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Physical and chemical optimisation of the seedball technology addressing pearl millet under Sahelian conditions

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Abstract

This study deals with the development of the seedball technology in particular for dry sowing under Sahelian conditions and pearl millet as crop. At first, our participatory evaluation in Senegal showed that (i) local materials needed for seedball production are locally available, (ii) the technology conforms to the existing management systems in the Sahel, and (iii) socio-economic conditions do not hinder seedball adoption. Afterwards, seedball was mechanically and chemically optimised. Pearl millet seedlings derived from the seedball variants were grown and compared to the control under greenhouse conditions. Our results showed that the combination of 80 g sand + 50 g loam + 25 ml water is the standard seedball dough, which produces about ten 2 cm diameter-sized seedballs. Either 1 g NPK fertiliser or 3 g wood ash can be added as nutrient additive to enhance early biomass of pearl millet seedlings. Ammonium fertiliser, urea and gum arabic as seedball components hampered seedlings emergence. Seedball + 3 g wood ash and seedball + 1 g NPK-treatments enhanced shoot biomass by 60 % and 75 %, root biomass by 36 % and 94 %, and root length density by 14 % and 28 %, respectively, relative to the control. Shoot nutrient content was not greatly influenced by treatment. However, multiplying biomass yield with nutrient content indicates that nutrient extraction was higher in nutrient-amended seedballs. On-station field tests in Senegal showed over 95 % emergence under real Sahelian conditions. Since early seedlings enhancement is decisive for pearl millet panicle yield under the Sahelian conditions, on-farm trials in the Sahel are recommended.

Keywords: Pearl millet early growth, seedball technology, local resources, dry sowing, seedling emergence, subsistence farming, smallholder farmer, cheap seed pelleting technique

1 Introduction

Under Sahelian conditions, seedling establishment is a major yield factor in pearl millet (*Pennisetum glaucum* [L.] R. Br.) production systems (Rebafka, 1993). This fact, apart from low seed quality and limited water supply, is mainly explained by low chemical fertility (Valluru *et al.*, 2010) of the widespread sandy soils (Arenosols according to the World Reference Base for soil resources – WRB; IUSS, 2014). Arenosols are characterised by low phosphorus (Rebafka, 1993; Muehlig-Versen *et al.*, 2003), nitrogen and organic matter content (Bationo & Buerkert, 2001). Unfortunately, the improvement of seedling establishment through seed coating (Rebafka *et al.*, 1993; Karanam & Vadez, 2010) and the application of commercial mineral fertiliser (NPK) (Bationo *et al.*, 1993; Bationo & Ntare, 2000; Bationo & Buerkert, 2001; Aune & Ousman, 2011; El-Lattief, 2011) is hardly feasible for smallholder farmers. This is due to lack of skills and financial resources (van der Pol & Traore, 1993; Cooper *et al.*, 2008), as well as lacking infrastructure.

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In the Sahel, farmers partly practice dry sowing with uncoated seeds to optimally use the vegetative period in order to ensure higher yield (Bationo & Buerkert, 2001). However, uncoated seeds bear high risks of loss through predation and early season droughts. In contrast, seed coating has the potential to improve seedling establishment. E.g., it mitigates high seed size variation when lack of uniformity poses challenges (Peske & Novembre, 2011), controls seed predation (Overdyck *et al.*, 2013), and ensures early nutrient supply (Rebafka *et al.*, 1993; Karanam & Vadez, 2010). Small seeded species have more advantages from seed coating relative to large seeds due to nutrient addition through the coating materials. Pearl millet is such a crop, having 7–10 mg weight per seed (Rebafka *et al.*, 1993), only.

The seedball technology, invented by Fukuoka (1978) in the frame of the permaculture concept, was introduced to improve rice seedling establishment under dry sowing conditions. It has been used in Australia for rangeland improvement (Atkinson & Atkinson, 2003). Apart, hardly any research ever addressed this technology. It combines local materials such as sand, loam and seeds. Other additives such as nutrients or pesticides can potentially be added, depending on local needs. NPK, organic compost (Badiane *et al.*, 2001) and wood ash (Saarsalmi *et al.*, 2012) can play significant roles in increasing the nutrient supply of plants. E.g., wood ash can serve the dual function of P nutrient release and low soil pH amelioration (Nkana *et al.*, 2002). These materials can be incorporated into the seedball coating materials as additives, addressing the often observed soil-related plant growth limitations in the Sahel (Herrmann *et al.*, 1994). However, their content needs to be optimised in order to avoid any effects that hinder seed germination, e.g. through high osmotic pressure.

The low reserve of 20 µg P per seed (Rebafka *et al.*, 1993) qualifies the pearl millet crop for nutrient supplementation at emergence. Pearl millet seeds have been successfully coated (Rebafka *et al.*, 1993; Karanam & Vadez, 2010; Peske & Novembre, 2011). However, a technology is lacking that is based on local resources and affordable to subsistence farmers in the Sahel. Therefore, the present study describes the development of the seedball technology for Sahelian subsistence pearl millet production systems and its potential for seedling improvement under poor soil conditions. The main objectives of this study were to physically (materials, size) and chemically (nutrients, osmotic pressure) optimise seedballs in order to improve early seedling performance (biomass, nutrient content) and prepare on-site testing.

2 Materials and methods

A participatory discussion with farmers in Louga, Senegal on coating pearl millet seeds with local materials and five greenhouse experiments are reported. The greenhouse experiments were conducted at the University of Hohenheim, Germany and at ISRA experimental station in Bambey, Senegal. We report here only the key methodologies and findings. The presentation is chronological, with later experimental layouts depending on the previous results.

2.1 *Participatory approach on seedball testing and adoption in the Sahel*

In Louga, Senegal, a participatory study was conducted with the Louga federation of farmers associations (FAPAL: *Fédération des Associations Paysannes de Louga*) for a period of four weeks. A workshop on seedball production was carried out to practically demonstrate to the farmers, how seedballs are produced. Sand, loam, water, and seeds were used as basic constituents, wood ash and animal dung as nutrient additives, charcoal and termite soil as conditioner, and chili pepper (*Capsicum annuum*) as repellent. Doughs were formed from gravimetric mixtures of these materials. Afterwards, seedballs of about 2 cm diameter size were handmade and dried in < 24 hours (h) to avoid unwanted germination. Every step taken in seedball production was carefully explained to farmers. Expert interviews, based on social status and gender, were conducted in Wolof language with the help of a translator. Data on the cultivation methods and management norms in the intervention zone Louga, as well as on the potential benefits and limitations of seedballs, were collected. An open-discussion class that allowed the farmers to freely interact about seedball was conducted. The opinions and perceptions of the farmers on seedball usage and applicability were evaluated. 20 female and 25 male farmers participated in this study.

The qualitative outcomes of our participatory study clearly indicated that the materials necessary for seedball production are freely available in the farm households, i.e. wood ash, charcoal, animal dung, sand as well as seeds and water. Loam and termite soil can be sought less than 4 km away from the settlements. Seedball sowing appeared to be simple using the “*drop-and-match*” technique in particular in the predominant sandy fields. Farmers stated that seed wastage could be minimised since a known number of seeds is inserted into the seedballs. As a compromise, seedball development (mechanical as well as chemical optimisation) using these farmers’ affordable local recourses became a main task.

2.2 Seed pre-germination test and material preparation

Local seed varieties collected from the Bambey area, Senegal were used for this study. Seed quality plays a vital role in crop establishment. Thus, checking the viability of any seed lot through a germination test is essential (Meyer & Schmid, 1999). Germination tests for the available seeds were conducted as reported by Throneberry & Smith (1955), but slightly modified. Fifty seeds were randomly selected from the seed lot and placed into 9.0 cm diameter by 1.8 cm height petri-dishes, each, in 12 repetitions. Whatman™ filter paper, 47 mm diameter was soaked in distilled water up to saturation. The water-saturated filter papers were placed into the petri-dishes and, after seed addition, inside a germination chamber. The germination conditions were set at 29.4 °C average temperature, 62 % relative humidity and 12 h / 12 h day/night cycle. On the 7th day, the germinated seeds were counted for each petri-dish.

Cheap and potentially locally available materials such as sand, organic compost, charcoal, animal manure, cattle urine and wood ash were identified as potential seedball components. NPK in minute quantity as a non-local resource was identified, too. The “local materials” used were classified into three groups: matrix, fillers and nutrient additives. Sand was used as matrix since it mimics the major soil property and is available everywhere, where millet is cropped in the Sahel. Loam, gum arabic and termite soil served as potential fillers. Loam is frequently available for free at least in Sahelian subsoils and characterised by higher cation exchange capacity relative to sand (Lorenz, 1999). Compost, charcoal, sheep and goat dung, cattle urine, wood ash and NPK as well as calcium nitrate tetrahydrate (CNT) served as potential nutrient additives. All materials, except urine and CNT, were air-dried at ambient temperature as well as hand-crushed or grinded with a mortar where necessary. Afterwards, these materials were sieved through a 2 mm mesh to remove over-sized particles.

2.3 Laboratory analyses

The pH, electrical conductivity, soluble cations, total P and N as well as organic carbon (C) were measured in all the tested seedball materials, except gum arabic. The pH of the materials was measured using a glass electrode pH-meter (1 : 20 H_2O). Electrical conductivity (1 : 20 H_2O) was measured using a portable electrical conductivity meter, Model 3320 obtained from Xylem Analytics Germany Sales GmbH & Co. KG, Germany (www.wtw.com). Water soluble cations (1 : 20 ratio wt. / wt.) – Ca, K and Na were photometrically measured using an Elex 6361 flame photometer (Eppendorf, Hamburg, Germany). Water-soluble magnesium (Mg) was measured with a Perkin-Elmer Model 3100 AAS PerkinElmer, Norwalk, CT, USA. Total C and N were measured from finely ground sample materials using VarioMacro EL instrument (Elementar, Hanau, Germany). Plant available P was extracted with calcium acetate lactate and determined colometrically based on the molybdenum blue method (Rodriguez *et al.*, 1994). It was measured with a Cary 50 UV-Visible Spectrophotometer (Varian, Mulgrave, Australia) at 710 nm wavelength.

In addition, the shoot P, Mg and K contents were measured in pearl millet seedlings after harvest. Finely ground shoot samples were digested with a HNO_3/H_2O_2 solution (10 minutes, 105 °C temperature, ventilated) in a microwave (MLS 1200 mega, Leutkirch, Germany). Afterwards, the extract was filtered using blueband filter paper. For K and Mg content determination, 25 ml from the filtrate was transferred to 50 ml volumetric flask and after, filled to 50 ml mark with distilled water. For P determination, 10 ml of the extract was mixed with 8 ml of John solution in a 50 ml volumetric flask that was then filled to the 50 ml mark with distilled water. Nutrients in the solution were measured as described above.

Table 1: *Chemical properties of the seedball components and nutrient additives used in this study.*

Component	$pH_{1:20\,H_2O}$	$EC_{1:20}$ ($\mu S\,cm^{-1}$)	C_{org} (%)	C : N
Loam	5.9	11	0.8	12
Charcoal	8.1	143	78.9	114
Manure	8.3	2560	32.3	19
Termite soil	8.3	55	0.1	7
Wood ash	11.6	8430	1.1	35
Mineral fertiliser	4.8	5160	0.3	–

Table 2: *Total nitrogen and phosphorus as well as the cation content of wood ash and mineral fertiliser used in this study.*

Content ($mg\,kg^{-1}$)	*Wood ash*	*Mineral fertiliser*
N_{total}	326	151,100
P_{total}	1880	67,200
K^+	65,100	152 500
Ca^{2+}	683	27,500
Mg^{2+}	860	7430
Na^+	2190	2470

2.4 Experiment 1: Mechanical optimisation of seedballs

Seed germination is often related to sowing depth (Chen & Maun, 1999; Benvenuti *et al.*, 2001). Shallow sowing depth stimulates more germination than surface placement (Benvenuti *et al.*, 2001). A sowing depth of 2–4 cm is considered optimum for the emergence of *Calligonum* L. species (Ren *et al.*, 2002). This depth is exactly applicable for pearl millet seeds with similar seed size. Bearing this in mind, two major factors: the (i) diameter of the seedball and (ii) location of seeds inside the seedballs, were considered during the seedball development. Where sowing depth is influential, seeds emerging from higher diameter seedballs or the core centre of seedballs might differ from those emerging from near the seedball's surface. On the other hand, randomised seed placement distributes germination failure risk and eases production.

The reason behind the mechanical optimisation is to determine the optimum seedball diameter and the best seed placement position that will not hamper seedlings emergence. In addition, an ideal seedball, after drying, will not break when dropped from about 2 m above the soil surface, i.e. the height when sown by an adult person.

The first part of the mechanical optimisation study was conducted at ISRA/CNRA research station, Bambey, Senegal, to observe seedling (i) emergence and (ii) development. Sandy topsoil material and loam were collected from an uncultivated area inside the station. These materials were prepared as described in section 2.2 (see above). Loam, termite mound material, and gum arabic were separately and permutatively combined with sand. Each combination was mixed with water to point of dough formation. Seedballs were manually moulded from the dough. The seedballs were of four different diameters: 1.0, 1.5, 2.0, 2.5, and 3.0 cm. Afterwards, they were dried under ambient temperature (25–30 °C). For the seedling emergence experiment, seven treatments were tested: (i) conventional sowing without seedballs served as absolute control. Otherwise NPK- and wood ash-amended seedballs of random and central seed placement formed from 80 g sand + 50 g loam + 25 ml water and 1–3 cm diameter range served as seedball treatments, labelled as (ii) Sball+3gAsh+1cmdiam, (iii) Sball+3gAsh+2cmdiam, (iv) Sball+3gAsh+3cmdiam, (v) Sball+1gNPK+1cmdiam, (vi) Sball+1gNPK+2cmdiam, and (vii) Sball+1gNPK+3cmdiam. Each seedball contained 15 seeds, placed in two different positions: (i) random and (ii) central placement. Number of repetitions was 6. Seedlings emergence, only, was counted on the 7th day after planting (DAP).

The second part of the mechanical optimisation study assessed pearl millet seedling height development, only. Three diameters (1.0, 2.0 and 2.5 cm) and six treatments were tested: (i) conventional sowing as absolute control, (ii) seedballs without amendments and amended ones with (iii) charcoal (Sball+30gCha), (iv) compost (Sball+30mlComp), (v) animal manure (Sball+4gMan) and (vi) termite soil (Sball+30gTerm). Each seedball contained 6 seeds. Number of repetitions was 6. Seedlings height and leaf development were measured on the 9th DAP.

Day and night temperatures of 36 and 23 °C respectively, were observed in the greenhouse throughout the emergence period. Seedballs were sown with the physical centre at 3.0 cm depth, i.e. approximately the depth at which pearl millet is sown by farmers. Each experimental unit consisted of a black 2-liter polyethylene bag, filled with sand at a bulk density of 1.6 g cm^{-3}. Each treatment was repeated six times in a completely randomised design. Soil moisture of 60 % field capacity was adjusted in each experimental unit every 24 h throughout the experiment.

2.5 *Experiment 2: Chemical optimisation of seedballs*

The objective of seedball chemical optimisation was to identify the optimum contents of seedball additives that conserve germination rates and at the same time enhance biomass development. Charcoal, wood ash, termite soil and gum arabic collected nearby Bambey, Senegal were tested as seedball additives. The experimental conditions (temperature, soil water content, sand-substrate, bulk density and germination bags) were same as in the mechanical optimisation. This study concentrated on wood ash, CNT and exclusively NPK fertiliser as nutrient additives. The intention was to optimise the nutrient content in a way that negative osmotic effects are avoided but maximum nutrient amounts incorporated into the seedball.

In the first part of the chemical optimisation study, only the seedlings emergence was assessed. Wood ash, cattle urine, charcoal and NPK served as nutrient additives. NPK 17 : 17 : 17, manufactured by Green Partners International GmbH & Co. KG, Germany was used. It contained 4.1 %, 4.8 % and 8.1 % ammonium, nitrate and carbamide N, respectively. So-called quartz sand, i.e. sieved alluvial sand from SW-Germany, was used as growth medium. It contained 2 wt. % coarse sand (630–2000 µm), 60 wt. % medium sand (200–630 µm) and 38 wt. % fine sand (63–200 µm). The intention to use this sand was to mimic the sandy soil textures as reported to be typical for Sahelian pearl millet sites by Hebel (1995). The loam for seedball production was collected from the subsoil of a field called "Goldener Acker" located at the University campus of Hohenheim, Germany. According to WRB classification system, the reference soil group there is a Luvisol. Wood ash, cattle urine, charcoal and NPK were added in variable quantities. Where urine was used as nutrient additive, no further water was added to produce the seedball dough. 2 cm diameter-sized seedballs were formed from 80 g sand + 50 g loam + 25 ml water. Seed number was adjusted to 6 and 10 per seedball. Seeds were randomly placed. Conventional sowing served as control. All treatments were sown at 3 cm depth. The experimental design was a randomised complete block with six replications per treatment. Seedling number was counted on the 7th DAP.

In the second part of the chemical optimisation study, sandy subsoil, collected from Rastatt (48° 49′ N, 8° 11′ E) in Germany, was used as substrate. The intention was to mimic the typical Sahelian pearl millet soils. The collected soil material was air-dried and passed through a 2 mm sieve to remove coarser particles. The soil is characterised by > 90 % sand, a pH_{CaCl_2} of 4.5, < 1 wt. % organic matter, a C : N ratio of 23 and a potential cation exchange capacity of 39 mmol kg^{-1} at around 0.7 m depth. Further properties of this soil can be accessed from Stahr *et al.* (2009). The seven tested treatments were: (i) conventional sowing as absolute *Control*; (ii) seedballs without amendments as *Sball* control; NPK-containing seedballs at two levels (iii) Sball+0.5gNPK (iv) Sball+1gNPK; (v) one wood ash-containing seedball variant (Sball+3gAsh); and CNT-containing seedballs at two levels (vi) Sball+0.1gCNT and (vii) Sball+0.5gCNT. Each seedball as well as the control contained ten seeds. The used fertiliser was NPK 15 : 15 : 15, 2–5 mm granular sized, white-coloured, containing < 2.0 wt. % water. CNT, ≥ 99 % pure, obtained from Carl Roth GmbH, Germany (www.carlroth.com), was used in addition as ammonia-free N-source.

Seedballs of 2 cm diameter size were formed and air-dried in < 24 h. The sowing depth for all treatments was 3.0 cm. Plastic containers of 12.0 cm in diameter and 14.0 cm in height were used. Each container was filled with sieved-sand at a bulk density of 1.6 g cm^{-3}. At the bottom of each plastic container, Whatman™ filter paper was installed to avoid sand materials from sipping through. The soil was air-dried before the treatments were sown. This was intended to mimic dry sowing as often practiced by Sahelian farmers. The experimental design was fully randomised, comprising six treatment replications. About 2.5 mm sized gravels covered the topmost 2.0 cm of each plastic container. This was to reduce soil water loss via evaporation. Water sprinkler was used for watering the experimental containers throughout this study. Watering started 48 h after sowing the treatments. 16 wt. % soil moisture content was adjusted daily using a weigh balance until harvest. A day/night cycle of 10/14 h was ensured. Day and night temperatures of 32 and 26 °C, respectively, with a relative air humidity of 48.5 % were maintained throughout the growth period. Seedling height and leaf number were repeatedly measured per week.

On the 28th DAP, the seedlings were harvested. Root (weight, length) and shoot (weight, leaf number) variables were measured. The dry matter was obtained after drying to a constant weight in an oven at 58–60 °C temperature range for 48 h. Dried shoots were analysed for P, Mg and K using the method described in section 2.3. Total nutrient uptake was calculated as: root biomass × nutrient content + shoot biomass × nutrient content. The roots were obtained by carefully washing the materials through a 2 mm sieve and were cut into lengths of about 1.0 cm with a clean pair of scissors to minimise root inter-twisting particularly during scanning. Measurement errors in root diameter as well as root length measurement are often associated with long (> 3 cm) root sections during scanning (Nwankwo *et al.*, 2013 – unpublished). Half of each sample was used for dry matter and the other half for root length determination. The stored roots were scanned with an EPSON Perfection V700 PHOTO dual lens scanner and the values of the root length and diameter were measured using WinRhizo® V2009c software (Regent Instruments, Nepean, Canada).

2.6 *Experiment 3: Seedball storage effects and on-station testing*

Seedball production is time demanding, without mechanisation requiring approximately 40 h for 10,000 units per person. This means quite an investment for the farmer. For the applicability of the technology, it is important to know whether the seedballs can be manufactured before the season (when labour load is low) and stored without causing decreasing germination rates.

The objective of the first experiment was, therefore, to identify whether storage time has an effect on number of germinated seeds. A second experiment was dedicated to the question whether seedballs function also under real Sahelian conditions using local materials. For this purpose, Sball+3gAsh and Sball+1gNPK treatments, containing 25 seeds per seedball were produced according to the same recipe as used in the two preceding experiments and tested against conventional sowing. The reason to constrain to wood ash and NPK as nutrient carrier was that these materials showed a positive growth effect in the chemical optimisation study and are available to Sahelian farmers, at least in small amounts. In contrast, CNT that showed the best biomass results is a pure chemical not available and affordable to these farmers.

For the first experiment, about 200 seedballs, per treatment, were produced at once and stored in the greenhouse of University of Hohenheim. Every week, germination tests were carried out with 20 seedballs per treatment for nine weeks period. Same greenhouse experimental conditions as stated in mechanical and chemical optimisation section (see sections 2.4 and 2.5), except average temperature that was 28.6 °C, were maintained. Average number of germinated seeds per seedball after eight days are reported.

For the field test under Sahelian conditions, Control, Sball, Sball+3gAsh and Sball+1gNPK treatments were tested for germination inside the ISRA/CNRA station, Bambey, Senegal. Seedballs were produced with local materials collected from the locality of Bambey. Each seedball contained 15 seeds; same seed number was inserted per planting pocket in the control i.e., the conventional sowing. The experimental site (14° 42′ N, −16° 28′ W) was characterised by a brown coloured sandy-loam soil characterised by a pH of 6.0 and a C : N ratio of 48. The exchangeable cations as extracted by NH_4-acetate from the first 0.3 m topsoil revealed in g kg^{-1}: 24.8 Ca, 5.1 Mg, 1.0 K, and 0.7 Na, as well as 26.5 mg kg^{-1} of plant available P as extracted by the Bray1 method.

Dried stands of *Vetiveria nigritana* and scarcely located seedlings of *Balanites aegyptiaca* were manually cleared off the site, which was fallowed for two years before this study. The planting area was 14 m × 15 m. Sowing was 3 cm deep, at a spacing of 1 m × 1 m, in a completely randomised block design of four treatment replications. No form of fertilisation was applied since we did not intend for any harvest. It was an off-season experiment; therefore, water was supplied via irrigation. Water equivalent to 20 mm rain every four days was supplied using sprinklers starting from the 2nd DAP. The intention of sowing before watering was to mimic dry sowing as often practiced by Sahelian farmers. Throughout the study, the observed average day and night temperatures were 27 and 19 °C, respectively. For reasons of genetic variation and environmental conditions, pearl millet seedlings may not survive after emergence under field conditions (Peacock *et al.*, 1993). Therefore, to check for seedlings survival after germination, repeated germination counts per planting pocket were conducted every week in a four weeks period. The number of emerged seedlings per planting pocket was noted.

2.7 *Statistical analysis*

Where statistical analysis was applicable, normal distribution and variance homogeneity were tested based on the Shapiro-Wilk test. As data were not evenly distributed, Welch's one-way analysis of variance using Proc. GLM was performed for all data sets of one-time measurements (e.g. biomass and dry matter). Proc. MIXED was performed for repeated measurements (e.g. plant height and leaf count). The treatment means were compared for significant differences at $p < 0.05$. Results are presented as means (± standard deviations) of the measured variables while the mean values represent the treatment means. All analyses were performed with SAS version 9.4 while Sigma Plot version 13.0 was used to plot all graphs.

3 Results

The used seed lot showed a germination rate of over 90 % in the greenhouse. Thus, the seeds were accepted as viable for the experiments.

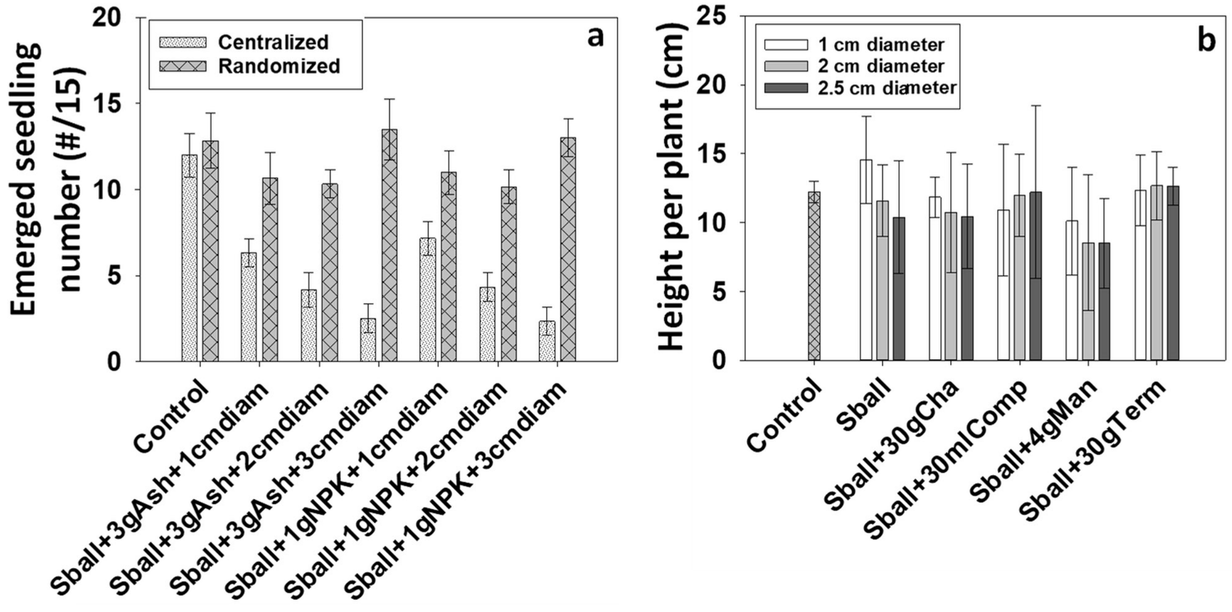

Fig. 1: *Treatment effects on pearl millet: (**a**) number of plants at day 7 after sowing, (**b**) plant height at day 9 after sowing at the greenhouse of ISRA/CNRA research station, Bambey, Senegal. Symbols show arithmetic means (n = 6) and error bars indicate standard deviations (±). Control = non-pelleted seeds, Sball = 80 g sand + 50 g loam + 25 ml water, Ash = wood ash, NPK = 15 : 15 : 15 mineral fertiliser, Cha = charcoal, Comp = compost, Term = termite soil, Man = manure, diam = diameter size in cm, centralized = seed placement at the core centre of the seedball i.e. seeds were inserted into the seedballs after the seedball was moulded, and randomized = scattered seed placement in seedball i.e. seeds were mixed with the seedball components before the seedball was moulded.*

3.1 Experiments 1 and 2: Chemical and mechanical optimisation of seedballs

Pre-trials (data not presented) have shown that the best base recipe for seedball dough is derived from a mixture of 80 g sand + 50 g loam + 25 ml water and that germination is best at a shallow sowing depth of about 3 cm as practiced by farmers. The greater the seedball diameter for centrally placed seeds in particular, the less the number of emerged plants one week after sowing (Fig. 1a). With respect to seed placement within seedballs, randomised placement showed an overall good performance, while central placement reduced number of emerged seeds in dependence of seedball diameter. There was no significant effect of seedball diameter on biomass development as presented by the plant height at day 9 after sowing. However, the manure-amended seedballs showed in general lower means (Fig. 1b). 2 cm diameter appears as good compromise between material needed, nutrient amount added and emergence rate.

Two striking effects of additives can be observed: gum arabic as well as urine heavily depress pearl millet emergence from seedballs (Fig. 2).

Seedling emergence was affected by treatment. Wood ash and CNT at high application rates of 3 and 0.5 g per standard seedball recipe significantly reduced seedlings emergence by 41 % and 64 %, respectively (Fig. 3a). Treatments showed effects on shoot and root variables at harvest. Sball+3gAsh, Sball+0.5gCNT and Sball+1gNPK treatments were 60 %, 202 % and 75 % higher in shoot and 36 %, 154 % and 94 % in root biomass compared to the control (3b and 3c). The root length density repeats these trends. Sball+3gAsh, Sball+0.5gCNT and Sball+1gNPK treatments showed 14 %, 12 % and 28 % increment in root length density relative to the control (Fig. 3d). Higher root diameter was observed in Sball+1gNPK treatment relative to the control. Root to shoot ratio did not respond to treatment (data not shown).

Treatment did not clearly influence the nutrient content of the seedlings (Fig. 3e). Sball+3gAsh, Sball+0.5gCNT and Sball+1gNPK treatments showed 82 %, 440 % and 193 % more P uptake, respectively, than the control (Fig. 3f). The total nutrient uptake is more indicative than the nutrient content. The former shows the already known pattern for all three investigated nutrients (Fig. 3f). In particular, K uptake was affected. It was 127 %, 380 % and 82 % higher in Sball+3gAsh, Sball+0.5gCNT and Sball+1gNPK treatments, respectively (Fig. 3f). Mg uptake was influenced by treatment as well. Sball+3gAsh, Sball+0.5gCNT and Sball+1gNPK treatments showed 66 %, 367 % and 68 % more Mg uptake than the control.

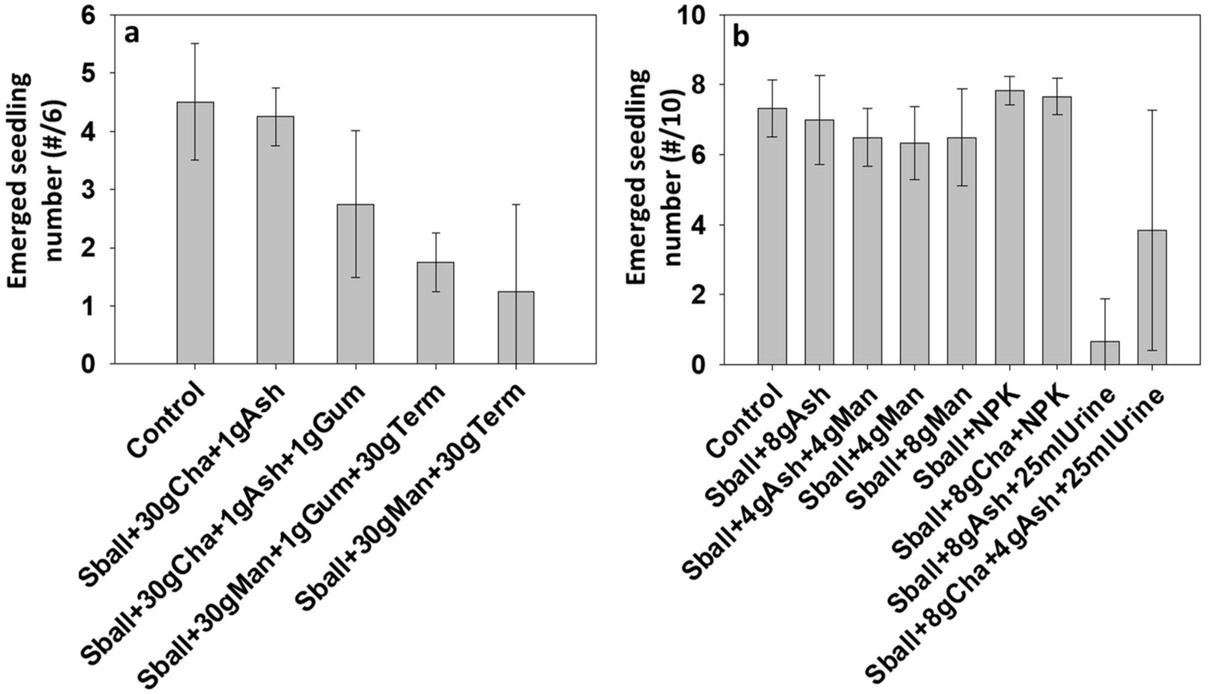

Fig. 2: *Treatment effects on pearl millet seedling number at the 7th day after sowing for (**a**) six and (**b**) ten seeds per seedball, observed at the greenhouse of University of Hohenheim, Germany. Bars represent arithmetic means (n = 6) and error bars indicate standard deviations (±). Control = non-pelleted seeds, Sball = 2 cm diameter sized-seedball made from a mixture of 80 g sand + 50 g loam + 25 ml water. Cha = charcoal, Ash = wood ash, Gum = gum arabic, Man = manure, Term = termite soil, NPK = 25 ml 17 : 17 : 17 mineral fertiliser in 200 ml g^{-1} solution and Urine = cattle urine.*

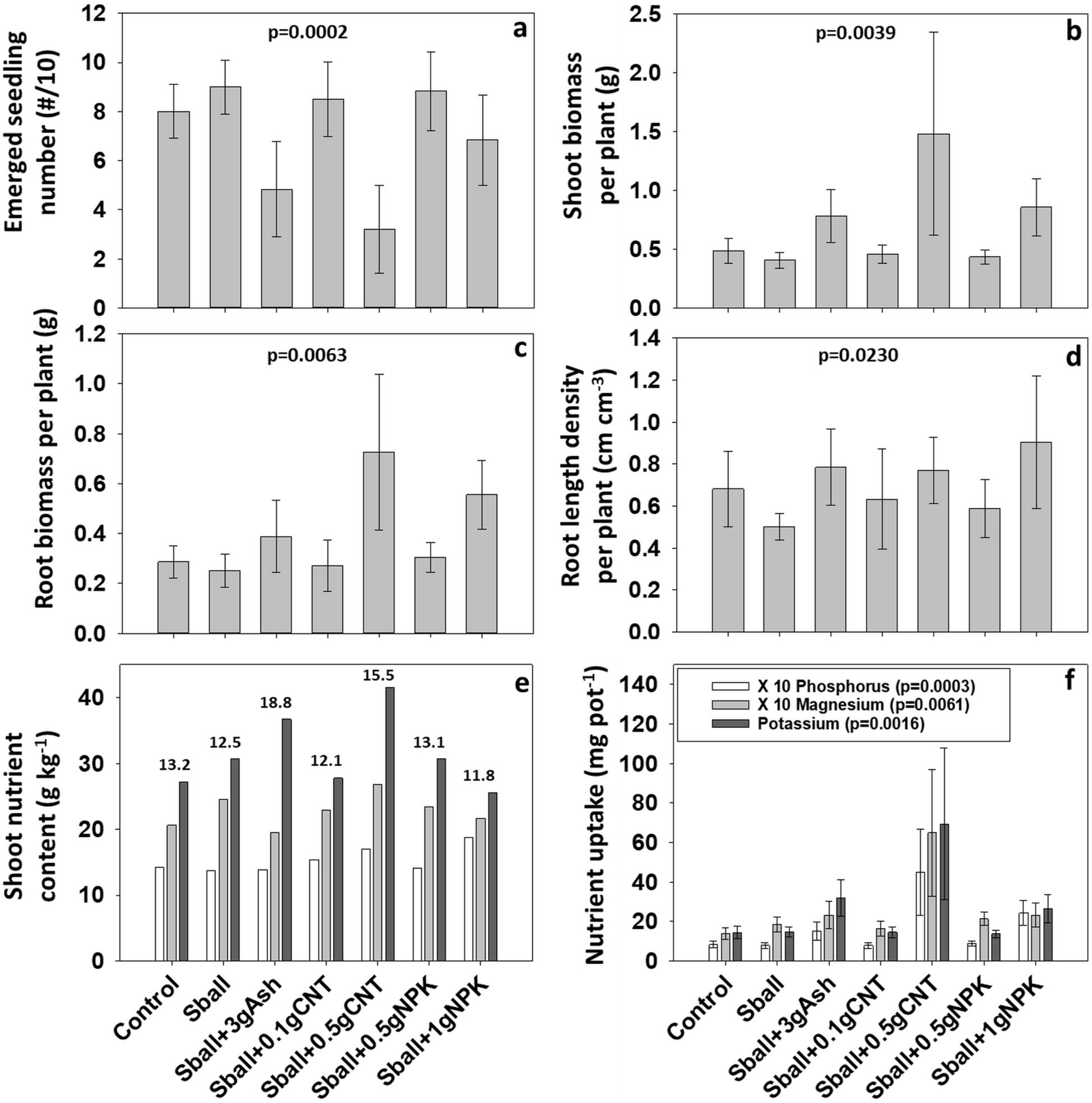

Fig. 3: *Treatment effects on pearl millet (**a**) emergence at 7th DAP, and (**b**) shoot biomass (**c**) root biomass (**d**) root length density (**e**) shoot nutrient content as well as (**f**) total nutrient uptake, at 28th DAP, observed at the greenhouse of University of Hohenheim, Germany. Numbers in (**e**) indicate the ratio of K to Mg content of the shoot. Symbols show arithmetic means ($n = 6$) and error bars indicate standard deviations (±), except for (**e**) where biomass was pooled due to small sample sizes. p = probability value, Control = non-pelleted seeds, Sball = 2 cm diameter sized-seedball made from a mixture of 80 g sand + 50 g loam + 25 ml water, Ash = wood ash, CNT = calcium nitrate tetrahydrate and NPK = 15 : 15 : 15 mineral fertiliser.*

3.2 Seedball storage effects and on-station testing

Plant height and leaf number as biomass proxies responded to treatments. Relative to the control, 29 % and 18 % increments in height were observed in Sball+1gNPK on the 12th and 16th DAP, respectively (Fig. 4a). Within 24 DAP, Sball+3gAsh, Sball+0.5gCNT and Sball+1gNPK treatments showed 11 % and 18 % and 17 % height increment, compared to the control. Sball+1gNPK treatment in particular enhanced leaf development, particularly between 15th and 25th DAP (Fig. 4b).

Seedlings emergence slightly declined in Sball+3gAsh and Sball+1gNPK treatments after about six weeks of storage (Fig. 5). As for the on-station seedball germination in Senegal, the germination rates for the Control (98.2 %), Sball (97.4 %), Sball+3gAsh (97.1 %) and Sball+1gNPK (96.1 %) treatments were comparable under field conditions. Over 20 seedlings per germination pocket was ob-

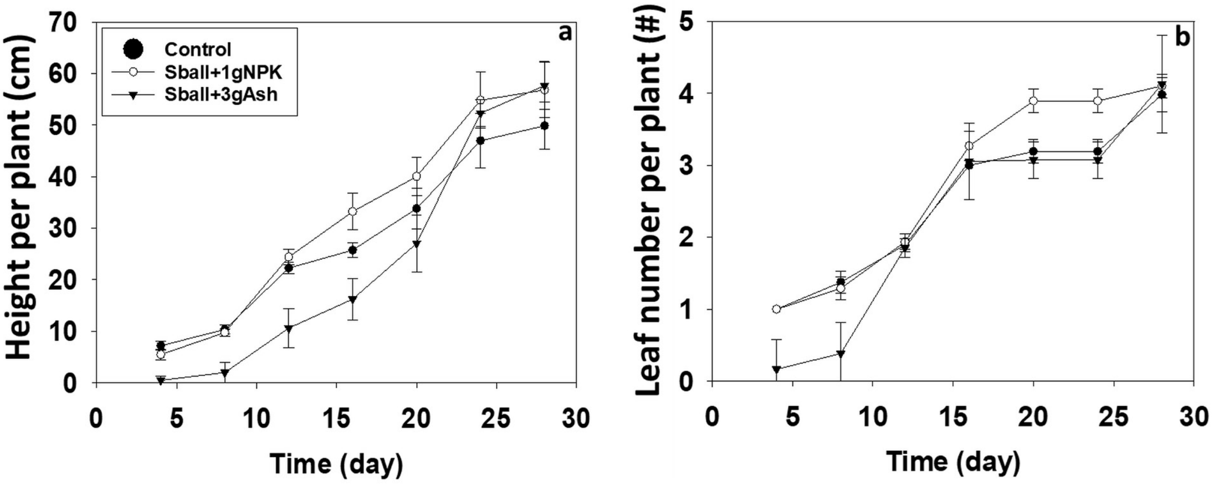

Fig. 4: *Pearl millet (**a**) shoot height and (**b**) leaf number development for different treatments at the greenhouse of University of Hohenheim, Germany. Symbols show arithmetic means (n = 6) and error bars indicate standard deviations (±). Control = non-pelleted seeds, Sball = 2 cm diameter sized-seedball made from a mixture of = 80 g sand + 50 g loam + 25 ml water, Ash = wood ash, and NPK = 15 : 15 : 15 mineral fertiliser.*

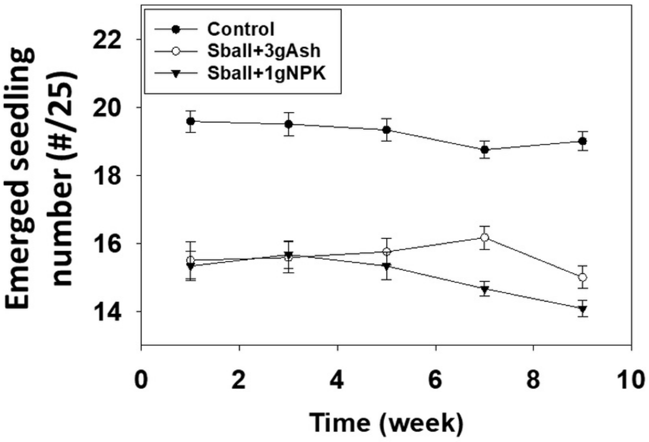

Fig. 5: *Absolute number of emerged pearl millet seedlings 8 DAP for three treatments as affected by storage time at the greenhouse of University of Hohenheim, Germany. Symbols show arithmetic means (n = 20) and error bars indicate standard deviations (±). Control = non-pelleted seeds, Sball = 2 cm diameter sized-seedball made from a mixture of = 80 g sand + 50 g loam + 25 ml water, Ash = wood ash and NPK = 15 : 15 : 15 mineral fertiliser.*

served for all treatments. The seedlings of Sball+3gAsh and Sball+1gNPK treatments in particular were more vigorous than those of the conventional sowing.

4 Discussion

4.1 *Participatory approach on seedball testing and adoption in the Sahel*

Technology adaptation and sustainable adoption are faster reached in a development context if target farmers are involved in all steps of technology development (Herrmann *et al.*, 2013). Therefore, Sahelian local farmers participated in this study as early as possible, i.e. identifying potential constraints to adoption of the seedball technology at pearl millet cropping sites with their predominant sandy soils.

Seedball technology seems to reduce seed usage per hectare at sowing. Seed wastage poses in particular a problem when children do the sowing and get physically exhausted. Then more than 300 seeds can be found in single sowing pockets (Klaij & Hoogmoed, 1993). Farmers preferred dry sowing practice because it prolongs the vegetation period and thus, potentially increases yield. Hand-sowing was preferred to the use of local sowing machines that demand cattle, horses or donkeys for traction and present a limitation.

The seedball technology absolutely conforms to the already established pearl millet management systems in the Sahel. Its application does not pose any form of disadvantage if the production is done during the dry season when opportunity costs are low, i.e. labour is not a limiting factor. Neither material availability nor social factors (gender and religion) per se, seem to hamper the adoption of the seedball technology at the Sahelian site investigated.

Female farmers appeared to be more interested in the technology, though. This might be explained by the fact that female farmers have less access to sowing machines and do need to support their husbands during the major sowing time at the beginning of the rainy season and are, thus, more keen to apply dry sowing.

4.2 Experiment 1: Mechanical optimisation of seedballs

Most likely, pearl millet seeds in central placement were unable to mechanically make their way through the substrate (Fig. 1a). With respect to the diameter, the biomass experiment did not provide a final argument (Fig. 1b). However, in a seedball of 1 cm diameter only a limited amount of seeds and nutrients can be incorporated. On the other hand, seedballs of 3 cm diameter need a lot of material (about threefold the amount of 2 cm diameter seedballs) that needs to be transported to the production site and afterwards to the fields, meaning elevated costs. Therefore, as a compromise, a diameter of 2 cm was considered optimum for seedball production.

4.3 Experiment 2: Chemical optimisation of seedballs

The negative effect of gum arabic on seedlings emergence (Fig. 2a) can potentially be explained by its strong tendency to absorb water itself. In consequence, if only low amounts of water are added, the seeds cannot compete. For urine and Macrotermes termite mound material (Fig. 2b), another explanation is necessary. The liberation of ammonia (Bremner & Krogmeier, 1989; Haden *et al.*, 2011) or similar ammonium compounds (Pan *et al.*, 2016) can intoxicate cereal seeds at direct contact. The urea compound in urine decomposes into ammonia. Own observations in other trials not reported here showed the negative effects of any ammonia containing fertiliser on pearl millet emergence. Macrotermes mound material can also contain relative high amounts ($> 50\,\mathrm{mg\,kg^{-1}}$) of ammonia (Hebel, 1995).

The probable reasons for failed emergence in the wood ash and CNT amended seedballs (Fig. 3a) are osmotic effects since both components have a very high solubility in water. All other treatments with lower share of osmotic compounds did not significantly reduce emergence compared to the control. It is well established that germination can be impaired in the case pearl millet seeds are coated with P at higher concentration (Rebafka *et al.*, 1993) or other materials (Peske & Novembre, 2011).

We did not assess the temporal root development in this study. However, positive effects were observed in the early root development of Sball+1gNPK treatment in other experiments, using computer tomography (Nwankwo *et al.*, 2018). N and P addition through NPK and wood ash, (Table 2) can be suspected to cause this effect. It is well documented that local nutrient supply as early as emergence influences early root development in pearl millet (Rebafka *et al.*, 1993; Karanam & Vadez, 2010; Valluru *et al.*, 2010). This is particularly true for phosphorus.

On the other hand, seedlings potassium content could be increased by ash and CNT application. While the ash effect can be explained by the high content of water soluble potassium in the ash itself, the CNT effect must be indirect, i.e. by better extraction of potassium from the soil mediated by a longer root network (Fig. 3c). The same argument can be applied for magnesium, since the 0.5 g CNT application yields highest content for magnesium as well. The potassium in the plant can contribute to biomass production (Fig. 3b and c) by increasing drought tolerance through better water use efficiency by effective regulation of the stomata. This is in agreement with the findings of Ashraf *et al.* (1994) on dry matter and biomass production of pearl millet shoot and root systems under drought conditions. Since wood ash ($860\,\mathrm{mg\,kg^{-1}}$) and the NPK fertiliser ($7430\,\mathrm{mg\,kg^{-1}}$) contained this nutrient (Table 2), only for CNT the effect needs to be explained by extraction from the growth medium (Cummins & Perkins, 1974). The seedlings of all our treatments contained Mg in higher amount than the range (0.102–0.126 %) reported as deficient by Embleton (1966).

In the acidic soils of the African Sahel where potentially plant available P can be fixed by soil aluminium (Scott-Wendt *et al.*, 1988), wood ash- and NPK-amended seedballs can potentially enhance P uptake in pearl millet. This is in particular true for the wood ash that locally increases the soil pH and thus counteracts Al-toxicity. This can be of great advantage, since early P uptake in pearl millet is decisive for higher dry matter and panicle yield under Sahelian conditions (Rebafka *et al.*, 1993; Buerkert, 1995; Karanam & Vadez, 2010).

Poor pearl millet seedling performance (Fig. 3b and c), as observed in our absolute control (conventional sowing) and seedball control (no nutrient amendment) treatment is often caused by low P and K nutrient uptake (Scott-Wendt *et al.*, 1988). The non-nutrient amended seedball treatment, Sball, showed similar K, Mg and P uptake as the control, indicating the importance of nutrient additives for the success of this technology. Nutrients positively influence biomass development and allocation in plants (Poorter & Nagel, 2000; Hermans *et al.*, 2006) in particularly if water is not limiting – as in this study. Conversely, low nutrient availability decreases plant nutrient uptake and consequently reduces leaf dry mass (Evans, 1996).

Similar observations have been reported on pearl millet when nutrients were supplied as early as the establishment stage (Rebafka *et al.*, 1993; Karanam & Vadez, 2010; Valluru *et al.*, 2010). Excessive shoot development in Sball+0.5gCNT treatment led to a lodging effect. Speculatively, the high N content of the CNT most likely triggered this effect. In rice, excessive N content was responsible for seedlings lodging (Mannan *et al.*, 2010). In this experiment, the wood ash treatment shows slow early development, but overtakes the control in the last phase. Possible reasons for the first effect is the high osmotic pressure exerted by the soluble components of the wood ash, and for the second effect the equilibrated nutrient supply, since wood ash – that derives from plant materials – is the most complex fertiliser that can be imagined.

The marginal plant height difference observed from 24th DAP onwards indicates nutrient depletion in the limited rooting volume by the well-established seedlings. Therefore, nutrient supplementation to maintain the seedlings is necessary, precisely three weeks after planting. This is exactly the time when the local farmers carry out weeding and thinning. Fertilisation can be supplemented at this stage to ensure a continuation of the already established seedling. This could be in form of animal manure, considering its availability as well as affordability in the Sahel.

4.4 *Experiment 3: Seedball storage effects and on-station testing*

Long-term cumulative osmotic effect arising from the wood ash and NPK contents of the seedball can be suspected for the declined seedlings emergence six weeks after storage (Fig. 5). Emergence rate was lower in the nutrient amended treatments, but still high enough with respect to farmer needs. In addition, number of emerged seeds per seedball can be adjusted by the number of seeds inserted. As a common practice, Sahelian farmers often thin down to 2–3 plants per pocket from > 30 emerged seedlings. Seedlings emergence rates as observed in this experiment of about 14 seedlings per pocket is, therefore, acceptable.

In the on-station test, the > 96 % seedlings emergence rate observed in all the treatments is a clear indication that seedballs are a viable option in sandy Sahelian fields. Since here no quantitative biomass variables were assessed, testing should be continued for whole cropping seasons.

5 Conclusions on the applicability and optimised formula of the seedball technology under Sahelian conditions

Opportunities exist, through the seedball technology, to improve the performance of pearl millet production under Sahelian conditions (poor soil + erratic rainfall). Farmers' perception about the technology was in general positive. The standard base dough consists of 80 g sand + 50 g loam + 25 ml water (+ 1 g NPK or 3 g wood ash). All components that potentially contain ammonia (urea, urine, manure) should be avoided since they consistently reduce germination rates. Once confectioned and dried, seedballs can be stored for prolonged periods (at least two months), showing only a slight trend of decreasing germination over time. Number of germinated seeds can be adjusted via the seed number per seedball. In farmers' environment, the production of seedballs can be based on simple volumetric ratios using traditional bins, plastic cups or bottle caps. A topic is workload, but this can be circumvented by seedball manufacturing before the planting season.

In this study, nutrient amended seedballs have proven to enhance seedling performance in the early growth stages (first 3–4 weeks). From a farmer perspective, as soon as crop establishment is guaranteed, further fertilisation (e.g. with organic manure) needs to be applied. Seedballs reduce the risk of loss on investment in particular with respect to fertiliser, requiring < 2 kg NPK per hectare, and lower seed number per pocket. On-station in Senegal, first tests have shown that seedballs can be produced with the indigenous local materials, and that germination is sufficient under the given Sahelian environmental conditions. The next steps are now to quantitatively test performance effects on-station and on-farm.

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