Biofortification of potato tubers with zinc fertilizer through soil

Abstract
Zinc deficiency is a well-documented problem in food crops, causing decreased crop yield and nutritional quality. Generally, the regions in the world with Zn-deficient soils are also characterized by widespread Zn deficiency in humans. Nearly 25% of the world's population is considered to be zinc (Zn)-deficient. An estimated 44.6% of preschool-age children are at risk of Zn deficiency, while 57% of non-pregnant and non-lactating women is deficient in Zn in Bangladesh. The key reasons for such deficiency are an intensification of cropping system and adoption of high yielding cultivars of crops. Plant breeding approach (e.g., genetic biofortification) is a long-term process requiring a substantial effort and resources. It is, therefore, essential to have a short-term approach to improve Zn concentration in tubers. Application of Zn fertilizer (e.g., agronomic biofortification) offers a rapid solution to the problem, and represents useful complementary approach to on-going breeding programs. Zinc plays a very important role in increasing the production as well as the quality of potato tubers. Soil application of Zn resulted in a significant increase of tuber Zn concentration with an increase of tuber yield of potato. Tuber yield 17-23% and tuber Zn concentration 56-116% increased over control as influenced by added Zn in soil @ 8 kg ha^{-1} and this rate also reached an average of 1.92-fold tuber Zn increase of the varieties. Therefore, agronomic biofortification strategy appears to be essential in keeping sufficient amount of available Zn in soil solution and maintaining adequate Zn transport to the seeds during reproductive growth stage. Enrichment of potatoes with high bio-available Zn is suggested as a way to generate significant health benefits for a large number of susceptible people across the world. Finally, agronomic biofortification would be a very attractive, quick and useful strategy in mitigating wide spread Zn-driven malnutrition related health problems globally and effectively.
Keywords
Malnutrition, bioavailability, BARI (Bangladesh Agricultural Research Institute), Alu (potato).

1 Introduction

Micronutrient malnutrition known as hidden hunger, is the most widespread nutritional problem all over the world, especially for women, infants, and children (Stein 2010). Nearly 25% of the world's population is considered to be zinc (Zn)-deficient (Allai et al. 2022, Poudel et al. 2023) and approximately 30% children in the world have stunted growth mainly due to Zn deficiency (Brown, 2007). In Bangladesh, over 41% children aged below five years are stunted while an estimated 44% children of the same age group are at risk of zinc deficiency (NIPORT, 2013; Rahman et al., 2016). Over two billion people across the world suffer from micronutrient malnutrition (Praharaj et al. 2021). Food insecurity, imbalanced diet, consumption of food grains with poor nutritional quality, lack of dietary diversity, etc., negatively affect human health (Gundersen and Ziliak, 2015).

It is estimated that about one-third of the cultivated soils globally contain low amounts of available Zn, resulting in impaired crop production and also the low nutritional quality of the harvested grains (Cakmak 2008); nearly 50% of cereal growing areas in the world have been found deficient in Zn (Cakmak 2008); more than 50% of the Asian soils are Zn deficient (Singh and Gupta, 2005). In humans, Zn deficiency can cause reduced immune and reproductive function, impaired brain function, physical retardation, and stunted growth, which is now a significant health concern in developing countries (Roohani et al., 2013) as well as in Bangladesh.

Biofortification aims to increase nutrient levels in crops during plant growth. The food's micronutrient level need to rise for improved human and animal health. Preliminary studies indicate that Zn enrichment of potato tubers is possible through Zn fertilization, and the magnitude depends on the crops and varieties (Mengist et al., 2021; Haynes *et al*., 2012).

Potato (*Solanum tuberosum* L.) is most important and common vegetable in Bangladesh. Next to rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.), potato is the third major food crop in Bangladesh. It also ranks just behind the cereals rice and wheat and achieved 3rd position among the food crops worldwide (Birch et al., 2012). More than a billion people eat potatoes regularly (Kromann et al., 2017); hence, one of the main sources of Zn to humans (Mengist et al., 2018a; Subramanian 2012; White et al., 2012, 2017).

Enrichment of potatoes with high bio-available Zn is suggested as a way to generate significant health benefits for a large number of susceptible people, especially in Bangladesh as well as Zn deficient areas in the world. Agronomic biofortification can be an economically sustainable and practically acceptable solution to solve Zn deficiency in potatoes (Mahmud et al., 2021; Bhatt et al., 2020; Baghla et al., 2019; Sarkar et al., 2018). Zinc loading in potato through soil-applied Zn resulted 56–116% tuber Zn concentrations increase over unfertilized control under study.

2 Materials and Methods

2.1 Planting materials and variety

The seed tubers (grade A, i.e., 28-41 mm in diameter) were kept under diffused light conditions for sprouting. Well-sprouted seed tubers were planted in the experimental field. A few seed tubers were cut longitudinally into 2-3 pieces; each piece had at least two eyes. The weight of each piece of tuber was about 15-16 g. The seed tubers were treated with Autostin (soaked in @ 2 g L^{-1} fresh water). The cuttings were exposed to the sunlight for few minutes. The cut tubers were planted in the field just after removing the surface moisture. The experiment involved six varieties: BARI Alu-7, BARI Alu-13, BARI Alu-25, BARI Alu-53, BARI Alu-73, BARI Alu-77. Among the varieties, BARI Alu-53 and BARI Alu-77 have late maturity, dense foliar cover with high yield potential, and dense root system, and BARI Alu-53 has the densest foliar cover among the varieties. The other four are the comparatively somewhat early maturing varieties with medium yield potential and moderate foliar cover.

2.2 Experimental design and treatments

The experiment was set up in a medium high land at Horticulture Farm, Bangladesh Agricultural University (BAU), Mymensingh ($24^0$42'56.04"N and $90^0$25'31.01"E, altitude=14 m), Bangladesh. The soil in the experimental field was a non-calcareous Dark Grey silt-loam.

In order to find out the effect of zinc on 6 potato genotypes a field experiment was conducted using a Randomized Complete Block Design (RCBD) with four different treatments and three replications during 2019-20. Next year in 2020-21, the field experiment was repeated to validate the results.

There were three blocks representing three replications. Each block contained 24-unit plots to accommodate treatment combinations (6 varieties x 4 treatments). Therefore, a total of 72 (24 x 3) unit plots were maintained in the experiments. The size of each unit plot was 3.6 m^2 (1.5 m x 2.4 m). Potato seed tubers were planted maintaining a row-to-row distance of 60 cm and 25 cm between plants in a row. Each unit plot had 4 rows, where 6 seeds were planted in each row, resulting 24 plants in each unit plot.

The experiment included the following four fertilizer treatments involving Zn0 (no Zn fertilizer), Zn1=4 kg Zn ha^{-1}, Zn2=8 kg Zn ha^{-1}, Zn3=12 kg Zn ha^{-1} applied as zinc sulphate heptahydrate ($ZnSO_4$, $7H_2O$) to soil at planting. The experiment was designed to evaluate Zn applications in soil, on concentration of Zn in harvested tubers.

2.3 Determination of dry matter and mineral concentrations

Potato tubers (peeled) were washed in running water followed by distilled water, prepared, oven-dried at 70^0 C, dry weight (dw) determined, ground to powder and analytical samples taken of 0.5 g with 5.0 ml Trace Element Grade (TEG) concentrated nitric acid (HNO_3) for pre-digestion overnight and digested with 3.0 ml of 30% (v/v) hydrogen peroxide (H_2O_2) at 140^0 C following an adaptation of the methods described by Subramanian et al. (2011); the current standard method used by Agri varsity Humboldt Soil Testing Laboratory for Management of Soils and Water, Department of Soil Science, BAU, Mymemsingh, Bangladesh. Finally, the acid digested plant samples were analyzed in the Atomic Absorption Spectrophotometer (AAS) for Zn content (µg g^{-1}) in Soil Resources Development Institute (SRDI)'s Laboratory for Management of Soils and Water in Dhaka, Bangladesh.

2.4 Statistical analysis

Plant parameters (yield and yield components) and tuber Zn concentration data were subjected to statistical analysis through the statistical program Minitab 17 (Minitab Inc., State College, PA, USA) following the basic principles as outlined by Gomez and Gomez (1984). When significant differences were found in ANOVA, means were compared using Tukey's test at $P \leq .05$. Multiple treatment comparisons were made using orthogonal contrasts. The analysis of variance (General Linear Model Procedure) and Tukey's pairwise comparison test by Duncan's Multiple Range Test (DMRT) at 5% level of probability, according to Gomez and Gomez, (1984). Atypical data were treated as missing values in the statistical analysis. Physical and chemical properties of soil of the experimental fields are presented in Table 1.

Table 1. Physical and chemical properties of soil used for the study.

Soil properties	
Soil texture	Silt loam
Sand	22.89%

Silt	73.23%
Clay	3.65%
pH (1:2.5 soil -water)	6.37
Total Nitrogen (%)	0.11
Available phosphorus (mg kg^{-1}) (Olsen extract)	9.52
Exchangeable potassium (meq/100 g soil)	0.11
Available sulphur (mg kg^{-1})	6.87
Total Zn (mg kg^{-1})	54.36
Available Zn (mg kg^{-1}) (Olsen extract)	0.81
Organic matter (%)	1.39

3 Results

Biofortification is a biological process by which the nutritional quality of food crops is improved through conventional plant breeding, modern biotechnology or agronomic management practices. The aim of this research was to enhance Zn concentrations of potato tubers with increasing or without affecting crop yield by using 6 varieties accompanied by the application of respective fertilizers in soil. The current experiments showed a statistically significant increase of tuber Zn concentration with an increase of tuber yield of potato but excessive application reduced both tuber yield and tuber Zn concentration.

3.1 Genotypic effects

The yield of potato tuber varied with varieties which can be attributed to differences in genetic make-up. Genotypes had significant effect on tuber yield of potato (data not shown). The tuber yield of trial average varied between 25.88 and 32.92 t ha^{-1} (Table 2) which illustrates a significant varietal effect. In Bangladesh potato cannot be planted year-round; but in winter (November to February-March) when average temperature remains 18-22^{0} C at the experimental field area. Experiments were intensively managed with irrigation.

Table 2. Varietal effect on marketable yield (t ha^{-1}) of potato tubers of Zn application in soil of trial 1, trial 2 and trial average

	Yield (t ha^{-1})		
Variety	**Trial 1 (2019-20)**	**Trial 2 (2020-21)**	**Trial average**
V1 (BARI Alu-7)	27.60±0.58 d	24.97±0.50 c	26.29±0.53 c
V2 (BARI Alu-13)	26.48±0.67 e	25.28±0.34 c	25.88±0.49 c
V3 (BARI Alu-25)	32.72±0.81 c	29.01±0.69 b	30.86±0.75 b
V4 (BARI Alu-53)	33.81±0.74 ab	31.74±0.78 a	32.76±0.74 a
V5 (BARI Alu-73)	33.04±0.77 bc	29.81±0.65 b	31.43±0.70 b
V6 (BARI Alu-77)	34.44±0.71 a	31.40±0.68 a	32.92±0.69 a
Max	34.44	31.74	32.92
Min	26.48	24.97	25.88
Mean	31.35	28.70	30.02
$LSD_{0.05}$	0.62 *	0.68 *	0.61 *
$LSD_{0.01}$	0.83 **	0.90 **	0.82 **
Level of significance	**	**	**

P-value	*<0.001*	*<0.001*	*<0.001*

** = Significant at 1% level of probability;

Values in the same column followed by same letter are not significantly different according to Tukey's test (*P<.05)*.

3.2 Agronomic Zn-biofortification of potato with soil applied Zn fertilizer

Application of Zn fertilizer in soil had significant effects on tuber yield of potato. Due to Zn application in soil, of the tested genotypes, as observed the 2019-20 and 2020-21 trials (not shown) including trial average results, tuber yield of potato increased in Zn level from 4 – 8 kg Zn ha^{-1} (Zn1 – Zn2 treatment) but decreased with the increase in Zn level at 12 kg Zn ha^{-1} (Zn3 treatment) for six potato genotypes. The highest tuber yield was 35.73 t ha^{-1} as noted in BARI Alu-77 followed by 35.10 t ha^{-1} as found in BARI Alu-53 (Table 3 and Figure 1).

Table 3. Interaction effects of Zn application in soil on tuber yield (t ha^{-1}) of six varieties of potato at Horticulture Farm, BAU, Mymensingh, Bangladesh ((results are the average of two trials:2019-20 and 2020-21).

Variety	**Treatment**			
	Zn0	**Zn1**	**Zn2**	**Zn3**
V1 (BARI Alu-7)	23.62 i	27.29 gh	28.12 f-h	26.11 h
V2 (BARI Alu-13)	23.35 i	26.76 gh	27.40 f-h	26.01 h
V3 (BARI Alu-25)	27.08 gh	32.36 cd	33.29 bc	30.71 de
V4 (BARI Alu-53)	28.75 e-g	33.95 a-c	35.10 ab	33.23 bc
V5 (BARI Alu-73)	27.66 f-h	32.37 cd	33.40 a-c	32.28 cd
V6 (BARI Alu-77)	29.68 ef	33.64 a-c	35.73 a	32.62 cd
Max	**29.68**	**33.95**	**35.73**	**33.23**
Min	**23.35**	**26.76**	**27.40**	**26.01**
Mean	**26.69**	**31.06**	**32.17**	**30.16**

Mean values with the same letters are not significantly different based on ANOVA followed by a Tukey's test at *P*< .05

[Zn0=no Zn fertilization, Zn1=@ 4 kg Zn ha^{-1}, Zn2=@ 8 kg Zn ha^{-1} and Zn3=@ 12 kg Zn ha^{-1} as applied in soil before planting].

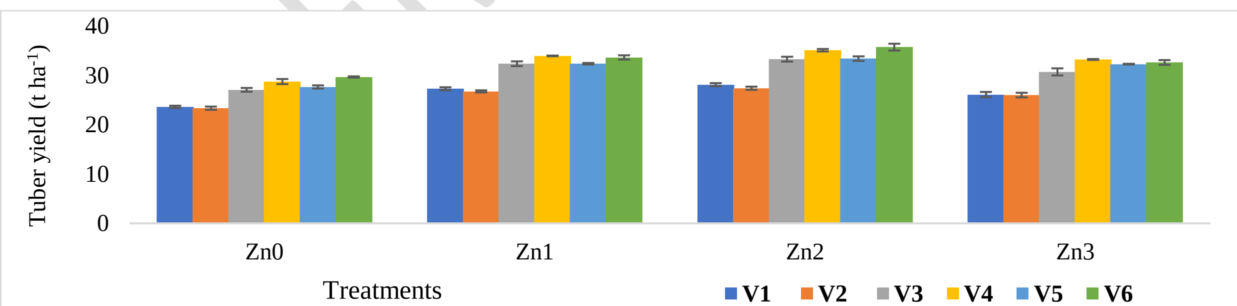

Figure 1. Effects of Zn treatments in soil on tuber yield (t ha^{-1}) of six varieties of potato at Horticulture Farm, BAU, Mymensingh, Bangladesh ((results are the average of two trials: 2019-20 and 2020-21).

The individual ANOVAs of the effect of Zn fertilizer rates on tuber yield revealed a significant effect on soil Zn application (*P = .000*). The Tukey ranking (*P* < .05) indicated a significant increase of the tuber yield between the control and the lowest Zn rate of soil Zn rate of all the potato varieties (Table 3). Combined ANOVAs revealed no significant effect on tuber yield (*P=.116*). Interestingly, no negative effects on yield of the high Zn applications were seen with the edaphic conditions and fertilizer types of this study.

A highly significant effect of Zn fertilizer treatments on tuber Zn concentration of peeled potato tubers was detected in the average results (Table 4) of field trial 1 in 2019-20 & trial 2 in 2020-21 when Zn fertilizer was applied in soil. Zn application in soil trial in 2019-20 which was repeated next year in 2020-21 for validation of results (data not shown). The trial average result showed a gradual increase in tuber Zn concentrations with increased application rates of Zn in soil (Table 4). The results also showed that the tuber Zn concentration increased with increasing Zn dose up to 8 kg ha^{-1} (Zn2 treatment) followed by decrease in tuber Zn concentration at 12 kg Zn ha^{-1} (Zn3 treatment) level for five varieties among six (Table 4 and Figure 2). 56–116% tuber Zn concentrations increased over control due to added Zn in soil and the increment of tuber Zn concentration due to added Zn @ 8 kg ha^{-1} in soil was found highest (31.55 µg g^{-1}) in BARI Alu-53 variety.

Table 4. Interaction effects of Zn treatments in soil on Zn concentration (µg g^{-1})) of tubers of six genotypes of potato (results are the average of two trials: 2019-20 and 2020-21).

Variety	Treatment			
	Zn0	**Zn1**	**Zn2**	**Zn3**
V1 (BARI Alu-7)	11.93 g	15.96 ef	23.66 bc	22.34 c
V2 (BARI Alu-13)	12.12 g	15.02 g	26.21 b	25.08 bc
V3 (BARI Alu-25)	14.51 e-g	18.12 de	22.65 bc	21.88 cd
V4 (BARI Alu-53)	15.96 ef	22.76 bc	31.55 a	33.02 a
V5 (BARI Alu-73)	12.69 fg	16.38 de	25.15 bc	24.18 bc
V6 (BARI Alu-77)	12.12 g	15.00 e-g	23.07 bc	21.74 cd
Max	**15.96**	**22.76**	**31.55**	**33.02**
Min	**11.93**	**15.00**	**22.65**	**21.74**
Mean	**13.22**	**17.21**	**25.38**	**24.71**

($P < .001$)

Values in the same column followed by the same letter are not significantly different according to Tukey's test (*$P < .05$*).

A highly significant effect of Zn fertilizer rate was seen on tuber Zn concentration in the year average result (ANOVA, *P* value < .005 for all comparisons). Soil applied Zn significantly increased tuber Zn concentrations in 6 potato cultivars (Table 4). The highest performer treatment (Zn2 treatment) increased the Zn concentration in tuber flesh 1.98, 2.16, 1.56, 1.97, 1.98, 1.90-fold over control in BARI Alu-7, BARI Alu-13, BARI Alu-25, BARI Alu-53, BARI Alu-73, BARI Alu-77 respectively (Table 4).

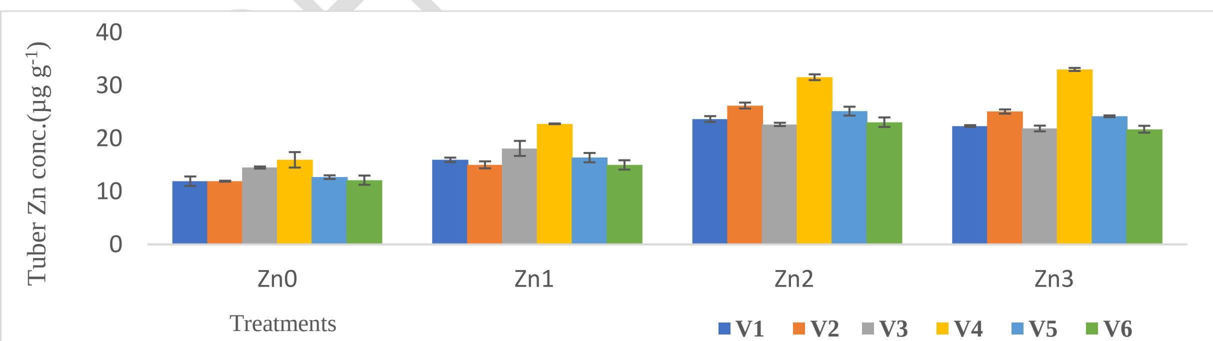

Figure 2. Effects of Zn treatments in soil on Zn concentration (µg g^{-1})) of tubers of six genotypes of potato (results are the average of two trials: 2019-20 and 2020-21).

Table 5. Varietal effects on tuber zinc concentration (µg g^{-1}) of potato by applying Zn in soil of trial 1, trial 2 and trial average.

Zn concentration (µg g^{-1})

Variety	Trial 1 (2019-20)	Trial 2 (2020-21)	Trial average
V1 (BARI Alu-7)	17.71±1.40 b	19.24±1.59 b	18.47±1.46 bc
V2 (BARI Alu-13)	19.12±1.93 b	20.00±1.88 b	19.56±1.88 b
V3 (BARI Alu-25)	18.99±1.09 b	19.59±1.08 b	19.29±1.03 bc
V4 (BARI Alu-53)	24.78±2.09 a	26.87±2.17 a	25.82±2.11 a
V5 (BARI Alu-73)	18.57±1.58 b	20.63±1.64 b	19.60±1.60 b
V6 (BARI Alu-77)	17.23±1.40 b	18.74±1.45 b	17.98±1.42 c
Max	24.78	26.87	25.82
Min	17.23	18.74	17.98
Mean	19.40	20.85	20.12
$LSD_{0.05}$	1.30 **	1.30 **	0.99 **
$LSD_{0.01}$	1.74 **	1.73 **	1.32 **
Level of significance	**	**	**
P-value	*0.000*	*0.000*	*0.000*

Means followed by same letter in a column do not differ significantly at 5% level of probability; ** = Significant at 1% level of probability.

The potato genotypes that showed high tuber Zn concentrations in the absence of Zn fertilization also showed in Table 5 and even higher tuber Zn concentrations following Zn fertilization (Table 4).

A highly significant effect of Zn fertilizer treatments was found Zn uptake by tubers from soil Zn application trial (ANOVA, *P* value < .005 for all comparisons). Zn uptake by tubers significantly increased with the progressive increase in Zn application levels from 0 to 12 kg ha^{-1} Zn application (Zn0 to Zn3 treatment) in two varieties of BARI Alu-53 & BARI Alu-73 among six; on the other hand, Zn uptake by tubers significantly increased with the progressive increase in Zn application levels from 0 to 8 kg ha^{-1} Zn application (Zn0 to Zn2 treatment) but decreased with the increase in Zn level 12 kg ha^{-1} Zn application (Zn3 treatment) in other four varieties of potato BARI Alu-7, BARI Alu-13, BARI Alu-25, BARI Alu-77 (Table 6 and Figure 3).

Table 6. Interaction effects of Zn treatments in soil on Zn uptake (g ha^{-1})) by tubers of six genotypes of potato (results are the average of two trials: 2019-20 and 2020-21).

Variety	Treatment			
	Zn0	**Zn1**	**Zn2**	**Zn3**
V1 (BARI Alu-7)	52.35 k	72.20 i-k	138.12 c-f	128.23 e-g
V2 (BARI Alu-13)	45.20 k	63.92 jk	129.99 d-f	122.86 f-h
V3 (BARI Alu-25)	75.77 i-k	98.73 g-i	144.90 b-f	138.31 c-f
V4 (BARI Alu-53)	96.25 hi	142.89 b-f	238.40 a	244.97 a
V5 (BARI Alu-73)	64.62 jk	96.51 hi	160.33 b-d	172.10 b
V6 (BARI Alu-77)	68.18 i-k	94.87 h-j	163.11 bc	157.23 b-e
Max	**96.25**	**142.89**	**238.40**	**244.97**
Min	**45.20**	**63.92**	**129.99**	**122.86**
Mean	**67.06**	**94.85**	**162.48**	**160.62**

Mean values with the same letters are not significantly different based on ANOVA followed by a Tukey's test at *P*< .05

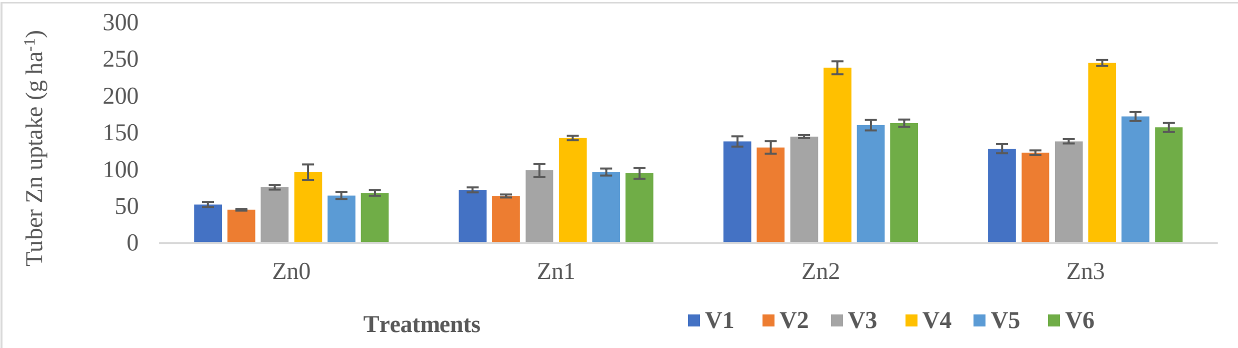

Figure 3. Interaction effects of Zn treatments in soil on Zn uptake (g ha^{-1})) by tubers of six genotypes of potato (results are the average of two trials: 2019-20 and 2020-21).

Correlation analysis

A comparison of the mean Zn concentrations with the mean tuber yields in the field trials with Zn fertilization in soil reveal that the micronutrient concentrations in tubers have a positive correlation with tuber yield (Figure 4).

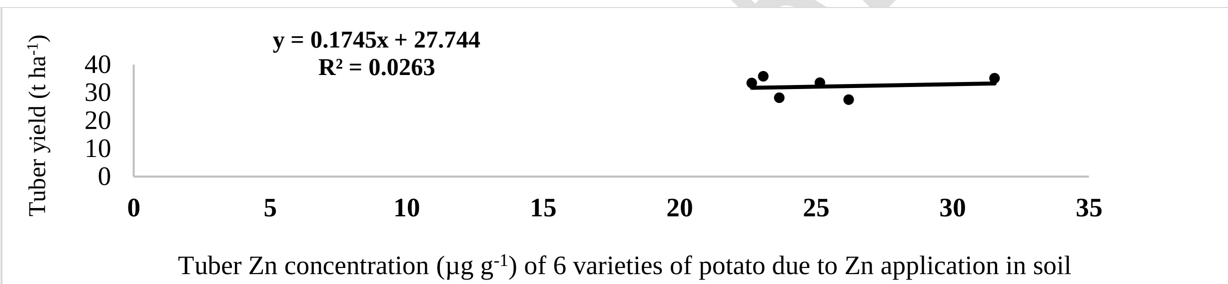

Figure 4. Relationship between tuber yield and tuber Zn concentrations (µg g^{-1}) for Zn added effects over control treatment in different varieties of potato.

Again, a comparison of the mean Zn uptake by tubers with the mean tuber yields in the field trials with Zn application in soil show that the micronutrient uptake by tubers have a positive correlation with tuber yield (Figure 5).

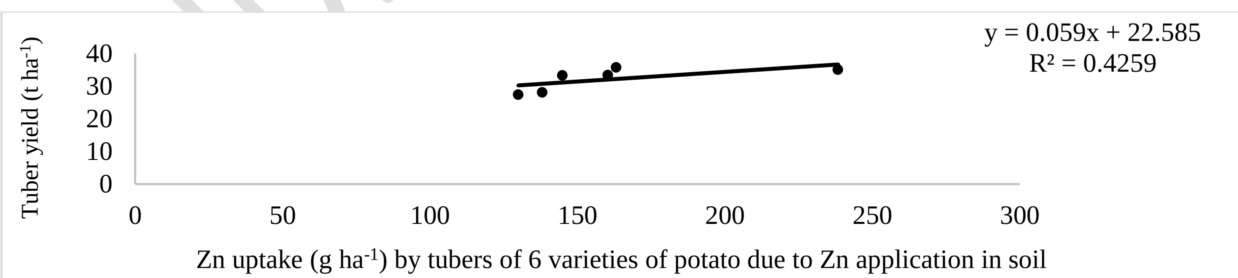

Figure 5. Relationship between tuber yield and Zn uptake by tubers (g ha^{-1}) for Zn added effects over control treatment in different varieties of potato.

Discussions

The field trials with Zn fertilizers showed a significant effect of the Zn fertilizer treatments on tuber Zn concentrations (Table 4). Soil chemical factors such as low pH in the BAU soils, and potato genotypic factors, may be some of the reasons for the good effectiveness of the soil Zn treatments in these experiments. To elucidate the efficacy and validation of soil applied Zn rates a repetition of field experiments were done. These experiments, conducted at the same location of previous field experiments, resulted in a 1.93-fold and 1.87-fold (average value) tuber Zn increase over control due to added zinc in soil @ 8 kg ha^{-1} & 12 kg ha^{-1} respectively (Table 4).

The present results are comparable to many works in the past. Kromann et al. (2017) conducted a study to evaluate a fertilizer approach's potential role in increasing Zn concentrations in Andean potato cultivars through a series of investigations in Ecuador. The results confirmed that Andean potato cultivars could be agronomically Zn-biofortified with soil applied Zn fertilizers. Zn rates @ 8 kg ha^{-1} applied in soil reached a 1.91-fold tuber Zn increase in the field trials. The results conform with those of Phattarakul et al. 2012; Zou et al. (2012) reported that soil Zn application is effective in Zn biofortification of food crops.

White et al., 2012 and Murmu et al., 2014 also reported from their study that Zn loading in potato through soil-applied Zn, increases Zn concentration in potato tuber up to 3-4 times (30-40 mg Zn kg^{-1} of dry matter) which is quite higher than most of the commonly known fruit crops. These findings are in agreement with Mahmud et al. (2021) who reported from their study that soil application of Zn resulted in a significant increase of tuber yield with an increase of Zn concentration in potato tuber.

Soil-applied Zn is, however, limited depending on soil properties and inherent Zn status in the upper soil layer (Sawicka et al., 2016). The efficacy of soil-applied fertilizer largely depends on the soil environment (pH, moisture content, soil organic matter, presence of antagonist nutrients etc.) and ability of plant to successfully absorb the nutrients.

The potato varieties that showed high tuber Zn concentrations in the absence of Zn fertilization (Table 5) also showed correspondingly higher tuber Zn concentration following soil applied Zn (Table 4). Nevertheless, Zn soil uptake and translocation to haulms and tubers may vary significantly among varieties. Many andigenum type cultivars have different root system architecture compared to tuberosum type cultivars (Wishart et al. 2013).

Zinc sulphate has been widely used to biofortify crops with Zn (White and Broadley 2011; Velu et al. 2014). The various forms of Zn fertilizer and ways of applying to the potato crop may influence the efficiency of uptake and translocation to tubers differently. In our trials we used zinc sulphate fertilizers because it is commonly used and readily available in Bangladesh, with the objective to study fertilizer effects more likely to be taken up and translocated to tubers. For practical recommendations on agronomic biofortification of potato with Zn additional studies are needed to define economic optimal compounds, application methods and rates.

Considering the low soil Zn level in Bangladesh soils that appear to be a major factor causing low human Zn intake, agronomic Zn biofortification of potato may prove to be an important approach to improve the critical human Zn status in Bangladesh.

The tuber yields positively responded to Zn fertilization applied in soil over the six varieties of potato. The highest tuber yield (35.73 t ha^{-1}) was recorded from the Zn dose of 8 kg Zn ha^{-1} (Zn2 treatment) obtained by BARI Alu-77, followed by BARI Alu-53 (35.10 t ha^{-1}). Interestingly, the tuber yields further declined to some extent in next higher Zn dose of 12 kg Zn ha^{-1} (Zn3 treatment).

The present results agree with Banerjee et al. (2016) who conducted a field experiment at Kakdwip, South 24-Parganas, West Bengal, in India during 2013-14 and 2014-15 to assess the Zn requirements of potatoes on a new alluvial soil (Entisol). They found an increase in tuber yield with increasing Zn dose up to 4.5 kg ha^{-1} in soil. Sarkar et al. (2018) observed that Zn fertilization produced higher tuber yield of potatoes and higher tuber Zn concentration. Brahmachari et al. (2010) also recorded a 9.2% yield increment for using Zn-fortified seeds. Mahmud et al. (2021) reported that soil application of Zn resulted in a significant increase in tuber yield with an increase in Zn concentration in potatoes. The same result applies to a study where the potato tuber seeds collected from the Zn-treated plots, gave better results regarding tuber yield and tuber Zn concentration. It is particularly important for Zn-deficient soil (Cakmak, 2010).

Dwivedi and Dwivedi (1992) showed that 10 kg $ZnSO_4$ ha^{-1} was adequate to increase potato tuber yield and starch content. They concluded that starch content in potato tuber was affected not only by Zn-rate but also by the method of Zn application. In their study, starch content of tuber was significantly affected by soil application (10 kg $ZnSO_4$ ha^{-1}) as well as seed soaking with Zn (R^2=0.602). Kumar et al. (2008a) opined that greater accumulation of starch depends on the higher rate of photosynthesis, better translocation of photosynthates from leaves to tubers and subsequent conversion to starch. Therefore, increased starch accumulation in tubers might be due to higher rate of photosynthesis with zinc application.

The increase in tuber yield due to Zn fertilization might be because Zn played a vital role in the biosynthesis of the IAA (Indole-3 Acetic Acid) and initiation of primordia for reproductive parts a result of the favorable effect of zinc on the metabolic reactions within the plants. However, such an investigation was not done in the present study. The increased tuber yield of potato might be attributed to the beneficial effect on tuberization as a result of Zn application (Mondal et al., 2015) and Zn content in tubers (Singh et al., 2009; Singh et al., 2010). The reason is zinc plays a key role in plant metabolism, particularly in auxin synthesis which is an essentially required for growth and development of a crop (Sarkar et al., 2018).

Zinc activates glutamic dehydrogenase enzyme, synthesis of RNA and DNA enhancing gliadin and glutenin contents which are the main protein components of gluten accumulated in the later stage of tuber forming. The present study hints that the scope exists to enhance tuber Zn concentration by applying Zn fertilizer. Lone et al. (2017) reported enhanced tuber Zn concentration due to increasing soil Zn supplied when sufficient Zn was available to the plants. This suggests a proper combination of N and Zn applications.

Soil applied Zn significantly increased Zn uptake by tubers of 6 potato varieties (Table 6) which shows that on an average, Zn uptake by tubers increased 2.46-fold and 2.42-fold over control (no Zn fertilizer) due to Zn application in soil @ 8 kg ha^{-1} & 12 kg ha^{-1} respectively. Similar findings were described by Banerjee et al. (2016) that zinc uptake by tubers, haulm and whole plant significantly increased with the progressive increase in Zn application levels from 0 to 6 kg ha^{-1} Zn application in soil.

The tuber Zn concentrations of commonly used potato varieties need to be improved to fulfill the Zn requirement for the people in Bangladesh. Zinc concentration in potato tubers can be enriched by: i) biofortification with Zn fertilizers (White et al., 2017; Kromann et al., 2017), ii) manipulating Zn transporters and ligands in potato plants (Mengist et al., 2021; Ricachenevsky et al., 2013) and iii) efficient germplasm screening for higher bioavailable Zn (Haynes et al., 2012). All these methods depend on fertilizer or the soil or both as the source of Zn to produce Zn enriched tubers. Soil-supplied Zn is, however, limited depending on soil properties and inherent Zn status in the upper soil layer (Sawicka et al., 2016). Zn concentration in any crop grown in Zn-sufficient soils also increases significantly with increased Zn application (Zhang et al., 2012). Systematic survey and mapping of plant available soil Zn concentrations across the Asian countries and other areas with apparent low soil Zn levels would aid the identification of areas with high potential for impact from Zn biofortification.

Conclusion

Plants are the beginning of the food chain and make loads of nutrients for other organisms to eat. Since zinc deficiency is highly prevalent in Bangladesh, and principally related to inadequate quality of diet, micronutrient management (especially Zn) has received greater attention in potato cultivation system to combat wide spread Zn deficiency. Potato responds well to the applied Zn fertilizer (4 - 8 kg Zn ha^{-1}). Therefore, improving the Zn uptake from soil and increasing its movement and bioavailability in the edible parts of the potato plant will benefit human and animal nutrition. Zinc plays an important role for growth, productivity and post-harvest quality of potato. Besides, Zn biofortification with potato tubers will be necessary in the future to fully understand the number of nutrients in the soil plant ecosystem and holds great effects for malnutrition problems in human health and it can be a potential option for mitigating wide spread Zn-driven malnutrition for the world population.

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