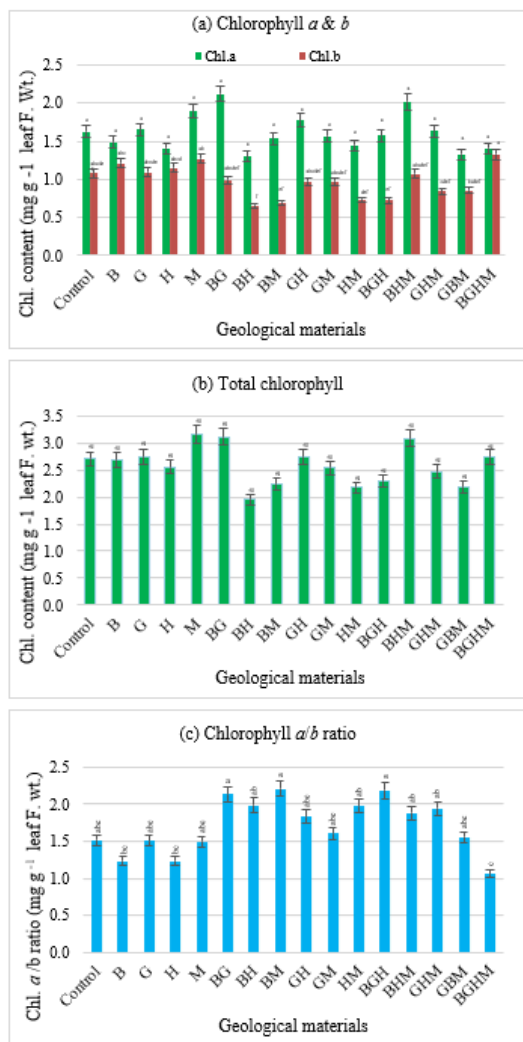


Figure 5

Average values of (a) chlorophyll a & b , (b) total chlorophyll ($a + b$) contents and (c) chlorophyll a/b ratio of fresh leaves (mg. g⁻¹ fresh weight) of *Zea mays* L. under different geological materials [values having similar symbols (a, b, c, ...geological materials (indicate no significant difference according to the Tukey test)]

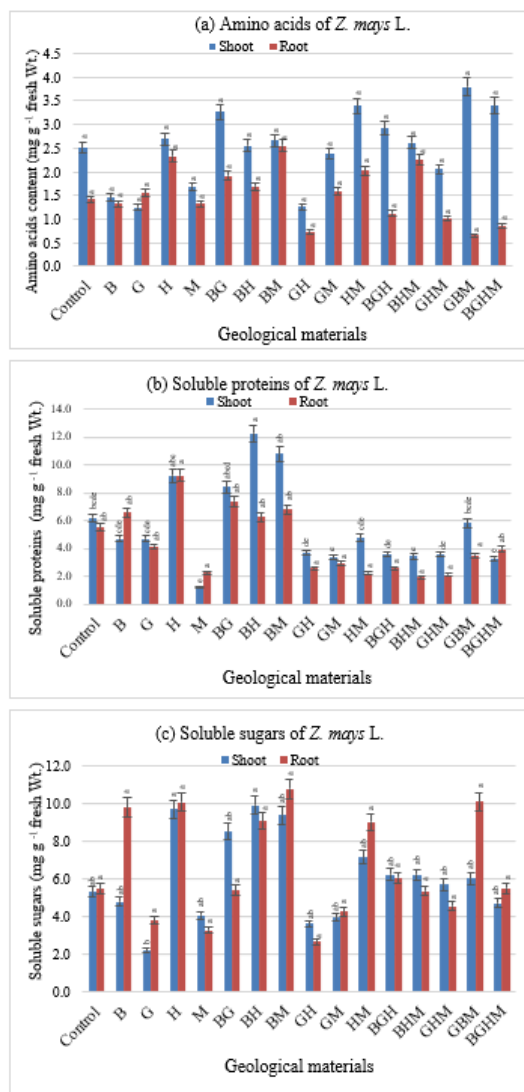


Figure 6

Average values of (a) amino acids, (b) soluble proteins and (c) soluble sugars (mg. g⁻¹ fresh weight) in shoots and roots of *Zea mays* L. under different geological materials [values having similar symbols (a, b, c, ...geological materials (indicate no significant difference according to the Tukey test)].

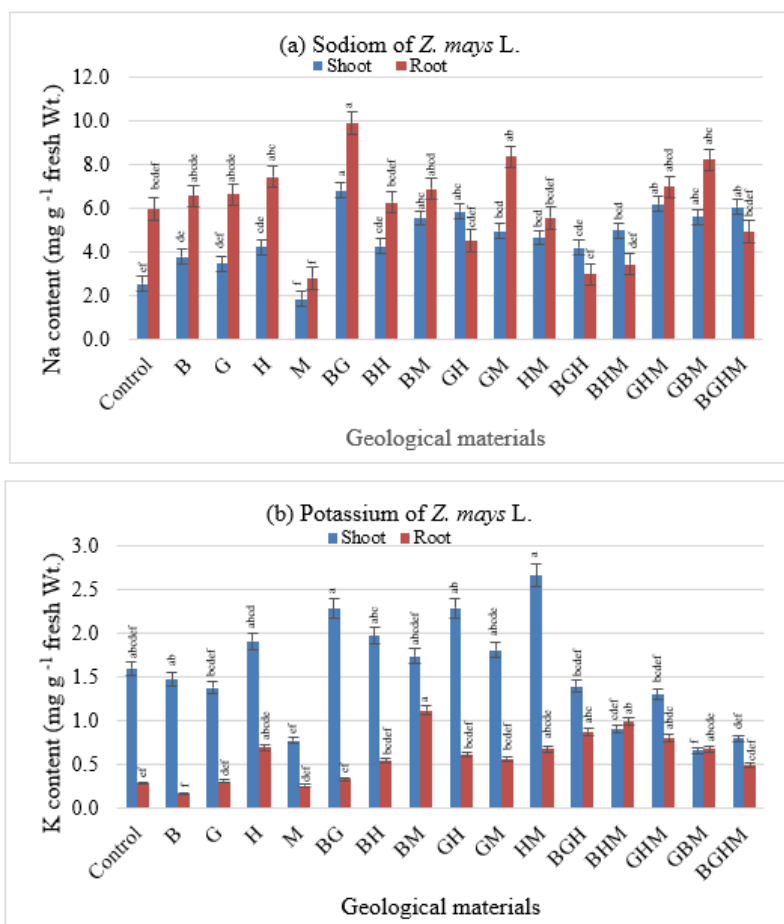


Figure 7

Average values of (a) sodium and (b) potassium contents (mg. g⁻¹ fresh weight) in shoots and roots of *Zea mays* L. under different geological materials [values having similar symbols (a, b, c, ...geological materials (indicate no significant difference according to the Tukey test)].

Supplementary Files

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