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Root zone nitrogen application enhances plant survival, reduces lodging, and improves grain yield of rice under submergence conditions

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ABSTRACT

Under stressful rice ecosystems, crop yield can be sustained by the use of tolerant genetic material and/or improved agronomic practices. An experiment was carried out during *Aman* season to assess the plant survival and productivity of rice under nitrogen (N) management during pre- and post-submergence periods. BRRI dhan52, AZ7006, and BU dhan1 were grown under 14 days of submergence (14 DS) and control conditions. Two N management strategies were used: (i) urea super granule (USG at 7 days after transplanting, DAT) and (ii) prilled urea (PU, 1/3rd at 7 DAT + 1/3rd at 7 days after de-submergence (DADS) + 1/3rd at maximal tillering stage). Plant survival, lodging, chlorophyll content in the leaves and yield component of rice were negatively impacted by submersion. Submergence for 14 days reduced dry biomass by 86.73 to 93.72% and grain yield by 18.85 to 55.12% in rice as compared to no submergence. However, the application of USG improved plant survival (91%), increased panicle bearing tillers (21 hill^{-1}), improved grain fertility (73%) and decreased spikelet sterility (27%) of AZ7006 as to PU treatment. By using USG in AZ7006, a minimum loss of grain and straw yield was achieved under 14 DS. The results of this study indicate that rice yield can be increased by 25.96% through applying USG under submergence condition. Therefore, the application of USG in the root zone offers a chance to increase the rice productivity of submergence tolerant varieties under flash-flood circumstances.

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Introduction

Over half of the world's population relies on rice (*Oryza sativa* L.) (FAO, 2021). In Bangladesh, rice is cultivated during three distinct growth seasons: *Aus, Aman, and Boro* (BRRI, 2022). Rainfed lowlands in the *Aman* (July to November) cover more than 54 million ha of land worldwide and produce around 19% of global rice production (Gautum *et al*., 2019). Flooding is a major abiotic stress in the rainfed lowland area and can occur at any stage of crop growth due to the intense and irregular precipitation during monsoon season. In the rainfed lowlands of South Asia, flooding usually causes complete submersion of rice. It frequently results in significant yield losses and has a negative impact on plant growth and survival (Bhowmick *et al*., 2014). Plants under submersion stress are subjected to conditions that are deficient in light, gas diffusion, soil nutrients, mechanical damage, and eventually disease and insect infestation (Nishiuchi *et al*., 2012). Floods can cause partial to complete submersion of crops for a day to few weeks; and crop damage can range from 10% to 100% depending on the type, length, and floodwater conditions (Mamun *et al*., 2022; Ismail, 2013). Therefore, plant adopts different mechanisms to tolerate the submergence stress. The most important mechanisms are the formation of aerenchyma in the roots and leaves, slow stem elongation, synthesis of proteins, increasing rate of alcoholic fermentation, and maintenance of high level of non-structural carbohydrate (Das, 2005). Rice can also adapt to various flood conditions through the opposing strategies of quiescence and escape (Jackson, 2006; Colmer *et al*., 2014). Currently, only a few high-yielding, submergence-tolerant cultivars have been developed and released onto the market (Vergara *et al*., 2014). BRRI dhan52 and BRRI dhan57 performed better in submerged conditions (Islam *et al*., 2019; Abedin *et al*., 2019). Earlier studies also reported that AZ7006 survive and produce substantial amount of grain yield even after complete submergence for 14 days (Bishas *et al*., 2022).

Although a lot of studies have been done on the morphological, physiological, biochemical and anatomical basis of submergence tolerance, there is limited information regarding pre- and post-flood nutrient management especially nitrogen (N) in rice. In addition, little is known about the physiology of post-flood N management, particularly with regard to the method of N application to enhance crop survival, post-flood regrowth, and recovery of submergence tolerant rice varieties on particular times following de-submergence. Rice survival and production can be increased by making sure that nutrients are managed properly after submergence (Gautam *et al*., 2015).

Even though N is thought to be the most crucial nutrient for increasing rice yields, farmers were reluctant to apply N to the fields that were likely to flood (Mamun *et al*., 2017).

If farmers decide to take the chance of applying nutrients to their crops, they merely use a modest amount of N fertilizers based on availability. But they do not know the actual requirements, appropriate time and effective method of application. Nonetheless, fertilizer management during the flooding recession demonstrates a notable rise in production. Applying N could result in a higher yield due to its ability to promote early tillering and stimulate recovery growth (Dwivedi *et al.*, 2018; Ram *et al.*, 2009).

Regarding N management options, top dressing of prilled urea (PU) after ten days of de-submergence is recommended for better recovery of submergence affected rice. When PU is applied as broadcast, the N loss is larger, and recoveries are low. More than half of the N that is broadcasted is not absorbed by plants and is lost through various process, including surface runoff, leaching, ammonia volatilization, and nitrification–denitrification. Therefore, an alternate strategy for effective N management is essential that can reduce N loss and increase use efficiency. Deep placement of urea as urea super granules (USG) is an effective method of N fertilization in rice, which can reduce N loss, increase use efficiency and improve rice yield (Mamun *et al.*, 2020). In order to support crop growth, this method can increase N availability and balance the efficiency of soil inorganic N uptake with the spatiotemporal expansion of roots. There has not been any research done to date in Bangladesh to assess the effectiveness of N application by USG in rice root zone areas during submergence. We hypothesized that application of USG in the root zone will improve plant survival rate under submergence condition resulting higher yield and profit compared to PU application. Therefore, the current study was carried out to ascertain the impact of submergence on the growth, survival, and productivity of rice and to enhance rice survival and productivity through N management practices during pre- and post-submergence periods. The findings of the study will provide a useful recommendation for N management for rice cultivation under several days of submergence.

Materials and Methods

Land preparation and physico-chemical properties of experimental soil

The experiment was carried out at Gazipur Agricultural University (GAU), Gazipur, Bangladesh during the *Aman* season (June to November) in 2021. Land in the submergence tank was prepared with a spade. The stubble and weeds were removed from the land of the tank. The land was finally well leveled. A ridge 8–10 cm high was built for reducing fertilizer loss from irrigation water lateral drainage. A soil sample was taken from the land of submergence during the last stages of land preparation to determine the physico-chemical characteristics of the soil. The textural class was clay loam, containing 22% clay, 45% silt, and 33% sand. The soil having a pH of 6.1, soil organic carbon 1.51% and total N 0.102%. Additionally, the available P, S, Zn, B, and Fe were 6.02, 10.32, 0.610, 0.211, and 1.32 μg g^{-1}, respectively. Moreover, the exchangeable K, Ca, and Mg were 0.114, 2.43, and 1.11 meq $100g^{-1}$ soil, respectively.

Experimental treatments and design

A total of 3 rice varieties were used as planting material in this experiment. All the seeds were collected from the Department of Agronomy, GAU, Gazipur. The experiment comprises of three factors, Factor A: Three rice varieties (BRRI dhan52 (tolerant), AZ7006 (tolerant), BU dhan1 (susceptible)) (BRRI, 2022; Mamun *et al.*, 2021); while Factor B: (submergence) 14 days of submergence (14 DS) and control; and Factor C: (N management) urea super granule (USG, size 1.8 g ball^{-1} at 7 days after transplanting, DAT), and prilled urea (PU, 1/3rd at 7 DAT) + 1/3rd at 7 days after de-submergence (DADS) + 1/3rd at maximal tillering stage). The experiment conducted following a randomized complete block design with three replications.

Crop culture

In the submergence tank, twenty-eight-day-old seedlings were transplanted with a 25 × 15 cm spacing and two seedlings per hill^{-1}. Gap filling was done by the same aged seedling within four days of transplanting. The doses of different fertilizers were N 86 kg ha^{-1} (urea 186.82 kg ha^{-1}), P 16 kg ha^{-1} (triple super phosphate, TSP 80.0 kg ha^{-1}), K 68.33 kg ha^{-1} (muriate of potash, MoP 136.67 kg ha^{-1}), S 10.5 kg ha^{-1} (gypsum 58.38 kg ha^{-1}) and Zn 1.32 kg ha^{-1} (zinc sulphate 3.67 kg ha^{-1}) (FRG, 2018). Total amount of TSP, MoP, gypsum and zinc sulphate were applied at the time of final land preparation. The PU was applied into three equal splits. First split (1/3rd) of PU was applied at 7 DAT, second split (1/3rd) at 7 DADS and third split (1/3rd) at maximum tillering stage of rice. Urea super granule (USG) was deep placed at once at 7 DAT.

Imposition of submergence treatments and properties of water of submergence pond

Up to 15 days prior to harvest, a 2 cm water depth was maintained in the control plot. Water depth for the submergence was kept at 2 cm until 12 DAT. Following that, a water depth of 75 ± 5 cm, sufficient for the rice plant's total submersion, was maintained from 13 to 27 DAT in the instance of 14 DS. Data on the quality of the water was collected while the crop was submerged. Dissolved oxygen (O_2) was 7.10 mg lit^{-1}, pH 7.12, electrical conductivity 1.3 mS, and turbidity 6.10 ntu (*Nephelometric Turbidity unit)* under submergence. The temperature of the water in the submergence tank was almost similar at different depths at 11:00 am. However, the concentration of dissolved O_2 was sharply decreased from the 30 to 75 cm of water depth.

Data collection

Plant height and tillering dynamics of the rice varieties were measured from 7 to 67 DADS. Three plants were collected randomly from each treatment to measure the plants height. Plants height were measured from the base to the tip of the plant using laboratory scale. The number of tillers were counted manually and then averaged. After 72 hrs of oven drying at 70 °C, the dry matter (DM) was determined using an electronic balance. A variety's capacity to withstand floods and resume growth following the removal of floodwater is referred to as its survival (Mamun *et al.*, 2021).

$$\text{Survival (\%)} = \frac{\text{Number of plants survive of a variety}}{\text{Total number of plants transplants of the variety}} \times 100$$

The intensity of lodging of each variety was recorded at 7 DADS based on visual observation (Akter *et al.*, 2021). Lodging score 0 indicates no plant is lodged. However, score 1, 3, 5, 7 and 9 directs 1-20, 21-40, 41-60, 61-80 and more than 80% of plants are lodged. Leaf chlorophyll (Chl) content was determined one day before submergence, 7 DADS and at flowering stage of the crop. Chl *a*, Chl *b* and total Chl value were measured for all the varieties (Fatema *et al.*, 2023).

Chl *a* (mg g^{-1} FW) = $[12.7(D_{663})\text{-}2.69(D_{646})] \times [V/1000 \times W]$

Chl *b* (mg g^{-1} FW) = $[22.9\ (D_{646})\text{-}4.68(D_{663})] \times [V/1000 \times W]$

Total Chl (mg g^{-1} FW) = $[20.2(D_{646}) + 8.02(D_{663})] \times [V/1000 \times W]$

Days to 50% flowering and days to maturity were recorded as treatment basis. When the panicles of about 50% tillers in each variety were fully headed, the days from seeding was treated as days to 50% flowering. Transplanting to time of maturity were recorded as days on treatment basis when plants were about 80% mature to be harvested. Once the crop reached full maturity, it was harvested. Plot by plot, grain was threshed, cleaned, and dried separately. Data on yield and yield components were recorded in accordance with established protocol (Mamun *et al.*, 2025). At harvest, four sample plants were measured for recording plant height. The distance between the panicle's base and tip was measured by laboratory scale.

Number of tiller and panicles from four hill were counted and averaged. We weighed a 1000-grain weight with an electronic balance (model: FX-300). The central 1.5 m^2 area of each plot was harvested in order to calculate the rice grain yield. Before being weighed and turned into t ha^{-1}, the grains were sun dried and winnowed. The grain yield was adjusted to 14% moisture content. For estimating straw yield, 4 hills were harvested. After separation of grains, the stems were air died and weighted. The straw weight was taken for all varieties in DM basis. The amount of N in grain and straw was determined using the plant samples that were gathered. The sample was powdered after being dried for 72 hours at 70 °C. The total N content of the ground sample was measured using the micro Kjeldahl method after it had been digested in concentrated H_2SO_4 (Daly and Congreves, 2023). Grain harvest index (GHI) was computed as

$$\text{GHI} = \frac{\text{Grain yield}}{\text{Grain yield + straw yield}} \times 100$$

Total N uptake and N harvest index (NHI) was determined by the following formulae:

$$\text{Nitrogen uptake by grain (kg ha}^{-1}\text{)} = \frac{\text{N in grain (\%)} \times \text{Grain yield (kg ha}^{-1}\text{)}}{100}$$

$$\text{Nitrogen uptake by straw (kg ha}^{-1}\text{)} = \frac{\text{N in straw (\%)} \times \text{Straw yield (kg ha}^{-1}\text{)}}{100}$$

$$\text{NHI} = \frac{\text{Grain N uptake}}{\text{Grain N uptake + straw N uptake}} \times 100$$

Nutrient trans-location coefficient (NTC) was computed as

$$\text{NTC} = \frac{\text{Nutrient accumulation in grain}}{\text{Nutrient accumulation in straw}}$$

Data analyses

The collected data were analyzed statistically using software "CropStat" version 7.2 (Ahsan *et al.*, 2023). The data were statistically analyzed using ANOVA and then subjected to Duncan's multiple range test ($p < 0.05$) to determine the significance of differences among treatments. Changes (% decrease or increase) of different plant parameters of rice variety under submergences as compared to control.

Results and Discussion

Survival and lodging of rice plants

The application of USG improved plant survival rate of all three rice cultivars compared to the PU application ($p < 0.05$) (Fig. 1a). Around 82% of BRRI dhan52 plants survived under the PU treatment, while 88% in the case of the USG application. Similarly, the survival rate of AZ7006 was 80% under the PU management practice, which rose to 91% under USG application practice. Similarly, 10% more plants of BU dhan1 survived under USG management practice as compared to PU application practice (Fig. 1a). Following the floodwater recession, 14 DS caused a notable difference in lodging among the rice varieties. But there was no significant variation in lodging among the varieties due to N management practices (Fig. 1b). AZ7006 had the lowest lodging under PU practice (10%), which was statistically comparable to USG practice (15%). Similarly, BU dhan1 had 40 and 45% plant lodging under PU and USG application, whereas BRRI dhan52 showed 20 and 25%, respectively (Fig. 1b).

The length of submergence and the variety's ability for tolerance determine whether rice plants survive under submerged conditions. AZ7006 had the highest survival rate and lowest lodging following BRRI dhan52 at 14 DS (Fig. 1a and b). On the other hand, BU dhan1 had a greater lodging and a poorer survival rate. This showed that BU dhan1 is a sensitive rice variety, while AZ7006 and BRRI dhan52 are submergence tolerant. However, when USG was applied to the root zone, the tolerant variety AZ7006 exhibited a 91% survival rate. In order to maintain a steady supply of N to the rice roots and promote plant health, the USG gradually released N into the soil. This increased the survival rate of rice plants during floods. However, the use of USG also reduces the amount of N that is lost during flooding (Hossain, 2022). When N is provided as PU, however, there is a chance that it will be lost through floodwater (Mamun *et al.*, 2013), which can result in poor plant performance regarding lodging and survival. The degree of damage to rice resulting from total submersion when in its vegetative stage is contingent upon the surrounding environmental factors (Das *et al.*, 2009; Yin *et al.*, 2010).

Plant height and tiller number

There was no variation in plant height before submergence, but 7 DADS ($p < 0.05$) (Fig. 2). One day before submergence, the plant height of rice ranged from 25 to 30.5 cm across the variety. All the rice varieties produced taller plants in control than 14 DS irrespective of N management practices. At 7 DADS, BRRI dhan52 produced plants of 35.33 cm height

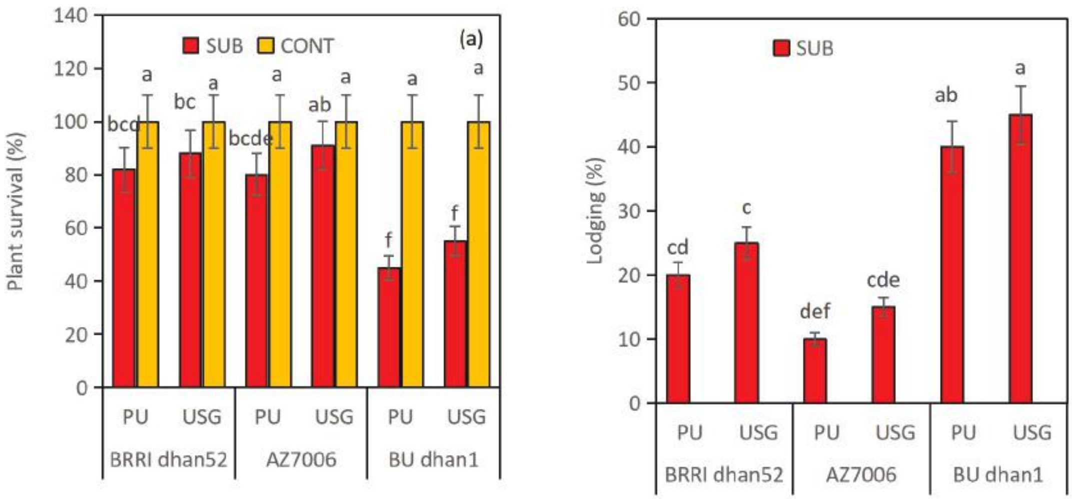

Fig. 1. Interaction effect of variety, submergence and N management on plant survival and lodging of rice. (a) Plant survival (%). (b) Lodging (%). SUB = Submergence, CONT = Control, PU = Prilled urea, USG = Urea super granule. Values with different letters on bars are significantly different ($p < 0.05$). Small bar on the graph indicated ± standard error.

under PU management, which increased to 38.93 cm under USG application. Similarly, BU dhan1 gave plants of 30.67 and 30.83 cm under PU and USG management practices, respectively. On the contrary, BU dhan1 formed plants of 49.40 and 42.67 cm under PU and USG management practices, respectively. Moreover, the plant height and tillers of rice increased with the progress of time irrespective of variety and N application (Fig. 3a to f). BRRI dhan52 produced a plant of 38.93 cm at one day before submergence, which increased to 141.0 cm at 67 DADS, AZ7006 gave a plant of 42.67 cm at one day before submergence, which increased to 134.8 cm at 67 DADS, and BU dhan1 had a plant of 30.83 cm at one day before submergence, which increased to 129.3 cm at 67 DADS while USG was applied to rice plots (Fig. 3a to c). All the rice varieties produced the maximum number of tillers at 52 DADS (Fig. 3d to f). At 52 DADS, BRRI dhan52 produced the maximum number of tillers (22 hill^{-1}) during USG application, while AZ7006 and BU dhan1 had maximum tillers while the same N management practice was added (Fig. 3d to f).

Regardless of cultivar, rice plant height reduced during 14 DS compared to control conditions (Figs. 2 and 3). The PU plot of BRRI dhan52, AZ7006, and BU dhan1 showed a drop in height of 32, 11 and 48%, respectively, under 14 DS, while the USG plot showed a decrease in height of 29, 30, and 46%, respectively. But under 14 DS, AZ7006 produced noticeably taller plants when PU was applied to the field. The genetic makeup of the cultivar determines the degree of shoot elongation that occurs

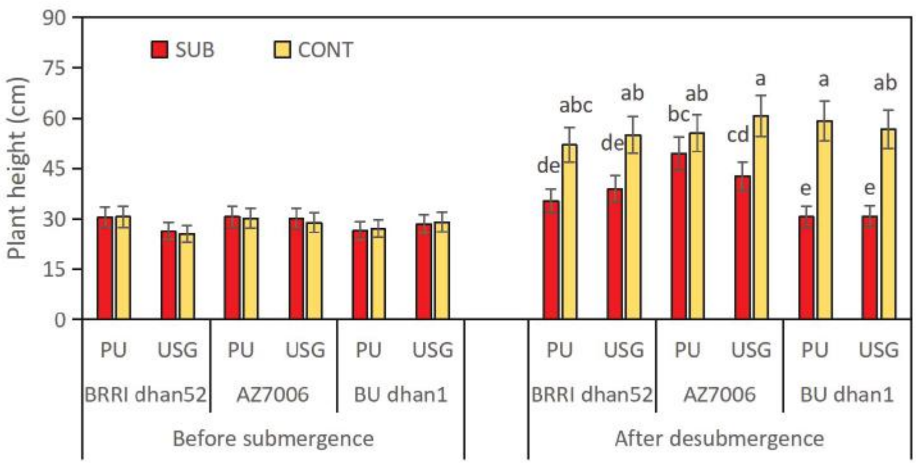

Fig. 2. Interaction effect of variety, submergence and N management on plant height of rice before and 7 DADS. SUB = Submergence, CONT = Control, PU = Prilled urea, USG = Urea super granule. Values with different letters on bars are significantly different ($p < 0.05$). Small bar on the graph indicated ± standard error.

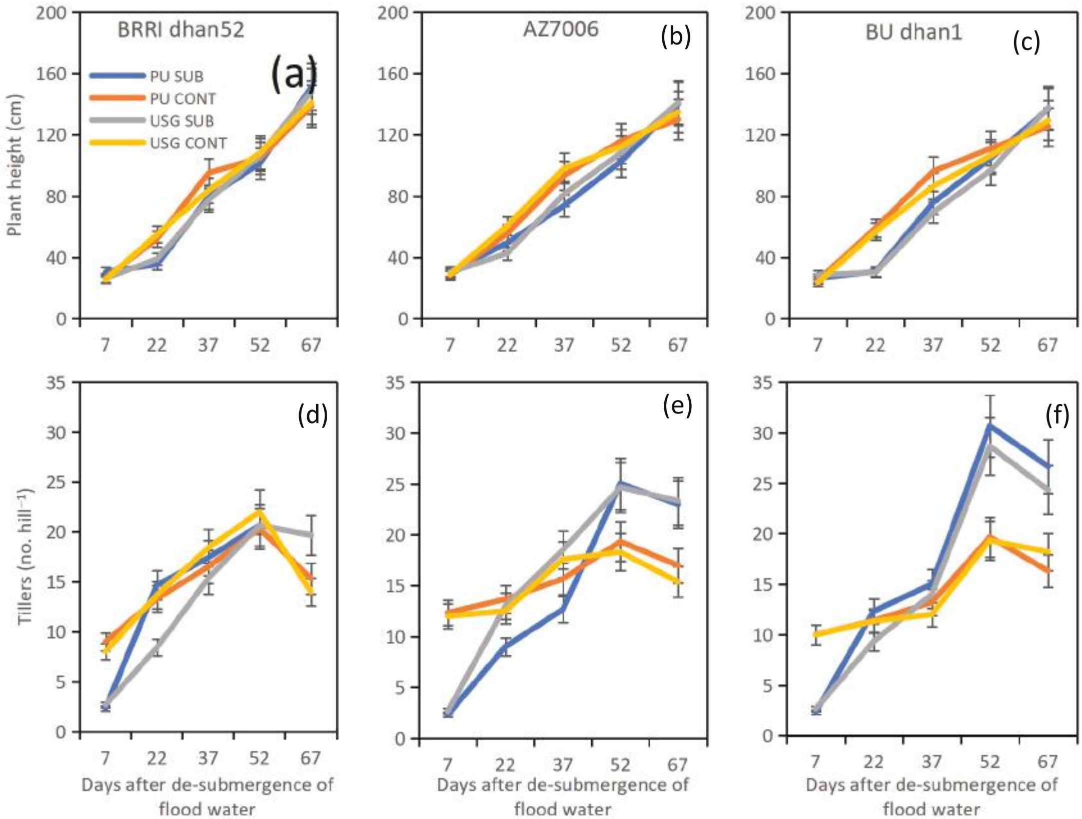

Fig. 3. Interaction effect of variety, submergence and N management on plant height and tiller of rice at different DADS. (a) plant height of BRRI dhan52. (b) plant height of AZ7006. (c) plant height of BU dhan1. (d) tillers production of BRRI dhan52. (e) tillers production of AZ7006. (f) tillers production of BU dhan1. SUB = Submergence, CONT = Control, PU = Prilled urea, USG = Urea super granule. Small bar on the graph indicated ± standard error.

during submergence, which is influenced by the submergence environment and the stage of seedling growth prior to submergence (Kawano *et al.*, 2008). Slow stem elongation under submergence conditions contributes to the constant energy supply needed to keep the plant body functioning (Fukao *et al.*, 2019). The plants in the USG-applied plot produced significantly shorter plants, indicating that USG application was advantageous for plants growing in submerged conditions. But many rice cultivars lengthened their shoots during complete submersion, which is one of rice's escape mechanisms (Kende *et al.*, 1998). In order to promote robust aerobic respiration and photosynthesis, it helps to assure sufficient supplies of CO_2 and O_2. However, in the present study, not a single variety elongated their shoots when submerged, most likely due to their potential quiescence strategy for submergence tolerance. Quiescence is another strategy used by rice to endure different types of floods (Vergara *et al.*, 2014). A lack of energy brought on by anoxia may cause plants to absorb fewer nutrients, which would stop their ability to elongate their shoots (Bui *et al.*, 2019). But under 14 DS, tiller production decreased as compared to control (Fig. 3d to f). In essence, flooding puts plants under intense pressure. A plant that receives too much water is deprived of O_2, CO_2, and light, which are necessary for photosynthesis. Because of this, during submergence, tiller output substantially decreases. When USG was applied to rice, all types showed further increased plant performance in terms of height and tiller production under submergence conditions. Previous research also revealed that submergence decreased tiller numbers and plant height of rice (Gautam *et al.*, 2015; Beyrouty *et al.*, 1992).

Biomass production

One day before submergence, the DM of rice ranged from 0.2 to 0.4 g hill^{-1} across the variety, where there was no statistical variation (p < 0.05) (Fig. 4). On the other hand, the interaction variety, submergence and N management showed a significant effect on DM of rice after de-submergence of flood. All the rice varieties produced higher DM in control than 14 DS irrespective of N management practice. Under 14 DS, AZ7006 produced 0.5 and 0.4 g DM hill^{-1}, BRRI dhan52 generated 0.3 and 0.38 g hill^{-1}, and

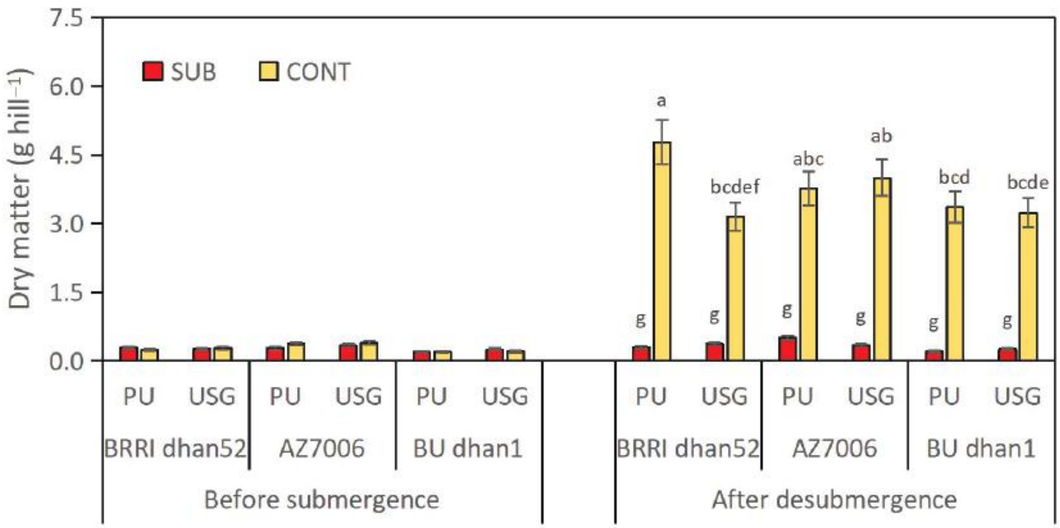

Fig. 4. Interaction effect of variety, submergence and N management on biomass of rice before and 7 DADS. SUB = Submergence, CONT = Control, PU = Prilled urea, USG = Urea super granule. Values with different letters on bars are significantly different (p < 0.05). Small bar on the graph indicated ± standard error.

BU dhan1 produced 0.21 and 0.26 g hill^{-1}, DM during PU and USG application at 7 DADS, respectively.

During submergence, rice plants displayed a considerable loss in dry matter. Plant DM of AZ7006, BU dhan1, and BRRI dhan52 dropped by 94, 86, and 93%, respectively, in the PU plot; in the USG plot, it reduced by 88, 94, and 92%, respectively (Fig. 4). In this trial, submergence decreased the growth of the shoots and the generation of tillers, which led to a decrease in DM under 14 DS. Rather than leaf area or total leaf dry weight, the primary cause of the increase in DM in the control was an increase in culm DM content (Yin *et al.*, 2010). Additionally, they found that within the first several days of submergence, plants tended to use more photosynthates for the development of culms rather than leaf area.

Chlorophyll content

Submerged rice plants showed a significant decrease in Chl content in leaf tissue ($p < 0.05$) (Fig. 5a to c). The Chl *a* of BRRI dhan52, AZ7006 and BU dhan1 was decreased by 44, 30 and 24%, respectively in PU plot, while it was 44, 32, and 45%, respectively in USG plot under 14 DS (Fig. 5a). Similarly, Chl *b* content of BRRI dhan52, AZ7006 and BU dhan1 was reduced by 41, 23 and 14%, respectively in the PU plot, while 58, 8, and 39%, respectively in USG plot due to 14 DS (Fig. 5b). Further, total Chl content of BRRI dhan52, AZ7006 and BU dhan1 was declined by 43, 28 and 22%, respectively, in the PU plot, while 47, 29 and 44%, respectively in USG plot under 14 DS (Fig. 5c). Submergence stress for 14 days degraded the Chl *a* content of rice leaf, more intensely in susceptible cultivars (Ella *et al.*, 2003; Panda *et al.*, 2006). In this study, BU dhan1 is a susceptible variety to submergence, therefore, Chl *a* content of this variety degraded comparatively more than others (Fig. 5a to c). When submergence was prolonged, there was a noticeable decrease in the concentration of total Chl. The sluggish synthesis and quick breakdown of the chlorophyll pigment most likely caused the drop in chlorophyll content under hypoxic stress (Ashraf, 2003). The results of this study regarding the reduction in total Chl pigment under excessive water stress are consistent with those of previous investigations (Elanchezhian *et al.*, 2013; Sarkar and Ray, 2016).

Phenology of rice

Flowering and maturity were delayed in all rice varieties exposed to 14 DS (Fig. 6a and b). Across the rice varieties, the flowering time ranged from 95 to 101 days under 14 DS condition, while it was 65 to 85 days for the control. Therefore, flowering was delayed by 16 to 30 days across the rice varieties under 14 DS (Fig. 6a). Further, increased time of submergence caused the enhancement of total crop duration from 155 to 161 days for 14 DS. So that the maturity time is delayed by 16 to 32 days under 14 DS across the rice varieties. BRRI dhan52 took 145 and 144 days to mature under control during application of PU and USG, respectively. On the other hand,

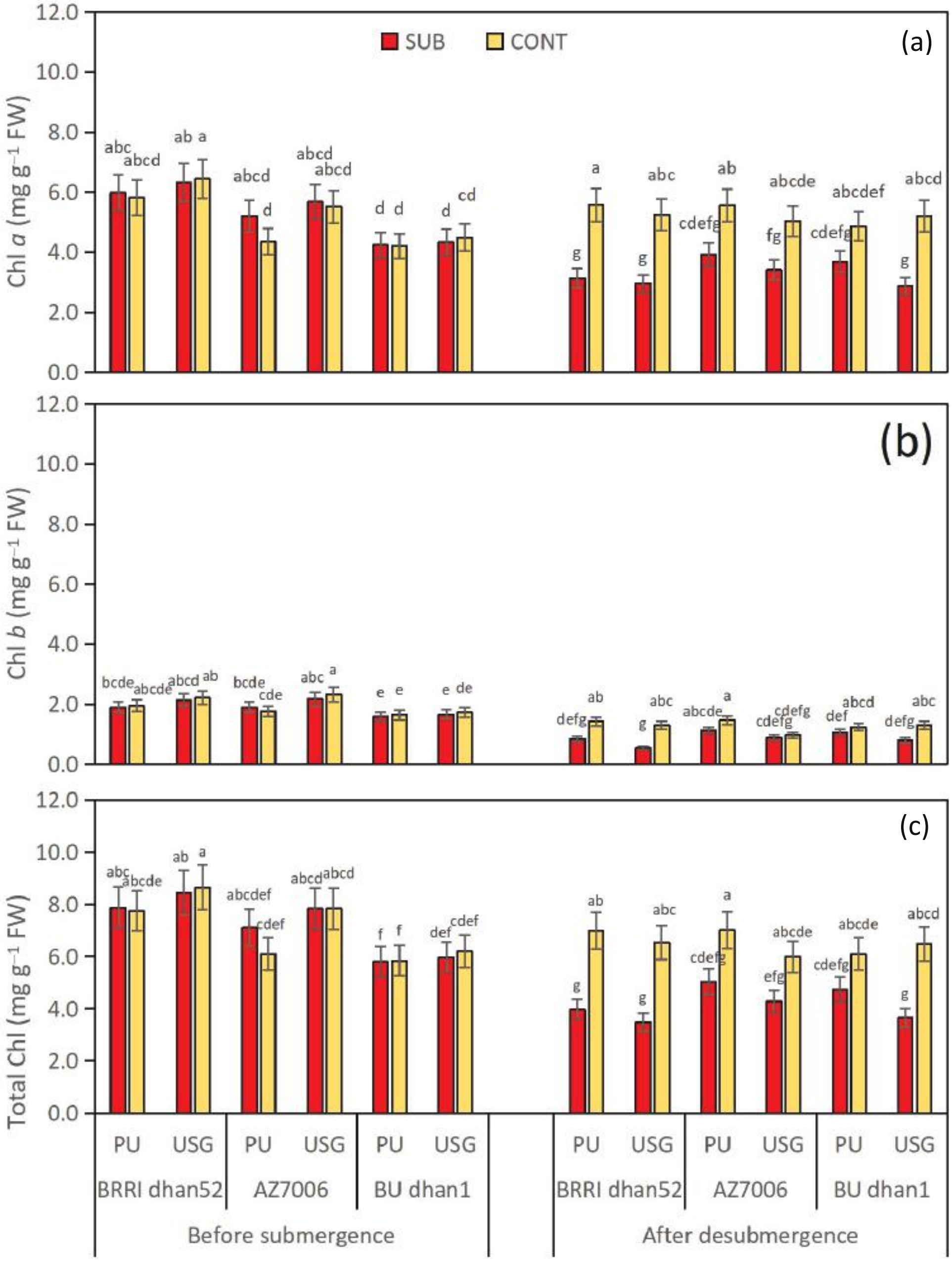

Fig. 5. Interaction effect of variety, submergence and N management on Chl content of rice before and 7 DADS. FW= Fresh weight. (a) Chl *a* content of rice leaf. (b) Chl *b* content of rice leaf. (c) Total Chl content of rice leaf. SUB = Submergence, CONT = Control, PU = Prilled urea, USG = Urea super granule. Values with different letters on bars are significantly different ($p < 0.05$). Small bar on the graph indicated ± standard error.

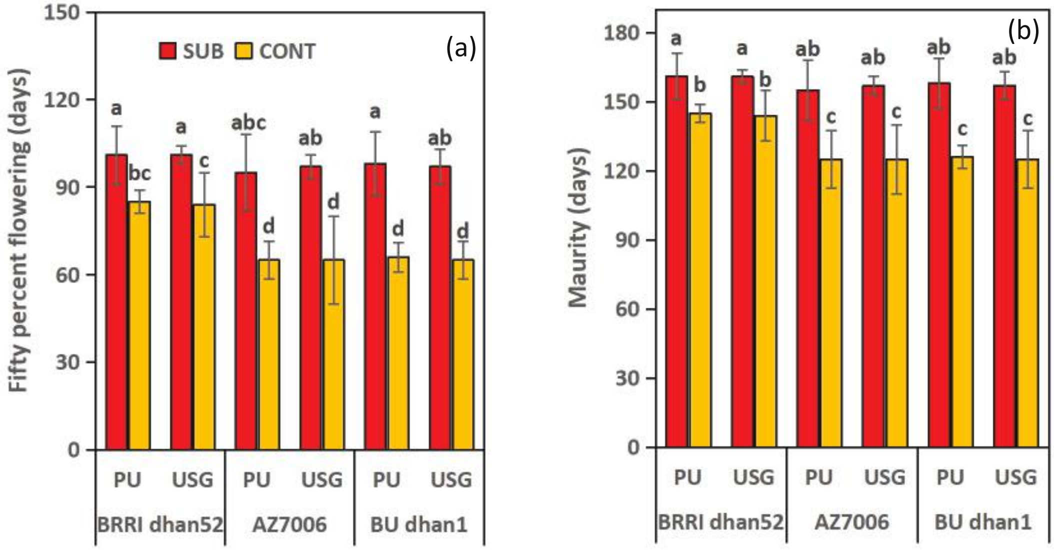

Fig. 6. Interaction effect of variety, submergence and N management on days to flowering and maturity of rice. (a) days to fifty percent. (b) days to maturity. SUB = Submergence, CONT = Control, PU = Prilled urea, USG = Urea super granule. Values with different letters on bars are significantly different ($p < 0.05$). Small bar on the graph indicated ± standard error.

this variety needed 161 days for maturity under 14 DS in same management practice (Fig. 6b). However, AZ7006 and BU dhan1 needed 125 to 126 days to mature under control, while 155 to 158 days were needed under submergence condition across the urea management plots. Because of the stoppage of vegetative development during submergence, the crop's duration was extended. Thus, after de-submergence, more time is required for regeneration and regrowth (Fig. 6a and b). As surviving plants needed time to recover, resume normal vegetative development, and overcome oxidative damage during and after de-submergence, flowering and maturity generally took longer after de-submergence (Dwivedi *et al.*, 2018). On the other hand, the apparent maturity delay was primarily caused by the delayed flowering. During the post-emergence phase, new shoots appeared from the stem base of damaged plants after the flood wrecked the crop's establishment. Re-establishment of the crop following flood damage could be regarded as real recovery growth during this period (Ram *et al.*, 2009).

Yield components

The number of effective tillers, grain production and 1000-grain weight varied significantly by the interaction of variety, submergence and N management practices at maturity ($p < 0.05$) (Fig. 7a to d). BRRI dhan52 produced 17 and 18 tillers hill^{-1} under 14 DS due to the application of PU and USG, respectively (Fig. 7a). Similarly, the effective tillers of AZ7006 and BU dhan1 were 18 and 20 hill^{-1} under 14 DS, respectively, with the application of PU. Likewise, in the case of the USG application, the panicle bearing tillers of AZ7006 and BU dhan1 were 19 and 21 hill^{-1} under 14 DS, while they were 14 and 16 hill^{-1} under control, respectively. BRRI dhan52 produced filled grain with 64 and 72 panicle^{-1} under 14 DS in PU and USG application, respectively (Fig. 7b). Similarly, the filled grains of AZ7006 and BU dhan1 were 141 and 101 panicle^{-1} under 14 DS, respectively, with the application of PU. Likewise, in the case of USG application, the number of filled grains of AZ7006 and BU dhan1 were 76 and 120 panicle^{-1} under 14 DS, respectively. In the case of unfilled grains, BRRI dhan52 produced 130 and 102 panicle^{-1} under 14 DS, while 142 and 114 under control condition in the case of PU and USG management practices, respectively (Fig. 7c). Similarly, the filled grains of AZ7006 and BU dhan1 were 75 and 93 panicle^{-1} under 14 DS, respectively with the application of PU. Likewise, in USG application, the number of filled grains of AZ7006 and BU dhan1 were 81 and 83 panicle^{-1} under 14 DS, respectively.

The 1000-grain weight of BRRI dhan52 was 20.9 and 21.8 g under 14 DS, while it was 19.8 and 20.2 g in the case of control with the PU and USG management practices, respectively (Fig. 7d). However, the 1000-grain weight of AZ7006 and BU dhan1 was 24.0 and 24.9 g under 14 DS, while 22.3 and 24.5 g under control, respectively with the application of PU. Similarly, in the case of the USG application, the 1000-grain weight of AZ7006 and BU dhan1 was 24.7 and 24.5 g under 14 DS, while it was 24.3 and 24.7 g under control, respectively.

Submergence is a severe issue during the early growth stages and seriously affects plants (Ismail *et al.*, 2009). According to this study, in the case of USG application, the effective tillers of AZ7006 and BU dhan1 were significantly higher than those of BRRI dhan52 under 14 DS (Fig. 7a). The size and quantity of panicles in rice are well recognized as selection factors for achieving sufficient productivity or grain yield. However, earlier research claimed that a drop in the number of panicles occurs when tiller growth is suppressed or when tiller mortality occurs because of either a shortage of O_2 or a prevalence of reduced light below 50 cm of water (Sugai *et al.*, 1999; Kato *et al.*, 2014). Due to submergence for 14 DS in all varieties and N management conditions, the proportion of grain fertility also decreased, although sterility increased (Fig. 7b). The main cause of rice plants' poor spikelet development, sterile grain, decreased grain weight, and ultimately significant yield reduction in a prolonged flood (Perata and Voesenek, 2007). When submerged, the quantity of grains panicle^{-1} substantially decreases in comparison to the control (Fukao *et al.*, 2006; Barding *et al.*, 2012). Reduced grain number panicle^{-1} is thought to be primarily caused by low light and low photosynthetically active radiation at the canopy level. The majority of the photosynthates in plants were used for

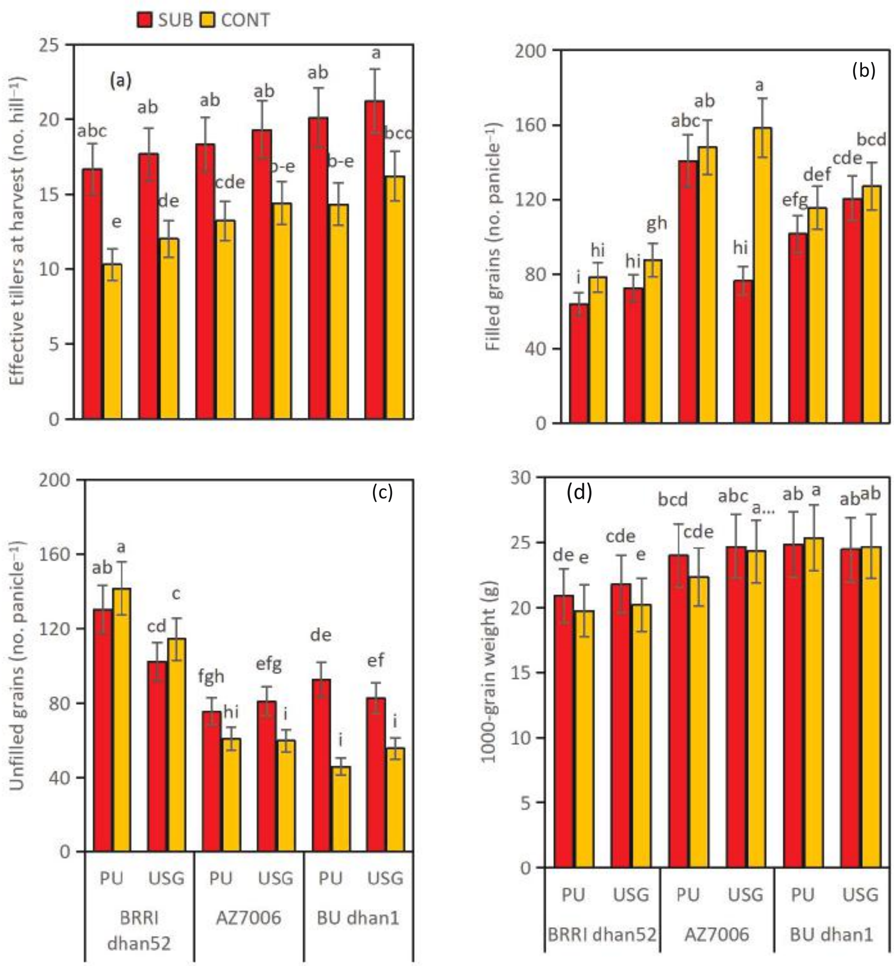

Fig. 7. Interaction effect of variety, submergence and N management on yield components of rice at harvest. (a) Production of effective tillers at harvest. (b) production of filled grain. (c) production of unfilled grain. (d) 1000-grain weight. SUB = Submergence, CONT = Control, PU = Prilled urea, USG = Urea super granule. Values with different letters on bars are significantly different ($p < 0.05$). Small bar on the graph indicated ± standard error.

vegetative growth rather than reproduction when floodwaters receded. Grain weight is mostly controlled by genetics and is minimally impacted by environmental factors and management techniques. On the other hand, extended submersion times resulted in a notable decrease in grain weight (Reddy and Mittra, 1985). The majority of the starch stored was needed to keep the plant alive and help it recover from submergence shock. According to reports, rice plants have the ability to restore sugars in a different way when they are submerged in water. This involves hydrolyzing sucrose and other stored carbs when the plants need a respiratory substrate (Sujatha *et al.*, 2008).

Grain and straw yield

The interaction of variety, submergence and N management practices exerted a significant effect on grain and straw yield of rice. The rice variety BRRI dhan52 produced 2.12 t ha^{-1} grain under PU management, which increased to 3.10 t ha^{-1} in USG application in the case of 14 DS ($p < 0.05$) (Fig. 8a). Similarly, AZ7006 yielded 3.14 t ha^{-1} under PU management, while this variety gave 3.56 t ha^{-1} grain under 14 DS with USG application treatment. BU dhan1 yielded 1.36 and 1.61 t ha^{-1} grain under 14 DS with the application of PU and USG, respectively. Like grain yield, BRRI dhan52 produced 2.82 and 4.23 t ha^{-1} straw in the case of 14 DS with PU and USG application, respectively (Fig. 8b). In the case of PU application, AZ7006 yielded 4.21 t ha^{-1} straw under 14 DS stress, while it produced 4.53 t ha^{-1} straw under USG application. BU dhan1 yielded 2.0 and 2.32 t ha^{-1} straw under 14 DS conditions with the application of PU and USG, respectively. Submergence caused a significant reduction of grain and straw yield (Fig. 8c). However, application of USG minimizes the rate of grain and straw yield reduction. In the case of BRRI dhan52, submergence reduced grain and straw yield by 46.05% and 41.49%, respectively under PU management practice, while the reduction of grain and straw yield was 24.39% and 18.81%, under the application of USG.

However, the grain and straw yield reduction of AZ7006 was 17.80% and 6.44% in the PU plot, while it was 26.90% and 16.88% in the case of USG plot. Moreover, 56.42% and 51.51% grain yield; and 48.32% and 44.89% straw yield of BU dhan1 were decreased due to submergence in case of the PU and USG application, respectively. Flooding poses a persistent threat to grain yield in rainfed lowland rice because it can cause significant damage and even plant death if it lasts more than a week (Iftekharuddaula *et al.*, 2016). Plants use storage carbohydrates as an alternate supply of respiratory substrate because current photosynthesis is quickly exhausted in submerged conditions. This creates a barrier to sufficient starch accumulation in the panicles for grain filling (Kawano *et al.*, 2009). In this experiment, the grain and straw yield was decreased under 14 DS as compared to the control. However, the amount of yield loss was low in the tolerant variety AZ7006 followed by BRRI dhan52 (Fig. 8a to c). The rice variety AZ7006 performed better in term of grain yield under 14 DS while USG was applied to the rice root zone. When N is applied to the root zone, plants grow more vegetatively during the early stages and produce an acceptable number of panicles in comparison to when they are not immersed. Straw DM was decreased in submergence compared to the control. Less photosynthetically active sunlight reaching the canopy level during submergence was thought to be the primary cause of tiller mortality and stunted development.

Nitrogen accumulation in grain and straw

All the rice varieties accumulated a higher amount of N under USG management practice than PU ($p < 0.05$) (Figs. 9a to b). BRRI dhan52 accumulated 28.53 and

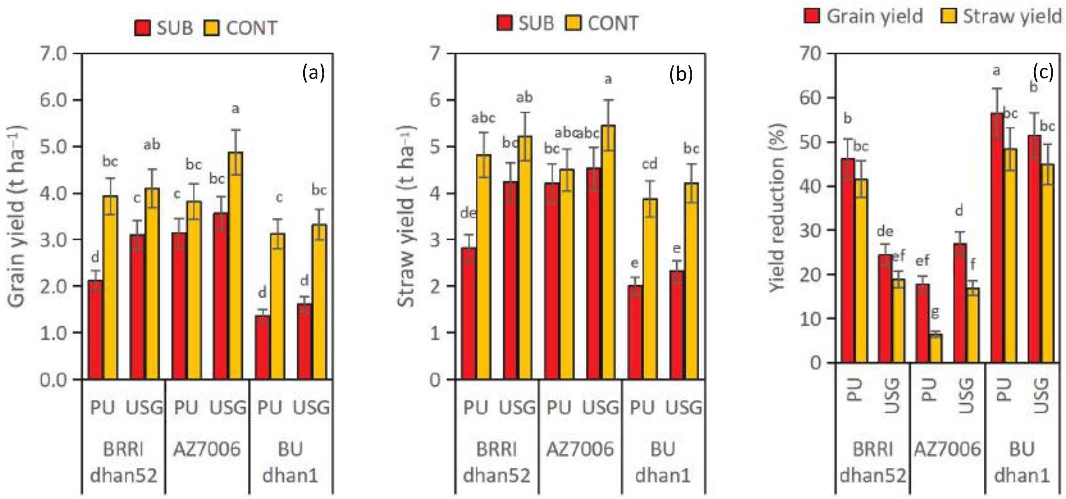

Fig. 8. Interaction effect of variety, submergence and N management on grain and straw yield of rice. (a) grain yield. (b) straw yield. (c) yield reduction. SUB = Submergence, CONT = Control, PU = Prilled urea, USG = Urea super granule. Values with different letters on bars are significantly different ($p < 0.05$). Small bar on the graph indicated ± standard error.

40.26 kg N ha^{-1} in grain under 14 DS with the application of PU and USG application, respectively (Fig. 9a). Under 14 DS, AZ7006 accumulated 28.53 kg N ha^{-1} in grain under PU, which increased to 40.25 kg N ha^{-1} under USG application. Similarly, BU dhan1 gathered 17.75 and 19.75 kg N ha^{-1} in rain under 14 DS with application of PU and USG, respectively. The straw of BRRI dhan52 accumulated 26.81 and 36.14 kg N ha^{-1} under 14 DS, while 37.24 and 42.61 kg N ha^{-1} under control with the application of PU and USG, respectively (Fig. 9b). Similarly, 43.65 and 43.06 kg N ha^{-1} were taken up by the straw of AZ7006 under 14 DS with the application of PU and USG, respectively. Further, straw of rice variety BU dhan1 accumulated 22.46 and 21.96 kg N ha^{-1} under 14 DS, while 35.59 and 36.77 kg N ha^{-1} were in under control with the application of PU and USG, respectively.

Grain and nitrogen harvest index

Higher grain harvest index (GHI) and N harvest index (NHI) were recorded under USG than PU management practice in all varieties under 14 DS (Figs. 10a and b). Under 14 DS, the GHI of BRRI dhan52 was 0.42 under PU, while it was 0.43 under USG management practice. Similarly, AZ7006 gave a GHI of 0.43 under PU, which increased to 0.44 under the USG treated plot (Fig. 10a). The GHIs of BU dhan1 were 0.40 and 0.41 under PU and USG management, respectively. However, the NHIs of BRRI dhan52 were 0.51 and 0.53 in 14 DS under PU and USG, respectively (Fig. 10b). Similarly, the NHI of

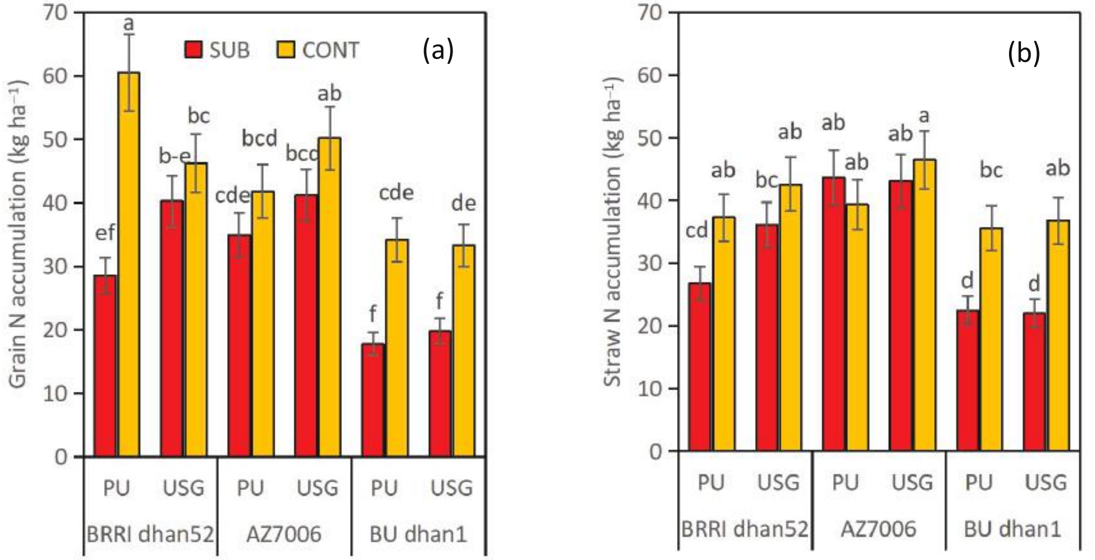

Fig. 9. Interaction effect of variety, submergence and N management on grain and straw N accumulation of rice. (a) Grain N accumulation. (b) straw N accumulation. SUB = Submergence, CONT = Control, PU = Prilled urea, USG = Urea super granule. Values with different letters on bars are significantly different ($p < 0.05$). Small bar on the graph indicated ± standard error.

AZ7006 was 0.44 under PU, which increased to 0.49 in 14 DS with the application of USG. Further, the NHIs of BU dhan1 were 0.44 and 0.47 in 14 DS with the application of PU and USG, respectively. The N translocation coefficient (NTC) varied significantly due to submergence and N management practice (Fig 10c). The NTC of BRRI dhan52 was 1.06 in PU, which decreased to 1.1 under 14 DS with USG application (Fig. 10c). Likewise, AZ7006 showed NTC of 0.8 and 1.0 under PU and USG application, respectively. A similar trend was also observed in the case of BU dhan1 regarding NTC.

In the USG plot, the NTC of BRRI dhan52 was 1.09 in control, which was 1.11 under 14 DS. The NTCs of AZ7006 and BU dhan1 were 0.80 and 0.79, respectively under 14 DS, which increased to 1.06 and 0.96, respectively, in the case of control with PU application. In the USG plot, the NTCs of AZ7006 and BU dhan1 were 0.96 and 0.90, respectively, under 14 DS, which increased to 1.08 and 0.91, respectively in case of control. The NTCs values indicated that the translocation of N from straw to grain decreased under 14 DS in all management practices. All the varieties translocate a comparatively higher fraction of N in the USG than PU applied plot. Low transfer coefficient shows inadequate nutrient absorption by grain, while higher NTC implies comparatively poor retention in straw or increased plant efficiency in transferring nutrients from straw to grain (Rahman *et al.*, 2022).

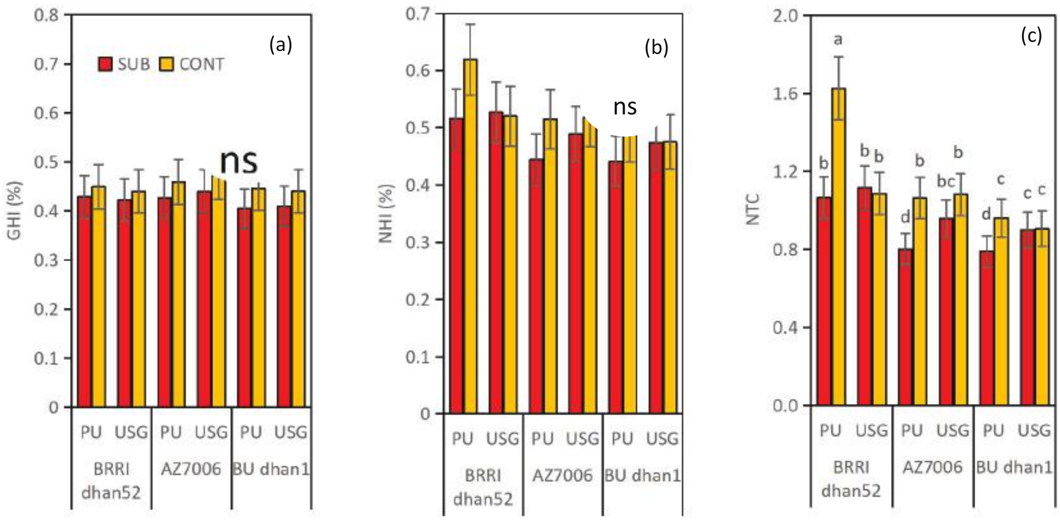

Fig. 10. Interaction effect of variety, submergence and N management on grain and N harvest index of rice. (a) grain harvest index. (b) N harvest index. (c) N translocation coefficient. ns = not significant, SUB = Submergence, CONT = Control, PU = Prilled urea, USG = Urea super granule. Small bar on the graph indicated ± standard error.

Association of different plant parameters

Grain yield of rice had a strong correlation with plant height after de-submergence (r = 0.86), survival (r = 0.90), DM production before (r = 0.78) and after de-submergence (r = 0.79), chlorophyll content before submergence (r = 0.77), straw yield (r = 0.98), grain (r = 0.98) and straw (r = 0.96) N accumulation (Table 1). However, the correlation between grain yield and plant lodging after de-submergence of floodwater was negative but very strong (r = 0.84). Grain yield showed a positive but weak correlation with plant height before submergence (r = 0.37) and at harvest (r = 0.45). Pair wise correlation was calculated to evaluate the relationship among different traits of rice varieties, with regard to morphological parameters and attributes related to grain yield under submergence for 14 days (Table 1). All the parameters showed positive association with each other except lodging, which exhibited a negative relationship with the rest of the morphological, yield and yield contributing attributes. The results revealed that the N management practices should be modified during rice cultivation under submergence conditions (Table 2).

Contribution of nitrogen management practices in rice production

The relative contribution of variety (genotypes), submergence (environment) and methods of N application (management) for grain and straw yield have been shown in Table 2. The relative contribution of variety was 37.51%, while submergence had a 17.26% contribution for grain yield. Regarding straw

Table 1. Correlation coefficient for the association among different parameters of rice genotypes after submergence stress condition

Parameters	PHBS	PHAS	DMBS	DMAS	SUR	LOD	CHLBS	PPH	GY	SY	GNA
PHAS	0.55*										
DMBS	0.73*	0.61*									
DMAS	0.46	0.95**	0.49								
SUR	0.45	0.71*	0.84**	0.67*							
LOD	-0.65*	-0.90**	-0.74*	-0.82**	-0.84**						
CHLBS	0.21	0.51*	0.66*	0.51*	0.94**	-0.71*					
PPH	0.61*	0.70*	0.38	0.81**	0.57*	-0.72*	0.48				
GY	0.37	0.86**	0.78*	0.79*	0.90**	-0.84**	0.77*	0.45			
SY	0.32	0.87**	0.73*	0.81**	0.88**	-0.82**	0.76*	0.46	0.98**		
GNA	0.27	0.77*	0.75*	0.72*	0.95**	-0.81**	0.88**	0.43	0.98**	0.98**	
SNA	0.43	0.95**	0.70*	0.86**	0.79*	-0.87**	0.62*	0.50	0.96**	0.96**	0.90**

*$p < 0.05$, **$p < 0.01$, PHBS = Plant height before submergence, PHAS = Plant height after de-submergence, DMBS = Shoot biomass before submergence, DMAS = Shoot biomass after de-submergence, SUR = Survival, LOD = lodging, CHLBS = Chlorophyll before submergence, PPH = Panicle hill^{-1}, GY = Grain yield, SY = Straw yield, GNA = Grain nitrogen accumulation, SNA = Straw nitrogen accumulation.

Table 2. Sum of squares from the analysis of variance of rice subjected to submergence

Sources of variation	DF	Sum of squares for grain yield	Sum of squares for straw yield
Replication	2	0.046 (0.12)	0.16 (0.38)
Variety (V)	2	13.86 (37.51)	16.21 (38.65)
Submergence (S)	1	17.26 (46.71)	15.73 (37.51)
V × S	2	0.81 (2.19)	2.51 (5.98)
Nitrogen (N)	1	2.32 (6.28)	3.49 (8.32)
V × N	2	0.42 (1.14)	0.51 (1.22)
S × N	1	0.01 (0.03)	0.03 (0.07)
V × S × N	2	0.77 (2.08)	1.10 (2.62)
Error	22	1.45 (3.92)	2.20 (5.25)
Total	35	36.95 (100%)	41.94 (100%)

Values within parentheses indicate the percent contribution of different sources of variation.

yield, variety and submergence contributed by 38.65% and 37.51%, respectively. The N management practices contributed only 6.28% for grain yield and 8.32% for straw yield.

Conclusion

Submergence of rice reduced plant survival, enhanced lodging and decreased dry matter production, chlorophyll content and reduced crop yield. However, rice variety AZ7006 performed better in terms of plant survival, tiller production, chlorophyll content, grain fertility, and 1000-grain weight of rice when the plot was treated with urea super granule (USG). Plants can sustain larger levels of photosynthetic activity during post-submergence phases when there is a better retention of chlorophyll concentration during submergence. Improved plant growth, rapid development, and higher grain yield were all made possible by the application of USG at the root zone. Further, more nitrogen uptake and translocation from straw to grain were observed by the deep placement of USG in the soil. These findings suggest that applying a USG can improve plant survival and output following the submergence recession. Therefore, application of USG might be suggested to improve rice yield in rainfed flood-prone areas.

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Conflict of Interest

The authors affirm that no financial or commercial relationships that might be construed as a potential conflict of interest existed during the course of the research.

Author Contributions

Conceptualization: MAAM (Md. Abdullah Al Mamun) and MNB (Md. Nasimul Bari). Methodology, Validation, and Data curation: MAAM and SA (Saruar Alam). Visualization: MAAM. Original draft preparation, Reviewing, and Editing, MAAM, MNB and MRT (Md. Raihan Talukder). All authors have read and agreed to the published version of the manuscript.

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