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Optimisation of the seedball technology for sorghum production under nutrient limitations

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Abstract

The seedball technology is a simple and affordable seed-pelleting technique that uses locally available materials such as sand, loam, wood ash and seeds to enhance early crop establishment. It has been shown to be effective for pearl millet (*Pennisetum glaucum* (L.) R.Br.) subsistence production in Sahelian environments. The objective of this study was to optimise the seedball technology for sorghum (*Sorghum bicolor* (L.) Moench) under greenhouse conditions. Series of pot experiments were conducted in order to identify optimal size, seed number as well as nutrient content under low- and normal-soil phosphorus availability. The identified optimal seedball formula for sorghum is: 80 g sand + 50 g loam + 25 ml water + about 20 seeds. As maximum 1.5 g NPK mineral fertiliser can be added as nutrient compound. Compared to the control treatment, seedballs significantly improved root and shoot biomass variables as well as nutrient uptake of sorghum seedlings grown for 19 days. The lower the substrate P level, the better the biomass enhancement effect of seedballs, i.e. likely caused by nutrient availability. The next step is on-farm field testing under Sahelian conditions.

Keywords: staple cereal, Sahel, dry sowing, subsistence farming, local resources, seed coating, peasant farmers

1 Introduction

Early seasonal drought arising i.a. from climate change (Ndehedehe *et al.*, 2020) and low chemical soil fertility in particular down to 0.2 m soil depth (Adams *et al.*, 2020) are the major challenges restricting crop yield in the Sahel region. These factors lead to poor establishment of cereal seedlings and in turn low panicle yield. However, early seedling enhancement in chemically infertile soil is a pre-requisite for high panicle yield. E.g., Sebnie *et al.* (2020) reported a yield increase of > 120 % when sorghum (*Sorghum bicolor* (L.) Moench) seeds were micro-dosed with 30.75 kg N and 34.5 kg P_2O_5 ha^{-1} commercial mineral fertiliser (NPK). In the context of Sahelian smallholder sorghum farmers, however, micro-dosing is hardly affordable due to lack of financial resources or non-functioning markets to acquire commercial fertilisers. Therefore, urgently needed is a cheap and effective innovation; seedball technology might be such a technology.

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The seedball technology is a local resource-based pelleting technique that combines sand, loam, seeds, and optionally nutrient additives such as wood ash or NPK to enhance seedling establishment under poor soil conditions (Nwankwo & Herrmann, 2018). The technology was mechanically (size, seed location) and chemically (nutrient content, osmotic effect) optimised for West African Sahelian (WAS) subsistence pearl millet production (Nwankwo *et al.*, 2018). Relative to conventional sowing, the seedball technology increased root and shoot systems in greenhouse and field trials. Since sorghum and pearl millet are the major staples produced by the WAS smallholder farmers, transferring the seedball technology to sorghum was frequently requested by farmers who made favourable experiences with that technology in pearl millet.

Consequently, the aim of this study was to optimise the seedball technology for Sahelian subsistence sorghum farming i.e., under low chemical soil fertility in sandy soils (Arenosols, acc. IUSS 2014). The primary objective was to enhance early biomass (dry matter, height) development and nutrient uptake. Therefore, we hypothesised that – compared to conventional sowing – the seedball technology (i) does

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not prohibit sorghum seedlings emergence if properly optimised with respect to physical and chemical properties, (ii) increases shoot and root biomass during the first three weeks after sowing, and (iii) enhances shoot phosphorus (P), potassium (K) and magnesium (Mg) uptake during this early growth stage.

2 Materials and method

Several greenhouse experiments were conducted at the University of Hohenheim, Germany. First, germination experiments of improved and local variety seed lots were conducted. They were followed by mechanical (seedball size) and chemical (nutrient content) optimisation of the seedball technology in pot experiments. This study reports the key findings in chronological order with later experiments depending on the previous findings.

2.1 Seed germination test and materials preparation

The objective of seed lot pre-germination test was to ensure that viable seeds were used in this study. Indigenous local (called *Mota Maradi*) and improved sorghum (called *IRAT-204*) seed lots collected from Maradi region, Niger Republic were used for this study. The thousand grain weight (TGW) of the improved and local seed varieties were 14.2 and 20.0 g, respectively. Germination tests of the seed lots were conducted in petri-dishes (90 mm diameter, 20 mm height) using Whatman™ filter papers. Eight petri-dishes for each variety were filled with 50 randomly selected seeds, saturated with distilled water and placed in a germination chamber. The chamber was set to an average temperature of 30 °C and a relative humidity of 58 %. Day and night cycles of 10 h and 14 h were set. Seed germination count was observed on the 9^{th} day.

Sand was collected from Rastatt (48°49' N, 8°11' E) in Germany. The physical and chemical properties of this soil were reported by Nwankwo *et al.*, (2018). Another so-called quartz-sand was obtained from Fritz Lutz GmbH, Germany. It contained 2 wt. % coarse sand, 60 wt. % medium sand and 38 wt. % fine sand. Based on soil P content, two levels of substrate were used – **normal**- and **low-P** substrates; these terms will be used in this report in the following.

The **normal-P** substrate represents sandy soil from Rastatt. It is characterised by > 90 wt % sand, an electrical conductivity ($EC_{1:20}$) of 23.45 $\mu S\,cm^{-1}$ a $pH_{1:20\,H2O}$ of 4.96, an organic carbon to total nitrogen ratio (C:N) of 18 and 9.8 $g\,kg^{-1}$ C_{org}. The exchangeable cations as extracted by ammonium acetate in $g\,kg^{-1}$. were 8.24 Ca, 0.63 K, 0.18 Na and 0.77 Mg. The plant available P as extracted by the Bray 1 method was 33 $mg\,kg^{-1}$.

The **low-P** substrate represents a mixture of Rastatt soil and 'quartz-sand' in the ratio of 1 to 4, respectively. The reason for the substrate mixture was to decrease the substrate P content in order to mimic the typical nutrient status, usually $< 8\,mg\,kg^{-1}$, of WAS soil as reported by Manu *et al.* (1991). The used **low-P** substrate is characterised by > 95 wt. % sand, an $EC_{1:20}$ of 17.98 $\mu S\,cm^{-1}$, a $pH_{1:20\,H2O}$ of 5.74 and 0.31 $g\,kg^{-1}$ C_{org}. Its exchangeable cations as extracted by ammonium acetate in $g\,kg^{-1}$ were 0.93 Ca, 0.55 K, 0.22 Na and 0.26 Mg.

Before use, these two substrates were sieved through a 2 mm mesh to remove undesired materials. Sand as seedball material was collected from the **low-P** substrate. Loam was collected from the subsoil of a field called *"Goldener Acker"* located at the University of Hohenheim, Germany. The germination prohibition effect of urea or ammonium fertilisers as nutrient additives in seedball is known (Nwankwo *et al.*, 2018); this was considered while selecting additives. NPK 15:15:15 was used. It had about 3 mm granular size and < 2 % water.

2.2 Experiment 1: Physical seedball optimisation

The objective of the physical optimisation was to identify the right seedball diameter that does not hinder sorghum seedling emergence. Seedballs were formed with varying amounts of sorghum seeds (5 and 8 seeds per seedball) at varying diameter sizes (2 and 3 cm). A mixture of 80 g sand, 50 g loam and 25 ml water was used for seedball variants formation. Seeds were randomly placed. The formed seedballs were air-dried within < 24 hours to avoid unwanted germination. Two treatments: (i) control i.e., uncoated sorghum seeds and (ii) seedball at different levels of diameter size and seed content were compared. Seedling emergence tests were conducted in trays of 70 cm × 45 cm × 6 cm length, width, and height, respectively, at a spacing of 4.5 cm × 7 cm and a sowing depth of about 2 cm underneath the substrate surface. Per tray 28 seedballs were sown in eight repetitions.

Low-P substrate was used in this study. Soil moisture of 60 % field capacity was adjusted in the germination trays every 24 h throughout. The soil density was 1.6 $g\,cm^{-3}$. Average day and night temperatures of 32.6 and 19.6 °C, respectively were recorded. The day and night relative humidity were 48.2 and 70.1 %, respectively. Germination count was made 10 days after planting (DAP).

2.3 Experiment 2: Chemical seedball optimisation

The objective of the chemical optimisation was to identify the maximal nutrient content that enhances shoot and root biomass production without suppressing seedling emergence. Seedball was formed from a mixture of 80 g sand,

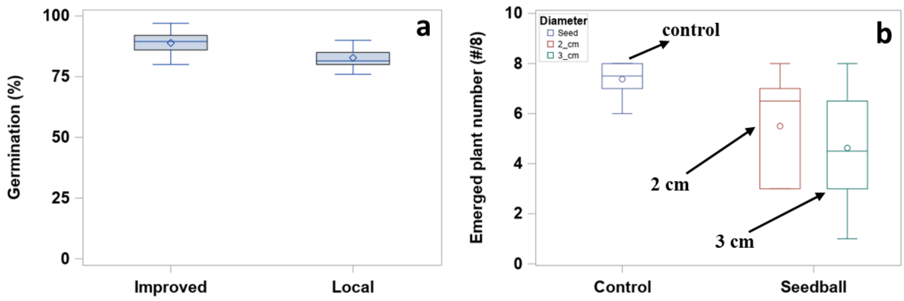

Fig. 1: *Germination tests of (a) sorghum seed lots and (b) conventional sowing versus seedballs 10 days after planting. The local seed lot was used in the seedball emergence test (b). Control = farmer practice i.e., non-fertilised sorghum; Seedball = seedballs made from a mixture of 80 g sand + 50 g loam + 25 ml water and sorghum seeds. Circular dots in the box plots show arithmetic means.*

50 g loam, 1.5 g NPK and 25 ml water. Therefore, two treatments: (i) the control i.e., uncoated sorghum seedlings and (ii) seedball i.e., seedball + 1.5 g NPK were compared. Nutrient level was introduced as a factor at two levels – **low-** and **normal-P** substrates. In order to mimic the Sahelian local farming system, the local seed variety was used for the study. Seedballs of about 3 cm diameter size containing 5 seeds each were used. The observed average greenhouse temperature readings were 31.6 °C day and 19.3 °C night temperatures. In four repetitions, the average relative humidity of 56 % was observed throughout the 19 days study.

At harvest, one-time measurements of leaf count, shoot height, shoot biomass, root length, root biomass and root diameter were taken. Height and biomass measurements were made using meter-rule and weigh balance, respectively. Roots were stored in 50 % ethanol for two weeks after biomass measurement. Root images were then taken with EPSON Perfection V700 PHOTO dual lens scanner. Using these images, root length and diameter were measured using WinRhizo® V2009c software (Regent Instruments, Nepean, Canada).

After seedling harvest, P, K and Mg shoot contents were measured from grinded pooled shoot samples. Concentrated HNO_3 and H_2O_2 solutions were used in a ratio of 2:1 to digest the plant samples for 10 minutes, applying 50 Watts in a ventilated microwave (MLS 1200 mega, Leutkirch, Germany). K and Mg were measured with a Microwave Plasma-Atomic Emission Spectrometer (MP-AES 4100, Agilent, Waldbronn, Germany). P was measured with the molybdenum blue method using a (Varian, Cary 50) spectrophotometer at 710 nm wavelength.

2.4 *Statistical analyses*

In both experiments, the germination pots were arranged in a complete randomised block design. All collected data were first cleaned and tested for uniformity; variance homogeneity and distribution were tested using Shapiro-Wilk test. For unevenly distributed data, Welch's one-way analysis of variance was performed using Proc GLM. Treatment means were compared for significant differences. We present results as treatment means (± standard deviations) in tables and box plots. All statistical analyses and plotted graphs were performed with SAS version 9.4.

3 Results

3.1 *Germination test, physical and chemical seedball optimisation*

The germination percentage was 82 and 86 % for local and improved seed lot varieties (Fig. 1a), respectively. Therefore, the used sorghum seed lots were considered viable for this study.

Seedballs do not reduce seedling emergence in sorghum to a rate that would need a management response by the farmer. At 2 and 3 cm seedball diameter size, about 4-5 out of 8 seeds per seedball emerged (Fig.1b). Since the germination count difference was not significant, the 3 cm diameter size was considered for further experiments since it allows to store more nutrients i.e., the factor that enhances most early seedling performance.

The seedball treatment significantly increased sorghum height in low (by 100 %) and normal-P (by 39 %) substrate (Fig. 2a), compared to the control. Seedball seedlings developed always more than three leaves per plant, which was not the case for the control treatment under low-P conditions (Fig. 2b). In addition, the seedball treatment relatively increased shoot biomass by 356 and 169 % under low and normal P-levels, respectively (Fig. 2c). Concerning all these biomass parameters, it is evident that the effect of seedballs is always greater for the low P-substrate. So, here the response structure registered in previous studies for pearl millet is confirmed (Nwankwo *et al.*, 2018). It appears that plants need to invest relatively less in root biomass when

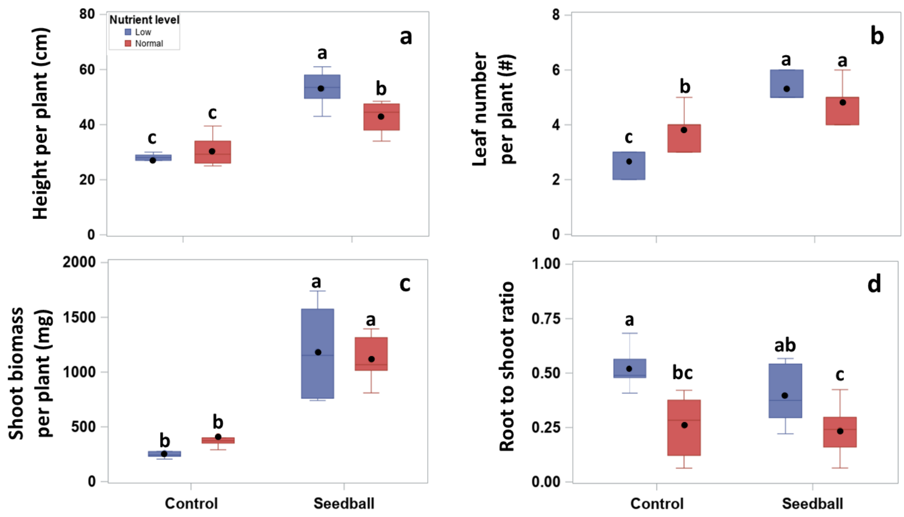

Fig. 2: *Sorghum (a) height (b) leaf number (c) shoot biomass, and (d) root to shoot biomass ratio 19 days after planting for control and seedball treatments (n = 6) at low and normal nutrient levels. Control = farmer practice i.e., non-fertilised sorghum; Seedball = about 3.0 cm diameter sized-seedball that contained 5 seeds made from a basic mixture of 80 g sand + 50 g loam + 25 ml water and 1.5 g NPK 15:15:15 mineral fertiliser. Circular dots in the box plots show arithmetic means, different letters indicate significance (Tukey test at 5 % level).*

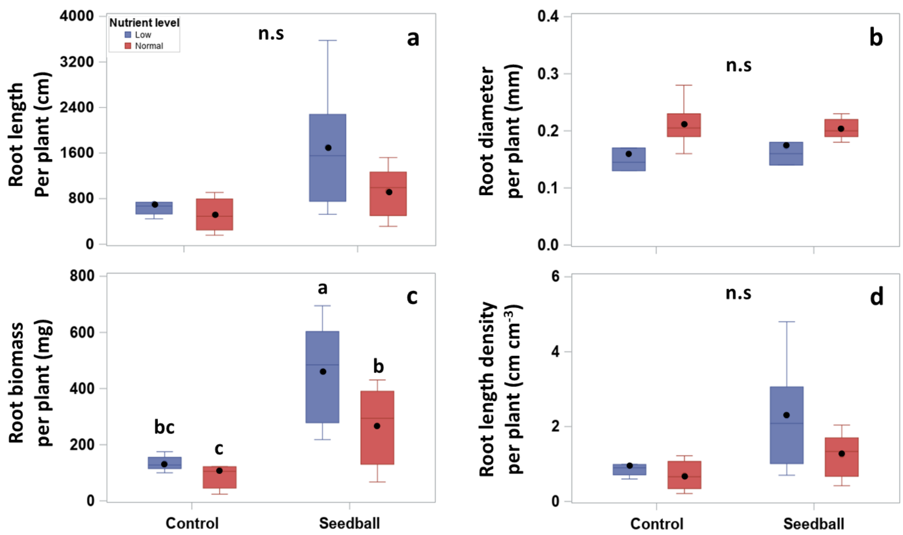

Fig. 3: *Sorghum root (a) length (b) diameter (c) biomass and (d) length density 19 days after planting for control and seedball treatments (n = 6) at low and normal P-nutrient levels. Control = farmer practice i.e., non-fertilised sorghum; Seedball = about 3.0 cm diameter sized-seedball that contained 5 seeds, made from a basic mixture of 80 g sand + 50 g loam + 25 ml water and 1.5 g NPK 15:15:15 mineral fertiliser. Circular dots in the box plots show arithmetic means, n.s. indicates no difference whereas different letters indicate significance (Tukey test at 5 % level).*

supported by seedballs and can use more of the reserves for aboveground biomass production instead (Fig. 2d).

Comparing the mean values of root length, diameter and length density did not yield statistically significant differences. However, this does not mean that there was no treatment effect. Seedballs increased both root length and length density by > 80 % in low-P soil if compared to the control (Fig. 3a and d). It seems that under low-P conditions the plant favours to develop a finer and more extended root system, since root diameter is lower but length is higher (Fig. 3a and b).

In contrast to the other root variables, root biomass was significantly influenced by treatment. Compared to the control, the seedball technology increased root biomass by 246 and 144 % in low and normal-P substrate, respectively (Fig. 3c). However, it is worth noting that the seedball treatment

Table 1: *Nutrient uptake by sorghum in the above ground biomass as affected by treatment (n=6) 19 days after sowing at the greenhouse of University of Hohenheim, Germany.*

Treatment	*Control*		*Seedball*	
Shoot nutrient uptake (mg pot^{-1})	*Low-P substrate*	*Normal-P substrate*	*Low-P substrate*	*Normal-P substrate*
Phosphorus (P)	0.11^{c} (0.02)	0.20^{c}(0.07)	0.71^{b} (0.25)	1.37^{a}(0.26)
Magnesium (Mg)	0.51^{c} (0.11)	0.65^{c}(0.22)	3.74^{a}(1.30)	2.77^{b}(0.53)
Potassium (K)	7.18^{b}(1.55)	11.23^{b}(3.88)	50.99^{a}(17.73)	40.68^{a}(7.79)

Control = farmer practice i.e., non-fertilised sorghum; Seedball = about 3.0 cm diameter sized-seedball made from a mixture of 80 g sand + 50 g loam + 25 ml water and 1.5 g NPK 15:15:15 mineral fertiliser. Values show arithmetic means and standard deviations in brackets, different letters indicate significance (Tukey test at 5 % level).

showed a high standard deviation not only with respect to the biomass but also with respect to root length (Fig. 3a), and root length density (Fig. 3d).

Treatments did not greatly influence shoot nutrient contents (data not shown). This indicates that the plant biomass production is mainly determined by available nutrients i.e., the plant produces biomass as long as an internally equilibrated nutrient content can be secured. Total nutrient uptake, however, was significantly higher in seedball treatments (Tab. 1). Not much variation was noticed in between substrates with different P-status as far as the control treatments are concerned. The highest P-uptake was observed in the seedball treatment at normal soil P-level showing the important role of P-nutrition. Sorghum grabs phosphorus where it can reach it. In contrary, Mg- and K-uptake was highest in the seedball treatment applied in low-P-substrate. Under low P, the root length density is increased. Due to the greater surface more Mg and K is taken up since it is taken up by convection.

4 Discussion: are sorghum seedballs a viable technology for subsistence farmers in the Sahel?

In general, the response structure of sorghum seedballs is similar to what is known from the technology application to pearl millet (Nwankwo, 2019). When sufficient viable seeds (5-8 per seedball) of sorghum are coated with local materials (sand, loam), germination as well as seedlings emergence is slightly retarded and germ number slightly reduced. However, these effects are not that strong that they would pose a problem to subsistence farmers in the Sahel. The germ number is still high enough that single plants will survive in seed pockets even after strong storm events as they often happen in the Sahel and are reported to damage the soft seedlings (Michels *et al*., 1995).

The standard seedball dough as it was developed for pearl millet (Nwankwo *et al*., 2018); a mixture of 80 g sand, 50 g loam and 25 ml water is also applicable to sorghum. It provides a compromise between local availability of resources, physical stability, and good germination conditions. Since the size of sorghum grains is larger than for pearl millet, the seedball diameter was adapted to 3 cm. The negative side of the larger volume is that more resources are needed, and this means for the farmer larger transport capacities to fetch the resources and to transport the seedballs to the field (about 10,000 are needed for 1 ha if planting distance is 1 m × 1 m). With regard to sowing depth, the application conditions as they were developed for pearl millet also apply to sorghum, i.e. 3 cm sowing depth. Though it was reported that sorghum seedlings may emerge from a depth of 35 cm (Carter, 1990), an increase in sowing depth will reduce the emergence rates.

In contrast to the pearl millet experience (Nwankwo *et al*., 2018), slightly higher amounts of nutrients can be added to the standard recipe i.e., 1.5 g NPK. Together with the larger seedball volume, about 200 % more NPK is applied to the single sowing pocket in comparison to the pearl millet variant. Sorghum seems to tolerate slightly higher osmotic pressure conditions. This is also indicated by the fact that sorghum can be sown on slightly saline soil (Daniells *et al*., 2001). Moradi & Younesi (2009) reported that sorghum germination and emergence rates were reduced at seed priming-induced osmotic potential of -1.5 with polyethylene glycol compared to control with distilled water.

The total nutrient uptake data indicate that the enhancement effect of the seedball technology on shoot height, leaf number, root length and consequently biomass 19 DAP is most likely caused by early nutrient supply and uptake. One here consistently observed effect of the nutrient supply is the shift of the root to shoot biomass ratio. It appears that germs well supplied with nutrients do invest less into the root system; the control of the low-P substrate showed the highest root to shoot ratio (Fig. 2d). Sebnie *et al*., (2020) reported that improved root and shoot variables in sorghum are often associated with nutrient supply. Also leaf number per plant was increased in sorghum if organic manure and thus nutrients were applied (Harris 1996). However, nutrients could also be applied using the micro-dosing technology (Aune& Ousman 2011) that appears less time and resource demanding, though it is worth discussing to which level nutrient amendments can still be denoted as micro-dosing. The arguments in favour of the seedball technology are the seed protection against predators, less seed wastage due to a lower seed number per pocket, the option for dry sowing, and less risk with respect to germination rates and loss of investment, since in the case of micro-dosing farmers' practice is often to mix seeds and fertiliser, and under water stress conditions then germination rates are low due to osmotic pressure effects.

P and Mg shoot contents of the sorghum seedlings in our study fall within the range observed by Doumbia *et al*., (1998) for 19 days old sorghum from field fertilisation trials. Nutrients play a vital role in drought resistance. Phosphorus was reported to improve root hydraulic conductivity in sorghum under water stress (Shangguan *et al*., 2005) as well as root and shoot biomass variables (Al-Karaki *et al*., 1995). K nutrient supply increased drought resistance as well as grain yield in sorghum (Asgharipour & Heidari, 2011). These findings indicate that sorghum plants with higher P and K content are more drought tolerant and have a greater chance to recover from early dry spells as often observed in the Sahel (Ndehedehe *et al*., 2020).

In the Sahel, where the available soil P-content can be as low as $1\,\mathrm{mg\,kg^{-1}}$ in some sites (Manu *et al*., 1991), seedballs with wood ash as P-source can be an alternative to local farmers who do not have access to mineral fertiliser due to market failure. However, as the nutrient uptake data show, the nutrient effect of seedballs is restricted to the first two to three weeks. After successful crop establishment, the farmers can then apply any kind of fertiliser (e.g. organic manure, composts, animal/human urine) as post-emergence practice to ensure continuity of crop performance.

5 Conclusions and recommendations

The results show that a transfer of the existing pearl millet seedball technology to sorghum is possible. In rural Sahelian villages the resources for seedball production are freely available, including the nutrient additive wood ash. Compared to micro-dosing less fertiliser is necessary, and thus the risk of loss on investment is lower. In addition, seedballs offer protection against predators and reduce the necessary seed amount. Massive production of sorghum seedballs (about $250\,\mathrm{kg\,ha^{-1}}$), however, can be a challenge to the local producers due to transport and time demand. Producing the seedballs prior to the season when alternative occupation is rare, may help manage this challenge. Confirming our hypotheses, seedballs (i) do not reduce sorghum seedling emergence to a critical degree (ii) increase shoot as well as root biomass, and (iii) enhance shoot P, K and Mg uptake in chemically infertile soils. The seedball performance is mainly due to its added nutrient content. The perspective is that sorghum seedballs can work also in the farmer environment if applied to soils with low – in particular with respect to P – nutrient status. Therefore, the technology should be tested under Sahelian on-farm conditions, where P-deficiency prevails i.e., sandy soils (Arenosols according to IUSS 2014).

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Conflict of interest

The authors declare that they have no conflict of interest.

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