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Accelerating Seed Germination and Juvenile Growth of Sorghum (*Sorghum bicolor* L. Moench) to Manage Climate Variability through Hydro-Priming

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Abstract: Agriculture in Mali, a country in Sahelian West Africa, strongly depends on rainfall and concurrently has a low adaptive capacity, making it consequently one of the most vulnerable regions to climate change worldwide. Since early-season drought limits crop germination, and hence growth, ultimately yield during rain-fed depending on production is commonly experienced nowadays in Mali. Germination and establishment of key crops such as the staple sorghum could be improved by seed priming. The effects of hydro-priming with different water sources (e.g., distilled, tap, rain, river, well water) were evaluated respectively for three priming time durations in tepid e.g., at 25 °C (4, 8, and 12 h) and by hot water at 70 °C (in contrast to 10, 20, and 30 min.) in 2014 and 2015. Seed germination and seedling development of nine sorghum genotypes were monitored. Compared to non-primed seed treatments, hydro-priming significantly [$p = 0.01$] improved final germination percentage, germination rate index, total seedling length, root length, root vigor index, shoot length, and seedling dry weight. The priming with water from wells and rivers resulted in significant higher seed germination (85%) and seedling development, compared to the three other sources of water. Seed germination rate, uniformity, and speed were enhanced by hydro-priming also. It is argued that hydro-priming is a safe and simple method that effectively improve seed germination and seedling development of sorghum. If used in crop fields, the above most promising genotypes may contribute to managing early season drought and avoid failure of seed germination and crop failure in high climate variability contexts.

Keywords: hydro-priming; sorghum; resilience; early season drought; semi-arid; West Africa

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1. Introduction

The farming population in the West Africa Sahelian regions experiences frequent droughts during the unimodal rainy season. Especially at the onset of the growing season this increases risks at the sowing and juvenile growth period. More and more, farmers experience rainfall amounts enough to seed but insufficient to warrant further growth, whilst gradually the periods between rainfall events grow irregular, more highly endangering crop establishment. In addition, high temperatures are common at the onset of the growing season provoking increased soil evaporation and hence moisture deficiencies, of which 90–95% usually occurs in the 5–10 cm topsoil layer [1], that is the usual key depth for crop sowing. Under such moisture-poor condition, it appears important to improve the germination speed and rate to permit seedlings using as fast as possible any available soil moisture [2,3]. To this end, seed priming is regarded as one way to secure and improve germination in a bid to increase crop yield under such drought-prone conditions [4,5].

Seed priming is defined as a pre-sowing treatment that exposes dry seeds to a certain solution that allows partial hydration, but consequently not a complete germination yet [6]. Although the germination is triggered before actual sowing, the idea of priming is to initiate the metabolic activities that prepare seeds for radical protrusion [7–9]. It recurrently has been stated that seed priming thus can accelerate and improve germination and early seedling growth, which is particularly appropriate under the typical drought stress conditions as occurring at the onset of the season in the Sahelian zone of West Africa [10,11]. Various priming procedures have been developed successfully, all aiming at increasing the speed of seed germination [10,12], and secure emergence through improved water absorption capacity [13,14].

Well-known, practical efficient priming techniques include (a) hydro-priming where seeds are soaked in a fluid such as water, (b) osmo-priming where seeds are soaked into an osmotic solution such as polyethylene glycol 6000 (PEG-6000), (c) halo-priming where seeds are soaked in salt solutions, and (d) priming with growth-stimulating hormones. The beneficial effects of priming have been demonstrated for various field crops such as maize [15,16], sunflower [17], and others (soybean, wheat, lentil, chickpea, mungbean, cowpea, etc.) [18]. Previous findings underscored that the success of seed priming was determined by the complex interaction of plant species, the water potentiality (i.e., water chemical composition) of the priming agent, the duration of priming, the solution temperature during soaking, seed vigor, and previous storage conditions of the primed seeds [15]. Parera and Cantliffe emphasized that hydro-priming is the simplest approach to hydrating seeds and concurrently minimize the use of chemicals. However, the key is that imbibed seeds show a decreased lag period before radical emergence, which is initially reduced, but finally improves the rate and uniformity of germination [18,19]. Furthermore, previous findings underlined that hydro-priming may improve field emergence and ensured early flowering and harvesting under water stress conditions, especially in dry areas [15,20]. Hydro-priming, therefore, is a recognized means to reduce overall germination time, get synchronized germination, improve germination rates, and improve seedling establishment in many crops including maize, soybean, wheat, lentil, chickpea, mungbean, cowpea, etc. [20]. Soaking seeds of sorghum, rice, maize, and cowpea in water and planting presoaked seeds on the same day (presoaking treatment), increased germination rate, and improved seedling emergence [21,22].

The extended documentation on priming underlined the different parameters and indicators used to assess the performance of priming as recurrently explained in handbooks and laboratory manuals [23]. Whilst some parameters such as germination rate index (GRI), seedling vigor index (SVI), and germination index have been used sporadically [24,25], most assessment studies typically used parameters such as final germination percentage, mean germination time, seedling dry weight, and root vigor index [2,23,26–29]. Despite all previous reports recommending such interventions to the Malian farmer it is pertinent to confirm the positive impact of hydro-priming as an effective and efficient means to combat early season drought stress on key staples in Mali given the well-known impact of the inhibition solution [15], presoaking duration [2,20] crops and cultivars [2], and temperature of the soaking solution [2,15]. This paper aims to therefore assess the hydro-priming effects on nine Sorghum cultivars by using different sources of water and priming duration under controlled conditions in Mali.

2. Materials and Methods

The study was conducted in the Agronomy laboratory of the Agricultural Research Station of Cinzana (Longitude: 5°57′ W, Latitude: 13°15′ N, and Altitude: 280 m), located at the Institut d'Economie Rurale (IER) Bamako, Mali. Three out of the nine sorghum cultivars examined were obtained directly from farmers, the six remainders were released materials by the IER national sorghum breeding program whilst the variety Banidoka was used as a reference, as each variety had its known characteristics (Table 1).

Table 1. Characteristics of the selected sorghum cultivars used during the screening experiments.

Sorghum Variety	Sorghum Cultivars	Days to Mature	Overall Cultivar Type	Optimum Rainfall Requirement (mm)	Source
Banidoka	Guinea	120	Land race	600–800	Farmer
CSM63E	Guinea	100	Cultivar	400–700	IER
Nieleni	Caudatum-Guinea	110	Hybrid	700–1000	IER
Saba-soto	Caudatum	100	Land race	* Receding flood	Farmer
Saba-tienda	Durra	90	Land race	* Receding flood	Farmer
Seguifa	Durra	100	Cultivar	400–700	IER
Sewa	Caudatum-Guinea	110	Hybrid	800–1000	IER
Tiandougou	Guinea	120	Cultivar	800–1000	IER
Tiandougou-coura	Caudatum-Guinea	120	Cultivar	800–1000	IER

Source: [29,30] * Grown after flood water has receded.

Aside from referring the performance of eight sorghum cultivars to the wide-spread cultivar Banidoka, the effect of priming parameters on all nine Sorghum cultivars was assessed by comparing the impact of priming with untreated sorghum seeds (these served as controls). Given the effect of the soaking solution on hydro-priming [2,7]. The effect of the water sources on priming performance was assessed by comparing five sources of water including distilled, rain, river, tap, and well water which all are available in the country. In addition, three different priming durations were compared for heated and tepid water. Given the impact of soaking time [19]. The soaking durations compared included 10, 20, and 30 min, whilst in the case of the tepid water, the seeds were soaked for 4, 8, and 12 h (Table 2). Seeds were soaked in the selected water sources which had been treated: either as tepid water at 25 °C or in water previously heated at 70 °C. Consequently, the experiment consisted out of 40 treatments on nine sorghum varieties, water sources (6 levels) soaking duration in tepid water (4 levels) and in hot water (4 levels), hence all in all we dealt with 40 treatments and combinations thereof (Table 2).

Table 2. Hydro-priming treatment combinations.

Water Sources	Duration (min.) of Seed Submergence in Hot Water at 70 °C				Duration (min.) of Seed Submergence in Water at Room Temperature (25 °C)		
	0	10	20	30	240	480	720
Distilled	X	X	X	X	X	X	X
Rain	X	X	X	X	X	X	X
River	X	X	X	X	X	X	X
Tap	X	X	X	X	X	X	X
Well	X	X	X	X	X	X	X

2.1. Description of Hydro-Priming in Tepid and Hot Water

Each seed treatment was soaked in an open container about 125 mL and kept at room temperature for the duration of the priming.

Prior to the implementation of the soaking treatments, all seeds were surface-sterilized with 5% sodium hypochlorite (NaOCl) for 5 min to avoid fungal infections. This treatment was followed by washing, with distilled water, which occurred twice to wash off the chemicals according to previous studies [31].

Twenty-five of the pre-treated seeds of each variety were placed in a 9-cm diameter Petri dish on two Whatman filter papers that were moistened at the onset of the experiment and on the fourth day after sowing with 3 mL of test solution obtained from each of the five water sources (Table 2). The seeds of the control type 1 treatment were moistened with 3 mL distilled water at the onset and at the 4th day after sowing. Throughout the duration of the experiment, the petri dishes with seeds were kept inside the germinator. The temperature of both the germinator and room were recorded daily.

2.2. Evaluation of Hydro-Priming in Tepid Water

The effect of priming on the nine Sorghum cultivars in tepid water was assessed by comparing them with the untreated seeds of the same cultivar (control). The effect of the water source on priming performance was assessed by comparing the five sources of water that farmers in Mali could have access to, including distilled, rain, river, tap, and well water. In the case of the solution temperature, in case of tepid water priming, seeds had been soaked for 4, 8, and 12 h. Hence, each of the seeds of the 9 sorghum varieties were subjected to 40 different priming treatments. There was a control treatment where no priming was carried out for each variety.

2.3. Evaluation of Hydro-Priming in Hot Water

The effects of different procedures of hydro-priming on the germination and seed establishment performance of nine sorghum varieties were evaluated while using 6 water sources soaking duration in tepid water (4 levels) and in hot water (4 levels). The water used was from the five aforementioned water sources e.g., distilled, tap, rain, river, and well water. The water used for presoaking was heated first to 70 °C before use. Seeds were submerged in warm water for 10-, 20-, or 30-min duration before sowing in petri dish (Table 2). A factorial arranged completely randomized design with three replications was used to assess the impact of the priming treatments through key assessment parameters (Table 3).

Table 3. Seed germination assessment parameters.

Assessment Parameter	Abbreviation	Calculation Base	Explanation of Assessment Parameter	Source
Germination Percentage	GP (%)	GP = (Number of seeds germinated)/(number of seeds sown) × 100	(Number of total seeds germinated over the number of total seeds sown time hundred).	[23]
Mean Germination Time	MGT (Days)	MGT = (∑(Dn)/(∑n)	n is the number of seeds germinated on each day counted, whilst D is the day of counting n.	[26]
Root Vigor Index	RVI	RVI = RL × GP	RL is the root length (cm), and GP is the germination percentage.	
Germination Rate Index	GRI (%/day)	GRI = ∑(GP1 + GP2 . . . GPn)/n	Summation of the germination percentage at each day (GP) divided by the total days (n) of germination.	[32]
Seedling Dry Weight	SDW (g/plant)	Dry samples weighted and expressed in g.	Weight determined after drying seedling samples at 105 °C for 24 h.	[33]

2.4. Statistical Analysis

Data were analyzed through an analysis of variance (ANOVA) using GenStat nine edition version 9.2.0 (2007). As part of the analyses all data were checked for normality and normal distribution before being subjected to ANOVA. The means of germination percentage, mean germination time, germination rate index, seedling vigor index, root vigor index, and seedling dry weight were compared with those of the treatments of the nine sorghum varieties, water sources (6 levels) soaking duration in tepid water (4 levels) and in hot water (4 levels). Multiple comparisons among treatments means were considered significantly different at $p \leq 0.05$ according to The Fisher's Protected Least Significant Difference (LSD) for means separation [34]. Water is a basic requirement for germination. It is essential for enzyme activation, breakdown, translocation, and use of reserve storage material [35]. Every enzyme shows maximum activity at an optimum pH. Their activity is slow above or below the optimum pH. Enzymes have active sites where the substrates bind. These active sites are damaged or in other words their shape is changed by changing the pH. Substrates no longer fit the active site and the reaction does not occur. A pH of about 7 is the optimum and as the pH moves further away from the optimum pH the enzyme activity starts to slow down. Given the potential impact of the chemical composition of the soaking solution on the germination performance [36], samples of each water source used were sent for chemicals analysis in the laboratory in 2014 and 2015.

3. Results

3.1. Chemical Composition of Sources of Water

Although not analyzed statistically because of limited time, we observed that chemical composition varied according to water sources. In general, highest concentration of total dissolved solid (TDS) was found in river and well water followed by tap, rain, and distilled water, respectively (Table 4). The pH was high in river (7.7) and well (7.2) water, whilst lowest in tap (6.5), rain (6.7), and distilled (6.7) water.

Table 4. Chemical composition of various water sources.

Parameters	Distilled	Rain	River	Tap	Well
pH	6.7	6.7	7.7	6.5	7.2
EC (25 °C) µS cm^{-1}	6.5	9.5	87.5	40.5	181.5
Hardness (mg/L)	3.5	5	38	18	63
$CaCO_3$ (mg/L)	2.0	3.5	38.5	16.0	63.5
TDS (105 °C) (mg/L)	8.9	13.0	82.9	61.6	139.7
Calcium, Ca^{2+} (mg/L)	0.5	0.5	8.5	2.8	17.5
Magnesium, Mg2+ (mg/L)	1.0	0.9	4.1	2.6	4.7
Sodium, Na+ (mg/L)	0.2	0.2	3.4	3.3	7.3
Potassium, K+ (mg/L)	0.3	0.7	2.7	1.4	8.3
Bicarbonates, HCO_3 (mg/L)	2.6	4.4	46.9	19.1	77.5
Sulphates, SO4 $^{2-}$ (mg/L)	0.6	0.9	5.2	3.4	2.3
Chlorine, Cl^- (mg/L)	0.3	0.3	2.5	2.6	1.9
Nitrates, NO_3- (mg/L)	0.1	0.1	0.9	1.2	0.6
Copper, Cu^2+ (mg/L)	0.0	0.1	0.0	0.0	0.0
Zinc, Zn (mg/L)	0.0	0.1	0.0	0.0	0.0

Values are means for chemical composition in 2014 and 2015.

The TDS influence pH level towards alkalinity and was higher in well (139.7 mg L^{-1}), river (82.9 mg L^{-1}) while it was low in rain (13.0 mg L^{-1}) and distilled water (8.9 mg L^{-1}). The concentration of calcium carbonate was high in well and river water lower in rain and distilled water (Table 4). The highest concentration of calcium was found in well water (17.5 mg L^{-1}) followed by river water (8.5 mg L^{-1}), and the remaining was low. The Bicarbonate (HCO_3) concentration was also higher in well (77.5 mg L^{-1}) and river water (46.9 mg L^{-1}) (Table 4). Micronutrients copper and zinc were slightly present only in rainwater which suggests the side effect on seed growth parameters. The presence of these micronutrients seems to inhibit seed germination and growth parameters which go beyond the scope of this study (Table 4).

3.2. Effect of Tepid Hydro-Priming on Seed Germination and Seedling Growth Parameters

3.2.1. Germination Percentage (GP)

The GP was significantly affected by varieties in tepid water ($p = 0.01$), while water sources, priming duration, and their interaction were not significantly different for germination percentage (Table 5). Among varieties, CMS63E, Banidoka, followed by Saba-tienda and Seguifa were statistically higher and different from other varieties in tepid water (Table 5) while Tandougou was significantly different from Nieleni, Sewa, Tiandougou-Coura, and Saba-Soto.

Table 5. Effect of tepid water priming at different durations and with water from different sources on seed germination and other growth parameters of nine varieties of sorghum.

Treatments	Assessment Parameters				
Variety	**GP**	**MGT**	**GRI**	**RVI**	**SDW**
Banidoka	99.0 ± 1.12	4.6 ± 0.02	96.2 ± 1.23	532.7 ± 15.30	0.13 ± 0.01
CSM63E	99.2 ± 1.12	4.5 ± 0.02	98.5 ± 1.23	436.0 ± 18.90	0.12 ± 0.01
Nieleni	87.2 ± 1.12	4.6 ± 0.02	84.0 ± 1.23	268.2 ± 18.43	0.07 ± 0.01
Saba-soto	82.1 ± 1.12	4.7 ± 0.02	78.3 ± 1.23	230.1 ± 19.07	0.10 ± 0.01
Saba-tienda	94.8 ± 1.12	4.6 ± 0.02	92.5 ± 1.23	467.1 ± 18.40	0.10 ± 0.01
Seguifa	94.8 ± 1.12	4.6 ± 0.02	91.6 ± 1.23	455.6 ± 18.76	0.11 ± 0.01
Sewa	84.9 ± 1.12	4.6 ± 0.02	81.8 ± 1.23	293.8 ± 18.31	0.08 ± 0.01
Tiandougou	91.6 ± 1.12	4.6 ± 0.02	89.1 ± 1.23	363.0 ± 18.90	0.09 ± 0.01
Tiandougou-coura	85.2 ± 1.12	4.7 ± 0.02	81.1 ± 1.23	186.4 ± 19.60	0.07 ± 0.01
p-values	<0.01	<0.01	<0.01	<0.01	<0.01
LSD	2.50	0.04	2.90	63.20	0.01
Water sources					
Control	91.0 ± 0.92	4.7 ± 0.01	85.1 ± 1.01	278.1 ± 16.90	0.08 ± 0.01
Distilled	90.1 ± 0.,92	4.6 ± 0.01	87.6 ± 1.01	402.5 ± 14.70	0.10 ± 0.01
Rain	90.1 ± 0.92	4.6 ± 0.01	88.1 ± 1.01	288.0 ± 16.55	0.08 ± 0.01
River	91.2 ± 0.92	4.6 ± 0.01	89.2 ± 1.01	434.2 ± 13.95	0.10 ± 0.01
Tap	91.0 ± 0.92	4.6 ± 0.01	89.6 ± 1.01	351.2 ± 13.90	0.10 ± 0.01
Well	91.6 ± 0.92	4.6 ± 0.01	89.2 ± 1.01	401.2 ± 14.41	0.11 ± 0.01
p-values	0.40	<0.01	<0.01	<0.01	<0.01
LSD		0.03	2.30	51.60	0.01
Priming duration (h)					
4	90.7 ± 0.92	4.6 ± 0.01	87.0 ± 1.01	306.8 ± 13.21	0.08 ± 0.01
8	90.7 ± 0.92	4.6 ± 0.01	87.8 ± 1.01	352.9 ± 12 13	0.11± 0.01
12	91.5 ± 0.92	4.5 ± 0.01	89.6 ± 1.01	426.2 ± 12.47	0.10 ± 0.01
p-values	0.40	<0.01	<0.01	<0.01	<0.01
LSD		0.02	1.70	36.50	0.01
p-values for variety × water sources	1.00	1.00	1.00	0.99	0.18
p-values for variety × duration	0.80	0.70	0.90	0.57	0.05
p-values for water × duration	0.50	0.90	0.50	0.04	0.23
p-values for variety × water × duration	1.00	1.00	0.28	0.99	0.54

LSD values at $p \leq 0.05$ according to the fischers' LSD test, GP: Germination percentage, MGT: Mean germination time, GRI: Germination rate index, RVI: Root vigor index, SDW: Seedling dry weight.

3.2.2. Mean Germination Time (MGT)

The effect of tepid water on mean germination time of varieties ($p < 0.01$), water sources ($p < 0.01$), and priming duration ($p < 0.01$) were significant. No significant interaction was found among varieties × water sources × priming duration (Table 5). Lower values of MGT, which refer to an increase of germination speed, were observed in tepid hydro-priming. Among different water sources, tepid (25 °C) significantly improved the mean germination time compared to the unprimed (Table 5). Priming duration in 12 h revealed that mean germination time was reduced in all water sources compared to the control and 8 h (Table 5). Deeper analysis showed that different water sources revealed that varieties respond differently while all water sources significantly improved mean germination time compared to control (Table 5).

3.2.3. Germination Rate Index (GRI)

Highly significant differences in GRI were found among varieties ($p < 0.01$), water sources ($p < 0.01$), and priming duration treatments ($p < 0.01$). No significant interaction was found among their interaction. The highest GRI was observed with CSM63E

(98.5%/day) and Banidoka (96.2%/day) followed by Saba-tienda (92.5% day-1) and Seguifa (91.6%/day). The varieties Nieleni, Sewa, Saba-soto, and Tiandougou-coura were not significantly different among them but were different from Tiandougou (Table 5). Among different water sources, tepid (25 °C) significantly improved the germination rate index compared to the unprimed (Table 5). Priming duration in 12 h increased germination rate index in all water sources compared to the control and 8 h (Table 5).

3.2.4. Root Vigor Index (RVI)

Root vigor index (RVI) as a function of root length and germination percentage was also significantly affected by varieties (p = 0.01), water sources (p = 0.01), and priming duration (p = 0.01) in tepid water. Significant difference was found between tepid water sources and priming duration ($p < 0.04$) but no interaction was found with varieties × priming duration and varieties × water sources × priming duration. The maximum RVI was observed with variety Banidoka. Varieties Saba-tienda, Seguifa, and CSM63E, were not different but statistically different from other varieties in tepid water (Table 6). In tepid water, varieties respond differently.

Table 6. Root vigor index of 5 water sources under different priming duration in tepid water.

Water Sources	**Priming Duration (h)**			**Mean RVI for Water Sources**
	4	**8**	**12**	
Control	188.3 ± 13.21	277.8 ± 12.96	368.2 ± 12.47	278.1
Distilled	362.7 ± 13.21	375.4 ± 12.96	469.4 ± 12.47	402.5
Rain	286.7 ± 13.21	267.9 ± 12.96	309.5 ± 12.47	288.0
River	400.7 ± 13.21	395.5 ± 12.96	506.4 ± 12.47	434.2
Tap	292.2 ± 13.21	398.0 ± 12.96	363.3 ± 12.47	351.2
Well	300.8 ± 13.21	382.2 ± 12.96	520.5 ± 12.47	401.2
Mean RVI for priming duration	305.2	349.5	422.9	
	p-value	SED	LSD	
Water sources	<0.01	26.3	51.6	
Priming duration	<0.01	18.6	36.5	
Water sources × priming duration	0.04	45.5	89.3	

p-value at $p \leq 0.05$, SED: Standard errors of differences of means, LSD: Least significant differences of means. According to Fischer's LSD post-hoc test.

The maximum RVI was observed in distilled, river, and well water, which were statistically equal. Tap water was not significantly different from distilled and well water but, except rainwater, the remaining water sources improved RVI compared to unprimed seeds. Rainwater was not significantly different from the control in tepid water study.

Priming duration in tepid water at 4, 8, and 12 h, with an increase of priming duration this trait has shown a significant improvement in comparison to control (Table 6). The highest RVI was recorded with 12 h (RVI of 426.2) statistically different from other priming duration, followed by 8 h (RVI = 352.9) and when soaked at 4 h (306.8) in tepid water (Table 6). Interaction effects of water sources treatment × priming duration on root vigor index were significant. Distilled, river, and well waters in duration 12 h showed the highest impact on root vigor index (Table 6).

3.2.5. Seedling Dry Weight (SDW)

Significant differences in SDW were found among varieties ($p < 0.01$), water sources ($p < 0.01$), and priming duration ($p < 0.01$). There was significant interaction effect of varieties and priming duration ($p < 0.05$) on SDW. Average seedling dry weight was significantly higher in Banidoka and CSM63E. SDW significantly increased with increase of priming duration (Table 7).

Table 7. Seedling dry weight of 9 sorghum cultivars presoaked under different priming duration in tepid water.

Variety	Priming Duration (h)			Mean SDW for Varieties
	4	8	12	
Banidoka	0.11 ± 0.01	0.13 ± 0.01	0.14 ± 0.01	0.13
CSM63E	0.11 ± 0.01	0.13 ± 0.01	0.10 ± 0.01	0.12
Nieleni	0.06 ± 0.01	0.07 ± 0.01	0.06 ± 0.01	0.07
Saba-soto	0.10 ± 0.01	0.12 ± 0.01	0.08 ± 0.01	0.10
Saba-tienda	0.08 ± 0.01	0.11 ± 0.01	0.10 ± 0.01	0.10
Seguifa	0.08 ± 0.01	0.12 ± 0.01	0.12 ± 0.01	0.11
Sewa	0.08 ± 0.01	0.09 ± 0.01	0.07 ± 0.01	0.08
Tiandougou	0.07 ± 0.01	0.10 ± 0.01	0.10 ± 0.01	0.09
Tiandougou-coura	0.05 ± 0.01	0.08 ± 0.01	0.08 ± 0.01	0.07
Mean SDW for priming duration	0.08	0.11	0.10	
	p-value	SED	LSD	
Varieties	<0.01	0.01	0.01	
Priming duration	<0.01	0.01	0.01	
Varieties × priming duration	0.05	0.01	0.02	

p-value at $p \leq 0.05$, SED: Standard errors of differences of means, LSD: Least significant differences of means according to fishers' LSD test.

There was no difference between priming duration 8 and 12 h. There was no interaction found with varieties × water sources, water sources × priming duration and varieties × water sources × priming duration (Table 7). In tepid water, the highest SDW was observed with Banidoka (0.12 g) and CSM63E (0.12 g), which was however statistically not different from the SDW of Seguifa (0.11 g). Varieties Saba-Soto and Saba-Tienda (0.10 g) were not significantly different from Seguifa (Table 7). The lowest SDW was observed with Nieleni and Tiandougou-Coura (0.07 g). All water sources except rainwater significantly improved SDW compared to unprimed (Table 7). Distilled, river, tap, and well waters were statistically equal in performance on SDW. Rainwater was not statistically different from control. Priming duration in tepid water, 8 h recorded the highest SDW (0.11 g/plant) which was statistically different from 4 and 12 h soaking. Priming duration from 4 h was not statistically different to the control (Table 7). The optimum priming duration is 8 h, when increasing after 8 h the seedling dry weight decreases. Significant interaction was found between varieties × priming duration, suggesting differential responses to priming duration.

3.3. Effect of Hot Hydro-Priming on Seed Germination and Seedling Growth Parameters

3.3.1. Germination Percentage (GP)

Varieties ($p < 0.01$) of water sources ($p < 0.01$) were significant in hot water on germination percentage (Table 8). There was no significant interaction effect on germination percentage. Saba-soto, Tiandougou, and Tiandougou-coura recorded the lowest GP in hot water; the highest was recorded in CSM63E, Banidoka, Saba-tienda, and Seguifa (Table 8) in hot water at 70 °C. Sources of water did significantly influence seed germination percentage. The highest germination was recorded in control water at 70 °C did not increase germination percentage, suggesting an inhibition of some enzymes needed for germination (Table 8).

3.3.2. Mean Germination Time (MGT)

Significant difference was found in varieties ($p < 0.01$). There was no significant effect of hydro-priming at 70 °C on mean germination time with water sources, priming duration, and all interactions (Table 8). Varieties CSM63E, Banidoka, and Saba-tienda (4.5 days) showed reduced mean germination time compared to Nieleni, Saba-soto, Seguifa, Sewa, Tiandougou, and Tiandougou-coura (4.6 days). The highest MGT was recorded in Saba-soto (4.7 days). Varieties respond differently to heated water sources at 70 °C (Table 8).

Table 8. Effect of water priming at different durations and with water from different sources on seed germination and growth parameters of nine varieties of sorghum in hot water.

Treatments	Growth Parameters				
Variety	**GP**	**MGT**	**GRI**	**RVI**	**SDW**
Banidoka	98.3 ± 1.12	4.5 ± 0.02	488.3 ± 1.23	226.0 ± 15.30	0.10 ± 0.01
CSM63E	98.3 ± 1.12	4.5 ± 0.02	485.6 ± 1.23	292.7 ± 18.90	0.07 ± 0.01
Nieleni	83.2 ± 1.12	4.6 ± 0.02	427.3 ± 1.23	130.9 ± 18.43	0.06 ± 0.01
Saba-soto	77.8 ± 1.12	4.7 ± 0.02	457.0 ± 1.23	80.6 ± 19.07	0.06 ± 0.01
Saba-tienda	90.9 ± 1.12	4.5 ± 0.02	426.7 ± 1.23	219.5 ± 18.40	0.05 ± 0.01
Seguifa	92.1 ± 1.12	4.6 ± 0.02	454.1 ± 1.23	168.2 ± 18.76	0.06 ± 0.01
Sewa	85.4 ± 1.12	4.6 ± 0.02	460.0 ± 1.23	128.5 ± 18.31	0.06 ± 0.01
Tiandougou	78.7 ± 1.12	4.6 ± 0.02	438.0 ± 1.23	79.4 ± 18.90	0.03 ± 0.01
Tiandougou-coura	78.2 ± 1.12	4.6 ± 0.02	461.2 ± 1.23	63.0 ± 18.60	0.03 ± 0.01
p-values	<0.01	<0.01	0.96	<0.01	<0.01
LSD	4.1	0.03	111.5	48.8	0.01
Water sources					
Control	91.6 ± 0.92	4.6 ± 0.01	451.5 ± 0.01	122.7 ± 16.90	0.04 ± 0.01
Distilled	86.0 ± 0.92	4.6 ± 0.01	456.6 ± 0.01	158.3 ± 14.70	0.06 ± 0.01
Rain	81.5 ± 0.92	4.6 ± 0.01	449.4 ± 0.01	109.3 ± 16.55	0.05 ± 0.01
River	85.8 ± 0.92	4.6 ± 0.01	453.9 ± 0.01	185.3 ± 13.95	0.07 ± 0.01
Tap	87.6 ± 0.92	4.6 ± 0.01	458.1 ± 0.01	181.9 ± 13.90	0.07 ± 0.01
Well	89.5 ± 0.92	4.6 ± 0.01	462.8 ± 0.01	168.4 ± 16.40	0.06 ± 0.01
p-values	<0.01	0.80	1.00	<0.01	<0.01
LSD	3.3	0.03	91.0	39.9	0.01
Priming duration (min.)					
10	87.3 ± 0.92	4.6 ± 0.01	449.4 ± 0.01	101.9 ± 13.21	0.05 ± 0.01
20	87.1 ± 0.92	4.6 ± 0.01	459.2 ± 0.01	170.7 ± 12.13	0.06 ± 0.01
30	86.6 ± 0.92	4.6 ± 0.01	457.5 ± 0.01	190.3 ± 12.47	0.06 ± 0.01
p-values	0.83	0.33	0.95	<0.01	0.01
LSD	2.4	0.02	64.4	28.2	0.01

LSD values at $p \leq 0.05$ GP: Germination percentage, MGT: Mean germination time, RVI: Root vigor index, SDW: Seedling dry weight.

3.3.3. Germination Rate Index (GRI)

No significant difference was found in hydro-priming at 70 °C on germination rate index with varieties, water sources, priming duration, and their interaction (Table 9).

Table 9. Effect of water priming at different durations and with water from different sources on seed germination and growth parameters of nine varieties of sorghum in hot water.

	Growth Parameters					
Treatments Variety	**GP**	**MGT**	**GRI**	**SVI**	**RVI**	**SDW**
Banidoka	98.3 ± 1.12	4.5 ± 0.02	488.3 ± 1.23	537.0 ± 24.23	226.0 ± 15.30	0.10 ± 0.01
CSM63E	98.3 ± 1.12	4.5 ± 0.02	485.6 ± 1.23	582.0 ± 30.03	292.7 ± 18.90	0.07 ± 0.01
Nieleni	83.2 ± 1.12	4.6 ± 0.02	427.3 ± 1.23	267.9 ± 29.30	130.9 ± 18.43	0.06 ± 0.01
Saba-soto	77.8 ± 1.12	4.7 ± 0.02	457.0 ± 1.23	210.0 ± 30.29	80.6 ± 19.07	0.06 ± 0.01
Saba-tienda	90.9 ± 1.12	4.5 ± 0.02	426.7 ± 1.23	423.5 ± 29.16	219.5 ± 18.40	0.05 ± 0.01
Seguifa	92.1 ± 1.12	4.6 ± 0.02	454.1 ± 1.23	306.9 26.62	168.2 ± 18.76	0.06 ± 0.01
Sewa	85.4 ± 1.12	4.6 ± 0.02	460.0 ± 1.23	268.9 ± 28.94	128.5 ± 18.31	0.06 ± 0.01
Tiandougou	78.7 ± 1.12	4.6 ± 0.02	438.0 ± 1.23	158.1 ± 32.60	79.4 ± 18.90	0.03 ± 0.01
Tiandougou-coura	78.2 ± 1.12	4.6 ± 0.02	461.2 ± 1.23	147.3 ± 33.80	63.0 ± 18.60	0.03 ± 0.01
p-values	<0.01	<0.01	0.96	<0.01	<0.01	<0.01
LSD	4.1	0.03	111.5	92.6	48.8	0.01
Water sources						

Table 9. *Cont.*

	Growth Parameters					
Treatments Variety	**GP**	**MGT**	**GRI**	**SVI**	**RVI**	**SDW**
Control	91.6 ± 0.92	4.6 ± 0.01	451.5 ± 0.01	237.2 ± 26.32	122.7 ± 16.90	0.04 ± 0.01
Distilled	86.0 ± 0.92	4.6 ± 0.01	456.6 ± 0.01	343.9 ± 23.29	158.3 ± 14.70	0.06 ± 0.01
Rain	81.5 ± 0.92	4.6 ± 0.01	449.4 ± 0.01	239.6 ± 25.92	109.3 ± 16.55	0.05 ± 0.01
River	85.8 ± 0.92	4.6 ± 0.01	453.9 ± 0.01	397.6 ± 22.32	185.3± 13.95	0.07 ± 0.01
Tap	87.6 ± 0.92	4.6 ± 0.01	458.1 ± 0.01	374.2 ± 21.99	181.9 ± 13.90	0.07 ± 0.01
Well	89.5 ± 0.92	4.6 ± 0.01	462.8 ± 0.01	342.0 ± 22.39	168.4 ± 16.40	0.06 ± 0.01
p-values	<0.01	0.80	1.00	<0.01	<0.01	<0.01
LSD	3.3	0.03	91.0	75.6	39.9	0.01
Priming duration (min.)						
10	87.3 ± 0.92	4.6 ± 0.01	449.4 ± 0.01	206.3 ± 28.32	101.9 ± 13.21	0.05 ± 0.01
20	87.1 ± 0.92	4.6 ± 0.01	459.2 ± 0.01	350.6 ± 24.32	170.7 ± 12.13	0.06 ± 0.01
30	86.6 ± 0.92	4.6 ± 0.01	457.5 ± 0.01	410.3 ± 25.32	190.3 ± 12.47	0.06 ± 0.01
p-values	0.83	0.33	0.95	<0.01	<0.01	0.01
LSD	2.4	0.02	64.4	53.4	28.2	0.01

LSD values at $p \leq 0.05$ GP: Germination percentage, MGT: Mean germination time, GI: Germination index, SVI: Seedling vigor index, RVI: Root vigor index, SDW: Seedling dry weight.

3.3.4. Root Vigor Index (RVI)

Significant difference was found in varieties ($p < 0.01$), water sources ($p < 0.01$), and priming duration ($p < 0.01$) on root vigor index. There was no significant interaction of hydro-priming at 70 °C on root vigor index. Varieties CSM63E, Banidoka, and Saba-tienda recorded the highest RVI while the lowest was found in Tiandougou and Tiandougou-coura (Table 9). Varieties Nieleni, Sewa, and Seguifa were not significantly different but were statistically different from Tiandougou and Tiandougou-coura. River, tap, and well water at 70 °C were significantly different from rainwater, but were not significantly different from distilled water. Distilled and rainwater were not significantly different from the unprimed control. Priming duration increased RVI from 10 to 20 mm. There was no significant effect of priming duration 20 and 30 mn in water at 70 °C (Table 9).

3.3.5. Seedling Dry Weight (SDW)

The seedling dry weight significantly varied with varieties ($p < 0.01$), water sources ($p < 0.01$), and priming duration ($p < 0.01$) in water at 70 °C. There was no significant interaction of hydro-priming at 70 °C on seedling dry weight (Table 9). Varieties CSM63E and Banidoka recorded the highest SDW while the lowest was found in varieties Nieleni and Tiandougou-coura (Table 9). Varieties Nieleni, Saba-soto, Sewa, and Seguifa were not significantly different but were statistically higher compared to Tiandougou and Tiandougou-coura (Table 9). All water sources significantly improved seedling dry weight compared to unprimed control in water at 70 °C. Distilled, river, tap, and well waters were significantly different from rainwater which was also different from unprimed control (Table 9). Priming duration of 10, 20, and 30 mn in water at 70 °C increased seedling dry weight compared to unprimed control. Priming duration 20 and 30 mn was significantly higher than 10 mn soaking in water 70 °C (Table 9), but which was not statistically different between themselves. Seed primed in water at 70 °C during 10, 20, and 30 min was not significantly different from tepid water, suggesting that hydro-priming in tepid or water at 70 °C leads to similar seed germination levels.

4. Discussion

In their dormant state, seeds are characteristically low in moisture level and therefore relatively inactive. However, moisture triggers germination as it activates enzymes, breakdown, translocation, and use of reserve storage material: hence in general, findings showed that hydro-priming durations enhanced seedling emergence percentage and reduced emergence time. Better seed emergence through hydro-priming suggests that proper priming duration can improve optimum plant establishment of sorghum in the field. Rapid emergence of seedlings could lead to the production of vigorous plants [37].

Given that water, through interacting with all the components of natural landscape and being influenced by natural and man-made factors, is enriched by a wide gamut of various substances in gaseous, solid, and liquid states, this creates an enormous variability of natural water types from the perspective of their chemical composition [37]. In terms of varieties performance, Banidoka and CSM63E were the best in either hydro-primed in tepid water (25 °C) or heated water at 70 °C, followed by Saba-tienda mainly in tepid water (25 °C). With regards to priming duration in water heated at 70 °C, 30 min recorded the highest effect compared to other treatments on RVI and SDW.

Compared to the unprimed treatment (control), the germination percentage, germination time, germination rate index, seedling root index, and seedling dry weight increased considerably after sorghum seeds had been primed with different sources of water. The findings showed that the improvements of germination and seedling growth as expressed by all monitored parameters were reduced when soaked in rainwater for most of the parameters including RVI, SDW, etc. (Table 5, Table 8, and Table 9).

Natural water is a dynamic chemical system containing in its composition a complex group of gases, mineral organic substances in the form of true solutions, and suspended and colloidal matter as well [38]. The differences in their composition explain why sorghum seed priming with various sources/types of water differently influenced the seed germination performance. Indeed, after eight days, remarkable differences were observed for seed germination and seedling growth of CSM63E, Banidoka, Saba-tienda, and Seguifa. Germination and early seedling establishment are critical stages, which can affect both quality and seedling growth parameters [5]. This is suggesting some inhibition effect on seed and seedling growth parameters. Due to their imbibition in water solutions, seeds benefit from permanent and sufficient moisture thus take a short time to germinate; however, non-primed seeds have to obtain from soil moisture their imbibition, which may lead to longer time for their germination if soil moisture is not sufficient. This explains the increased germination performance with the hydro-priming technique [39].

It is evident that hydro-primed seeds exhibit activation of cellular defense responses, due to which they can better tolerate subsequent biotic or abiotic stresses in the field [39]. Seed priming enhances speed and uniformity of germination [21]. This can extend many biochemical modifications which are basically needed for starting germination process viz. dormancy breaking, hydrolysis, enzyme creation, and seed imbibition [39]. Thus, seed priming could contribute to facilitating emergence phage with vigorous root and shoot of sorghum which is very important at the beginning of the rainy season in the Sahelian zone. A deep and thick root system is helpful for extracting water from considerable depths [40]. Similar findings have been reported on the improved germination of sunflower cultivars through accelerated imbibition by seed priming [41].

Seed priming significantly increased a series of seedling performance parameters such as the GP, MGT, GRI, RVI, and SDW of sorghum. The improvement of these parameters might be due to the fact that the seeds soaked in water had rapid translocation of nutrients after hydrolysis of the cotyledon reserves to growing seedling. Additionally, primed seed known to be closely associated with their high imbibition rate and mtDNA damaged reparation, which could be the reason for the increased germination percentage. When compared with different sources of water, distilled, river, tap, and well water of all durations showed greater influence on final germination percentage seedling development. River and well water showed high influence on seed and seedling growth parameters suggesting favorable pH at germination [42]. During seed germination, various stored substrates are reactivated, repaired if damaged, and transformed into new building materials necessary for the initial growth of the embryo, its subsequent growth, and seedling establishment in its natural habitat [43].

The improvement in seed germination and seedling development due to seed priming treatment is in line with previous research work [5,31,44], and reported that both fresh and hot water primed seeds showed significant increase in germination performance.

As far as we know it is the first time in Mali that physicochemical composition of well water can boost sorghum seedling germination and development. The results show also that tepid hydro-priming treatment was comparatively superior to heated at 70 °C in root vigor index among all water sources applications. These findings are in agreement with previous studies [43,45,46]. Several researchers reported the positive effect of hydro-priming on seedling emergence rate, seedling establishment, early vigor, and the faster development of the seedling [47].

Various seed priming techniques using different sources of water, and either tepid or water heated at 70 °C can significantly improve seed germination and seedling plant development of sorghum varieties, although the overall response varied with the different sources of water, priming duration, and varieties. All the water sources improved seed germination and seedlings growth parameters compared to control, but well, distilled, river, and tap water were better than rainwater which suggest the presence of some element such as Cu and Zn which inhibits seed germination and growth (Table 4).

5. Conclusions

The results indicate that seed germination and various seedling growth parameters of sorghum varieties were improved by tepid water and hot hydro-priming with various water sources and under different priming durations. Tepid or hot water increased seed germination percentage, mean germination time, seedling growth rate, root vigor index, and seedling dry weight compared to the unprimed control seeds of all nine sorghum cultivars. Our results showed that hydro-priming in tepid or hot water shows to be a promising technique to improve seed germination and seedling growth parameters which needs to be confirmed in field trials. River and well water sources were the most promising sources in this study. The 8 h priming duration with fresh water is the most promising option, although seeds have to be immediately sown to benefit from the hydrated effect. The promising duration in hot water was 30 min which have significantly impacted germination percentage, mean germination time and germination rate index. When immediate sowing is possible, tepid or hot hydro-priming of sorghum seed is recommended as an effective way to reduce risk of crop failure regularly resulting from the unpredictable rainfall situation in Mali. The varieties Banidoka, CSM63E and Saba-tienda could be recommended in an integrated drought and heat management option for crop establishment failure in semi-arid zones of Mali and elsewhere.

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