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Seedball technology development for subsistence-oriented pearl millet production systems in Sahelian West Africa

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List of Abbreviations

C	Carbon
Ca	Calcium
Cha	Charcoal (as treatment)
Cm	Centimeter
CNRA	National Center for Agronomic Research
CNT	Calcium nitrate tetrahydrate
C:N	Carbon to nitrogen ratio
Comp	Compost manure (as treatment)
C_{org}	Organic carbon
DAP	Days after planting
Diam	Diameter size (as in treatment)
EC	Electrical conductivity
FAPAL	Smallholder Farmers Association of Louga, Senegal
G	Gram
GLM	Generalized linear model
H	Hour(s)
INRAN	National Agricultural Research Institute of Niger Republic
ISRA	Agricultural Research Institute of Senegal
K	Potassium
Kg	Kilogram
M	Meter
Man	Manure (as treatment)
Mg	Magnesium, milligram
Ml	Milliliter
Mm	Millimeter
Mmol	Millimoles
N	Nitrogen
NPK	Commercial mineral fertilizer
N.s	Not significant
P	Phosphorus
Proc	Procedure
PVC	Polymerized vinyl chloride
Sball	Seedball (as treatment)
SMIL	Sorghum and Millet Innovation Lab
Term	Termite soil (as treatment)
USAID	United States Agency for International Development
WAS	West African Sahel
WPA	Water People Agriculture
Wt	Weight
^{0}C	Degrees Celsius
>	Greater than
<	Less than
*	Multiplied by (product of)
µg	Microgram
%	Percent

1. General introduction

1.1. Study background

The West African Sahel (WAS) is a home for millions of peasants, who live in villages, practise and depend on subsistence agriculture (Bationo and Buerkert, 2001) for a living. Local peasants can afford only little or even no external inputs, and lack access to functional markets (Buerkert and Schlecht, 2013). Pearl millet (*Pennisetum glaucum* (L). R. Brown) is their major cereal (Dendy, 1995; IUSS, 2014). Often considered as a subsistence and famine crop, the productivity of pearl millet as a staple food is stable because it is grown by most households (FAO, 1995). Compared to other cereal crops grown in this region, pearl millet production is fostered for several reasons. E.g., it contains more protein than maize and sorghum (Saleh et al., 2013); it is more tolerant to drought stress than most cereal crops (Baltensperger, 2002; Saleh et al., 2013), it thrives well on poor sandy soils where other crops fail (NRC, 1996) as well as responds better to fertilizer amendments (Baltensperger, 2002). These arguments indicate that producing pearl millet in the WAS is less risky compared to other cereal crops, and explains why pearl millet is the most adapted and grown, as well as suitable crop for arid and semi-arid regions of the world (Dendy, 1995).

Smallholder pearl millet per capita production in the WAS did not significantly increase in the past four decades. Among the factors that constrain pearl millet yield, poor seedlings establishment is the most common (Klaij and Hoogmoed, 1993; Karanam and Vadez, 2010; Valluru et al., 2010). Poorly established seedlings, often, lead to low grain yields (Rebafka et al., 1993; Karanam and Vadez, 2010). These can be as low as 166 kg ha^{-1} as in Niger Republic, a WAS country, after the 1980 severe drought (McIntire and Fussell, 1989), compared to a relatively high yield of 917 kg ha^{-1} under good management practices (Bationo et al., 1992). The low, on average, yield is particularly threatening the food security of the fast growing population in this region (Nyong et al., 2007).

Our climate is continuously changing; temperature is increasing whereas water resources are decreasing (Hulme et al., 2001). These changes pose adverse effects on agriculture in general (Schlenker and Lobell, 2010). For this reason, food insecurity is expected to exacerbate in future, in particular if adequate adaptation measures are not taken. Early seasonal drought arising from erratic rainfall especially at the season's onset, often retard seedlings establishment (Sivakumar, 1988). Obviously, steady water supply to the seedlings through irrigation can curtail early seasonal drought (Fox and Rockström, 2003). However, the local farmers practise rain-fed agriculture, a low-input system. Crop failure is often the consequence of early seasonal drought; farmers lose invested money, and food insecurity increases. Re-planting requires additional inputs, thereby, increasing the production costs.

Seed treatment options (Scott, 1975; Rebafka et al., 1993; Karanam and Vadez, 2010), mineral fertilization (Badiane et al., 2001), micro-dosing (Hayashi et al., 2008; Twomlow et al., 2010) and the use of irrigation schemes (Fox and Rockström, 2003) can potentially improve seedlings establishment and crop yield under WAS conditions. However, these options were developed outside the smallholder farming framework. As a result, the adoption of these practices by the WAS local farmers in particular is pending till date.

1.2. Problem statement and justification of the study

The nutrient-deficient (Bationo and Buerkert, 2001) as well as low water holding capacity *Arenosols* characterize the WAS region (IUSS, 2014). Thus, nutrient supplementation is required to enhance seedlings establishment, which is decisive for improved panicle yield (Rebafka et al., 1993; Karanam and Vadez, 2010). Despite the effectiveness of seed coating, seed priming, micro-dosing and irrigation at enhancing pearl millet seedlings establishment under WAS conditions, lack of financial resources (Van der Pol and Traore, 1993) as well as skills partly disallow smallholder farmers access to these technologies. Consequently, over four decades of research did not lead to successfully transferred technology to the target people. The yield of pearl millet is still restricted by the traditional cropping system - a consistent low-yield practice that needs urgent improvement. There is a tremendous need for an innovation based on local materials that is simple to practise by smallholder farmers, particularly in the absence of the innovators. The dry sowing, often carried out by the Sahelian farmers to prolong the vegetative period as well as seasonal rainwater usage by the crop, is prone to crop failure due to erratic rainfall at the beginning of the season. Re-establishment incurs extra-expenses. In addition, the uncoated seeds used for dry sowing are susceptible to pests such as birds and ants (Nwanze and Sivakumar, 1990) as well as field rodents.

Fowler and Rockstrom (2001) and Schlecht et al. (2006) suggested that innovations targeting the smallholder African farmers in particular should be based on local materials, simple to understand as well as effective. In this context, the seedball technology exactly suits the WAS smallholder pearl millet production (Nwankwo and Herrmann, 2018). Seedballs consist, in their base recipe, for about ten balls of 80 g sand, 50 g loam, 25 ml water and 2.5 g seeds. They can contain additives such as nutrients, pesticides, rodenticides or inoculants, depending on preferences and necessities. They particularly address seedlings establishment under dry sowing. To the best of our knowledge, to date, there are no studies that have optimized the seedball technology for pearl millet production in the WAS. This study aimed at filling this gap and at the same time increasing pearl millet seedlings performance and panicle yield under low chemical soil fertility and early seasonal droughts using local resources.

1.3. Seed treatment options and hindrance factors

Seed treatment is based on protecting agents such as pesticides, fungicides, insecticides (Scott, 1975) or specific nutrient additives to increase crop performance and yield. On nutrient poor soils, such as

Arenosols and on-station conditions in WAS, phosphorus (P) seed coating (Rebafka et al., 1993; Karanam and Vadez, 2010) and priming (Raj et al., 2004; Aune and Ousman, 2011) i.e. soaking seeds for a certain period with water, increased early biomass production, seedlings emergence and pearl millet panicle yield. A challenging question remains: how implementable are these technologies in local farm environments.

The adoption of innovations by farmers depends on farmers perceptions of the risk and benefits (Feder and Umali, 1993; Sofoluwe et al., 2011), socio-economic and cultural factors as well as the characteristic of the innovation itself (Pannell et al., 2006). Prokopy et al. (2008) observed education level, access to information and income as the major determinants of best practices adoption among farmers. Putting the above factors together, it is clear that these seed treatment options in particular were not developed for the WAS smallholder farmers. Herrmann et al. (2013) suggested that research for development should involve the target farmers as early as the development stage of a technology. The reason behind is to assess the farmers' perception and make the necessary changes in order to increase the chances of adoption. It is, therefore, relevant to explore simple options based on local farmers' affordable local resources that can address the risk of pearl millet production in the WAS.

1.4. Potential of local materials and impacts of seedball on agriculture

The seedball technology as invented by (Fukuoka, 1978) in the context of permaculture has great relevance in dry land farming in particular. Seedball, as an innovation, is based on local materials such as sand, loam and water. It mitigates seed predation (Overdyck et al., 2013) and improves seedlings emergence (Fukuoka, 1978; Nwankwo et al., 2018). In Southern Australia, a semi-arid region, seedballs were used to revegetate rangelands (Atkinson and Atkinson, 2003).

Contrary to the seed coating with pure P, the seedball technology totally conforms to the agricultural management practices in the WAS environments, without any identified religious or gender barriers as at the time of this study. According to Nwankwo and Herrmann (2018), the major advantages of seedball over seed coating, seed priming or mineral fertilization are: (i) the simple applicability; (ii) low costs; and (iii) its sustainability in an economic and ecological sense i.e. minimizing the number of seeds inputs at sowing. However, the seedball technology needs to be mechanically and chemically optimized for pearl millet production i.e. with respect to the right diameter size (diam), share of local materials as well as nutrient additives used.

1.5. Guiding principles and objectives

The idea for this study was to cover the continuum from technology development to adoption. Therefore, it was necessary to work in parallel in greenhouses/laboratories, on-station and on-farm. With respect to farmer involvement, a participatory approach was chosen, i.e. involving farmer associations – as multiplicators – as early as possible, in order to gain access to local materials, to know potential constraints, and adapt the technology to farmers' needs (respecting gender) and potentials.

The specific objectives of this study were to:

(1) Review the seedball technology relative to seed priming and coating with pure P, and identify its potential constraints as well as applicability in the WAS;

(2) Optimize the seedball technology for pearl millet production in the WAS region using local resources;

(3) Validate seedball technology performance under Sahelian field conditions; and

(4) Determine agronomic benefits of seedball technology for smallholder farmers in particular.

1.6. Guiding hypotheses

The hypotheses of this study were:

(1) Seedballs can be developed based on locally available resources such as loam, sand, wood ash, and/or a minute amount of commercial mineral fertilizer (NPK);

(2) Seedball application lowers cropping risk of poor seedling establishment and increases panicle yields of pearl millet under subsistence production systems in the WAS; and

(3) Seedball influences nutrient distribution in the root zone to enhance early root and shoot development of pearl millet within the first three weeks of planting.

1.7. Structure of thesis

This thesis as a whole follows the conceptional continuum from the identification of potential constraints for technology performance and adoption over details of seedball technology development, to exploration of potential mechanisms behind biomass improvement. Following chapter 1 that presents the general introduction, chapter 2 is a review article published in the International Journal of Agriculture Innovations and Research, titled “Viability of the seedball technology to improve pearl millet seedlings establishment under Sahelian conditions - a review of pre-requisites and environmental conditions”. It tackles the potential of the seedball technology to improve pearl millet early biomass indicators a well as the potential application constraints and chances of adoption by the Sahelian farmers. Chapter 3, published in Journal of Agriculture and Rural Development in the Tropics and Subtropics as “Physical and chemical optimisation of the seedball technology addressing pearl millet under Sahelian conditions” explores the mechanical (diameter size, seed placement) and chemical (nutrient content, osmotic potential) aspects of the seedball technology to obtain a general recipe that performs under the given environmental conditions. Chapter 4, published in the Journal of Plant Nutrition and Soil Science, focuses on understanding the mechanisms of seedball-induced root and shoot enhancement of pearl millet seedlings. It explores the P content and EC of NPK-amended seedballs in the root zone of pearl millet seedlings, and the subsequent development of shoot biomass indicators within the first three weeks after planting. Chapter 5 integrates all results and discusses them with respect the conformity of the seedball technology to the agronomic practices of the WAS smallholder pearl millet farmers and growth as well as development enhancement of pearl millet seedlings by the seedball technology. It further summarizes the achievements of the seedball technology project, discusses open questions as well as gives recommendations for future research.

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2. Viability of the seedball technology to improve pearl millet seedlings establishment under Sahelian conditions - a review of pre-requisites and environmental conditions

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2.1. Abstract

Poor and erratic rainfall, poor chemical soil fertility and low water holding capacity of widely spread sandy soils are major constraints in the pearl millet (*Pennisetum glaucum* (L.) R. Brown) cropping system of the WAS. These factors lead to poor seedlings germination and vigor, and in turn low yields. Since the early growth stages determine final crop performance under Sahelian conditions, improvements should focus on this time span critical for final crop performance. Lack of financial resources and skills often prevent Sahelian farmers from adopting many of the existing solutions to improve crop performance such as seed treatments, NPK and application of irrigation. Due to short growing period and labor constraints at sowing, Sahelian farmers partly practise dry sowing. However, this practice is associated with a high risk of crop failure due to regularly occurring early droughts. Re-sowing might then be constrained by seed and labor availability. Urgently needed is a cheap technology based on locally available resources that reduces seed needs, increases early seedling vigor and reduces the crop failure risk. Seedball might be such a technology. Seedball is an easy and affordable "*seed-pelleting*" technique that combines indigenous local materials such as sand, loam, water and seeds in a gravimetric ratio to enhance seedling establishment. Amendments such as fertilizer or pesticides can be added depending on target preferences and local problems. Our evaluation shows that seedballs have the potential to improve the Sahelian pearl millet cropping systems since the technology is mainly based on local resources and, thus, can be adapted to local needs by individuals through added nutrient additives such as NPK and wood ash. Additionally, seedball production does not conflict with other pre-seasonal labor loads or gender issues, and is coupled with low financial demands.

Keywords: dry planting, dry sowing, germination constraints, local resources, seedling emergence, seedling vigor.

2.2. Introduction

In the WAS, pearl millet (*Pennisetum glaucum* (L.) R. Brown) is the major staple crop, mainly produced on *Arenosols* (IUSS, 2014) that are low in both available N and P (De Rouw, 2004). Millet yields are severely constrained by the combined effects of low and variable rainfall (Nicholson and Palao, 1993; D'amato and Lebel, 1998), low soil chemical fertility (Herrmann et al., 1994) as well as financial and labor scarcity (Cooper et al., 2008). One farmer adaption strategy to these difficult conditions is dry planting (Bationo and Buerkert, 2001), in particular for remote fields. However, this strategy bears a very high risk of crop failure due to early droughts that regularly occur and lead to poor seedlings emergence and sometimes, total crop loss (Salack et al., 2014). Consequently, farmers need to replant but are often faced with seed and labor shortages due to restricted financial resources (Cooper et al., 2008). Innovative options that can improve Sahelian pearl millet-cropping system comprise seed coating (Rebafka et al., 1993), fertilizer placement (Twomlow et al., 2010; Aune and Ousman, 2011), irrigation systems (Woltering et al., 2011) or NPK (Badiane et al., 2001; El-Lattief, 2011). Nonetheless, these options are often unaffordable for subsistence farmers or simply not in spatial reach. For example, the sophisticated machine used for P coating of pearl millet to increase panicle yield (Rebafka et al., 1993) necessitates high financial inputs. Additionally, NPKs are often not accessible on the local markets. As a consequence of lacking financial resources (Cooper et al., 2008), skills (Brick and Visser, 2015) and dysfunctional markets, resource poor and illiterate farmers are doomed to deal with poor pearl millet performance on repeatedly cropped *Arenosols*.

In designing and introducing agricultural innovations especially for African farmers, utilization of information depends on education and literacy level (Doss, 2001), which most Sahelian farmers lack. Particularly when focusing on poor subsistence farmers, management options need to be simple and based on cheap local materials. One such option is the seedball technology. It was developed by Masanobu Fukuoka within the permacropping approach to improve rice performance in dry fields (Fukuoka, 1978). Seedballs are produced using a gravimetric mixture of soil materials, additives that mainly serve as nutrient sources, and several seeds. They usually have around 2 cm diameter size, can be easily produced by hand during times of low workload in the off-season, rely on indigenous local resources, and are cheap and affordable to acquire. This paper reviews potential and pre-requisites of the seedball technology to improve the establishment of pearl millet seedlings under typical conditions of the WAS.

2.3. The socio-economic environment

Sahelian farmers are mostly subsistence-oriented and frequently rely on a few cultivation plots. A landholding can be as small as four hectares per village shared and cultivated by over fifteen farmers (Neef and Heidhues, 1994). Scarcity of financial resource is the major factor hindering adoption of established mitigations strategies dealing with adverse effects of climate change (Tschakert, 2007).

The economic empowerment of women is globally recognised as a key factor towards reducing poverty and economic growth (Blackden and Bhanu, 1999). In most African farming systems, men retain the right to land, but can provide access to women through marital customs (Doss, 2001). In few cases females can head households (Saito et al., 1994), controlling the overall agricultural activities in particular true for widows. On the contrary, regularly female spouses serve as aids (Safilios-Rothschild, 1985), working under the instructions of their husbands. Innovations, addressing cropping systems in the African Sahel (Rebafka et al., 1993; Karanam and Vadez, 2010; Twomlow et al., 2010; Aune and Ousman, 2011) rarely focus on women empowerment. African female farmers in general, are less likely to adopt innovations for reasons such as complex and heterogeneous households, complicated and dynamic gender roles within households, and huge variation at responding to changes in economic circumstances (Doss, 2001). Nevertheless, women provide more agricultural labor than men in the whole of sub-Saharan Africa (Saito et al., 1994). Women first help their husband to crop his field before they are allowed to invest in their own plots.

In the African Sahel region, women account for > 50 % of the population. But they receive a disproportionately low share of public investment and are disadvantaged by a range of socio-cultural, regulatory and institutional factors. Even in the agricultural sector where women tend to predominate, credit and land ownership have historically been directed to the male head of the household despite of the fact that Sahelian women often outperform their male counterparts. In Burkina Faso, agriculture accounts for 36 % of the gross domestic product to which women contribute 29 % and men 7 %. In Mali these shares are 26 % to 14 % in favour of women (Blackden et al., 2003). These figures indicate the crucial role of women in agriculture that is often overlooked (Chen, 2008). Women’s farmland are often located at far distance from the homestead (Jackson, 1985). Land privatizations can cause the less privileged African women to completely lose their already acquired lands or reduce access to it (Lastarria-Cornhiel, 1997). These gender imbalances limit agricultural productivity as a result of underutilization of human resources. Factors such as financial demand, indigenous resource input, labor requirement and education that restrict gender-specific adoption need to be evaluated before transferring any innovation to the field.

Seedballs need only local inputs such as sand, loam, seeds and water that are abundantly available at low costs. Little instruction is necessary to teach people how to produce seedballs. A major demand is labor. However, seedballs can be produced during the off-season when opportunity costs are low. Transport cost from the homestead to the field is higher for seedballs than for conventional seeds. Women usually crop only small plots, marginalizing the transport costs. Taking these arguments together, the seedball technology may be particularly attractive in particular for women who own low fertility fields, farther away from the homestead that need to be sown at non-optimal times since men's fields are preferentially sown at the beginning of the cropping season.

2.4. The natural environment

The WAS represents a transition zone between the arid Sahara in the north and the humid tropical savannahs in the south, noted for its steep north–south gradient in mean annual rainfall (Le Houerou, 1980). The cropping year is characterised by a long dry and a short humid season usually about three months. The northern Sahel that receives annual rainfall of 200 to 400 mm mainly represents grazing lands whereas the southern Sahel with an annual rainfall range of 400 to 600 mm serves as the pearl millet cropping domain. During recent times the WAS has seen a cyclic climate pattern at a decadal time scale. The deterministic reasons for the long-term fluctuations are not yet fully understood (Salack et al., 2014). It is likely that non–El Nino-Southern Oscillation (ENSO) – related variations in sea surface temperatures (Giannini et al., 2003; Brooks, 2004), and large-scale changes in land cover and land–atmosphere interactions (Charney, 1975; Hulme and Kelly, 1993; Zeng et al., 1999; Hulme et al., 2001), increasingly affect the Sahelian climate. The WAS has suffered from several devastating droughts and famines in the last decades, in particular in the early 1970s and the late1980s (Olsson et al., 2005). Farmers in WAS have to account for climatic variability at intra– and inter–annual as well as decadal time scales (Mertz et al., 2009). The possible consequences include species and variety losses. The variable and erratic rather than the overall low rainfall is considered as one of the most limiting factors for agricultural production (Nicholson and Palao, 1993; D'amato and Lebel, 1998; Graef and Haigis, 2001) in this semi–arid environment. Seasonal weather forecasts have shown to be unreliable (Sivakumar, 1988). First, it is difficult for farmers to adapt to a variable seasonal length that is presently unpredictable. Therefore, farmers invest into risk diversification e.g. by adopting dry sowing (Bationo and Buerkert, 2001) as a mitigation option. Secondly, early droughts pose a huge threat to seedlings survival directly after germination. It is of high interest to farmers to improve millet establishment and early vigor since the early growth stages are decisive for the final yield (Rebafka et al., 1993; Valluru et al., 2010). The question of how to cope with these dry spells (Fox and Rockström, 2003) is still a trending topic in the Sahel, particularly in the context of smallholder farming.

Therefore, reducing the risks of early seasonal drought and nutrient deficiency associated with dry sowing and infertile soil might be possible through seedball technology by amending seedballs with the suitable nutrients-additives to increase both nutritional status and drought tolerance in the seedlings. This might increase seedlings survival and vigor, reduce repeated sowing and subsequently increase the vegetative period of the crop.

2.5. The soil aspect

The major soils for Sahelian pearl millet productions are Luvic *Arenosols* (Muehlig-Versen et al., 2003; Karanam and Vadez, 2010). These soils are slightly acidic ($pH_{H_2O} < 6$) and inherently deficient in plant available P (Rebafka, 1993; Muehlig-Versen et al., 2003). They are extremely low in organic carbon (C_{org}) (< 1 %) and total N content (Bationo and Buerkert, 2001) as well as available calcium (Ca) (Voortman et al., 2004) but bear high potassium (K) reserves (Herrmann, 1996). Additionally, they are coarse textured (> 70 % sand to 1 m depth), have a low water retention capacity (often < 10 Vol. %), a high hydraulic conductivity (Bley, 1990), and are easy to till (Klaij and Hoogmoed, 1993). Different processes lead to surface crusting that negatively influences water infiltration at the start of the growing season (Casenave and Valentin, 1989). Though rainfall is low, leaching losses of up to 200 lm^{-2} can accumulate over the season (Fechter, 1993). The so-called spatial micro–variability of soil properties (and corresponding yields) poses another challenge to the farmers (Herrmann et al., 1994), and are sometimes used as risk diversification strategy (Brouwer et al., 1993). As population pressure forces an intensification of land use, integrated soil management is essential for cropping success. Such an approach combines improved soil moisture storage measures and the use of organic and inorganic fertilizers as well as other soil amendment options (Koning et al., 2001) to increase yield. Though atmospheric net nutrient input regularly occurs during the dry season, these are, with exceptions for P, too low to replenish the losses via cropping, leaching, wind and water erosion (Herrmann, 1996). Extreme dryness, poor soil structure and lack of vegetative cover can increase the susceptibility of semi-arid soils, in particular *Arenosols* to wind and water erosion (Michels et al., 1995; Andrew, 2007), often leading to catastrophic crop losses.

Seedballs can - in the microenvironment - increase water retention due to their higher clay content and induce water transport towards the root by having a different water retention characteristic. The higher clay content can also contribute to a higher amount of rechargeable nutrient such as P, Ca and magnesium (Mg) directly around the seedlings roots.

2.6. The cropping aspect

In small seeded species such as subterranean clover (*Trifolium subterraneum*), P and Ca seed reserves were exhausted as early as fourteen days (Krigel, 1967). In oats, most of the P reserves from the seeds were translocated to the developing roots and shoot during the first eight days after germination (Hall and Hodges, 1966). These results indicate that small-seeded species need nutrient supplementation as early as seedlings emergence. Pearl millet seeds are generally small and consequently bear a low nutrient stock. A single grain weighs 7–10 mg that contains P reserves of only about 20 μg. Therefore, additional nutrient input through pelleting appears promising (Peske and Novembre, 2011). In particular, an external supply of P soon after emergence is advisable (Rebafka et al., 1993). Although pearl millets are naturally tough and can thrive in infertile soils (Duivenbooden and Cissé, 1993), higher yields can be attained if seedlings are nutritionally enhanced as early as the emergence (Karanam and Vadez, 2010; Valluru et al., 2010). An inevitable advantage of vigorous early growth arising from sufficient seed reserves is resistance against early stress conditions (Read, 1983). This is vital in the Sahelian region where plant establishment is often impaired by drought and sand windblast, occurring regularly prior to the rainfall events (Banzhaf, 1988).

Pearl millet and cowpea are the major Sahelian crops, since they are adapted to the harsh climatic and poor soil conditions. Due to the population pressure, fallowing is consecutively, abandoned and cropping is extended into marginal lands. Decreasing crop surface per household increasingly forces farmers to intercrop. A crop rotation as recommended by Bationo and Ntare (2000) is hardly feasible anymore. Lack of fertilizer access on the markets as well as poor financial resources of households lead to nutrient mining (Van der Pol and Traore, 1993) that is in long-term detrimental for the crop yield. One measure to counteract in particular nutrient deficiency during the early growth stages is micro-dosing (Buerkert and Schlecht, 2013). This means small amount of fertilizer closely placed to the seeds in the sowing pocket. These small amounts of fertilizer do not include a high risk of no return on investment in case of crop failure. Traditionally, farmers wait with sowing activities until 0.10–0.15 m of the top soil are humidified by the starting rains. Any delay in sowing then decreases yield potential (El-Lattief, 2011) due to a shortened vegetation period and leaching of the already poor available nutrient fractions. Seedballs can potentially lower cropping risks by prolonging the growing period through dry sowing. When seeds are untreated, predation by rodents, pests and insects are often inevitable, causing the need for re-sowing. Seedballs ability to encapsulate seeds in hard form may reduce seed predation. A typical scenario herein is the observed 35 % reduction in seed predation of Tawa tree (*Beilschmiedia tawa*) when its seeds were placed in balls made of nutritionally enriched clay in New Zealand (Overdyck et al., 2013).

Nutrient-enhancement effects of local materials such as wood ash (Saarsalmi et al., 2012), compost manure (Zmora-Nahum et al., 2007), charcoal (Santalla et al., 2011) and termite mound materials (Karak et al., 2014) on soil and crops have been studied in the past. Wood ash has both long and short time effects on soils, and varies in its chemical contents depending on the burnt compounds, combustion process and ash conditioning (Augusto et al., 2008). Its application does not pose risks to the environment (Demeyer et al., 2001), but affects the soil chemistry in two ways; as a liming agent and as a source of nutrients (Nkana et al., 2002). Charcoals serve as soil conditioners and as sequesters of C in recalcitrant and in reactive forms (Novotny et al., 2009), improving exchange capacity, surface area and nutrient contents (Glaser et al., 2002).

Seedballs can potentially counteract the aforementioned cropping constraints by (i) reducing seed predation due to the -in the dry state- hard shell and providing small amounts of lacking nutrients that can improve seedlings establishment. Additionally, by directing water resources and again nutrients that might be otherwise leached from the surrounding towards the roots due to the higher water suction of the finer material. The only requirement is an optimisation using the specific local resources. Seedballs do not increase the nutrient status of soils. Therefore, the nutrients added need to be embedded in a holistic fertilisation strategy (Voortman, 2010) that provides the necessary nutrients once the crop establishment is achieved.

2.7. Seed treatment technologies

Different seed treatment techniques to improve pearl millet crop performance have been studied in the past. These include seed coating with P (Rebafka et al., 1993; Karanam and Vadez, 2010), and seed coating and priming with *Pseudomonas spp*. under greenhouse and field conditions (Raj et al., 2004). These techniques enhanced seedlings establishment and improved crop yield under field conditions. Karanam and Vadez (2010) tested P coating using three-hybrid pearl millet varieties planted in pots (three seedlings per pot) or Polymerized vinyl chloride (PVC) cylinders (one seedling per cylinder), the latter option to allow for a longer growth span. The soil material used was derived from an *Alfisol* with low P status. In their findings, seed coating at a rate of approximately 400 g P ha^{-1} increased shoot biomass by > 400 % at early stages, and panicle weight by 50 %. The seed coating process of mixing pearl millet seeds with grounded KH_2PO_4 salt and glue solution at a specific-homogenized rate of 0.1 ml g^{-1} seed is already too sophisticated. Rebafka et al. (1993) tested the effect of enhanced seedling establishment achieved through P (ammonium dihydrogen phosphate) seed coating, on the final yield of pearl millet in an acid sandy, P deficient soil in Niger (West Africa). They observed a dry matter increment of up to 280 % in seedlings, and increased grain yield by up to 45 % in the field. However, the seed coating requires the use of highly sophisticated machine - a precision rotation pan - at a coating rate of not more than 0.5 mg P seed^{-1} using bentonite as coating substance. Farmers may not replicate this coating practice due to its high skill demand. Again, the bentonite-containing phosphate salts used as the coating agent may not be available in the local markets, and might be practically impossible to be formulated by the farmers. Additionally, ensuring an accurate coating rate of exactly 0.5 mg P seed^{-1} may be difficult, and this specified rate can impair germination when higher, or reduce yield when lower. In the findings of Raj et al. (2004), bio-priming pearl millet seeds with *Pseudomonas fluorescens* isolates resulted in an improved germination and seedling vigor, and subsequently led to up to 22 % increased grain yield in the field. However, the preparation (including centrifugation and pelleting), harvesting and storage of *Pseudomonas fluorescens* requires a King's B broth amended with 20 % glycerol and a cooling facility of -80 ^{0}C. Additionally, an ultra-violet-visible spectrophotometer was used to adjust the density to 108 cfuml^{-1} before inoculation. Prior to inoculation, seeds were surface-sterilized with 0.02 % mercuric chloride, and further soaked in a bacterial suspension amended with 0.2 % carboxymethyl cellulose to facilitate the adherence of the bacteria to the seeds. This process is first, complicated due to high knowledge-demand with respect to the chemistry of the priming solutions, which the smallholder farmers lack. Second, the storage and cooling facilities require electricity and cooling devices. These are not within the spatial reach of the Sahelian subsistence farmers.

The decisive question for applicability is, whether farmers are able to apply a seed treatment technology, and this is depending on the level of mechanisation that is necessary. An innovation that needs high financial investments, components that are not locally available or includes technical aspects that are not manageable by local blacksmiths, will not find adoption in a subsistence-oriented agricultural environment. Therefore, a simple-to-understand and easy-to-apply alternative innovation is necessary; seedballs could be such a technology.

Seedballs as patently invented by Masanobu Fukuoka in which loamy soil was combined with compost, water and rice seeds, can be effective in converting bare land into forest (Fukuoka, 1978). As sowing technology, they can replace traditional seeds offering benefits of (i) enhanced early nutrient delivery (ii) reduced seed predation (iii) controlled seed amounts and (iv) reduced labor input at sowing. If we theoretically apply this technology to the Sahelian environment, we can state the following. In contrast to other technologies, seedballs do not need enhanced technological equipment. The basic constituents (i.e. sand, loam, any kind of fertilizer e.g. compost, seeds, water) are in the hands of the farmers and accessible to both sexes. Producing seedballs needs little training. Production itself can be made by hand in a community action. However, if greater surfaces are to be planted, mechanisation is mandatory, since one hectare needs under Sahelian conditions and pearl millet as a crop approximately 10,000 seedballs (i.e. 1 seedball per planting pocket at a sowing distance of 1 m*1 m). Manufacturing can happen before the vegetation period if seedballs can be sufficiently dried immediately after production in order to impede unwanted germination. This is possible under the high daytime temperatures in the Sahel. Early production before the season allows for dry sowing. This is in particular an important aspect, since sowing at the start of the vegetation period is constrained by labor shortage.

The two crucial aspects for potential success of seedballs are that (i) seedballs show sufficient germination, and (ii) a growth advantage compared to conventional sowing. The pre-requisites for seedball production are (i) the availability of its components such as sand, loam, seeds, water, and organic or inorganic manure (ii) the dry and sunny atmospheric condition in the Sahel that ensures that seedballs dry in less than twenty-four hours (h) after production, and (iii) human resources. These pre-requisites are, at low and affordable cost, within the reach of the every Sahelian farmer and his or her household. First of all, the seedballs need to be mechanically optimized in the sense that size, composition and number of seeds contained lead to a sufficient number of germinated seeds. The second step is then to add nutrient components. If these are NPK or wood ash, the amount needs to be optimized in order to avoid osmotic effects that hamper germination or early plant development. Once seedballs are mechanically and chemically optimized, the next question is what kind of sowing technique is appropriate. In theory, seedballs can be applied directly onto the surface, as done in Australia for rangeland improvement (Atkinson and Atkinson, 2003). However, it appears reasonable that incorporation into the soil is favoring water supply and thus better germination and growth. Timing of sowing is probably important, too. The technology was developed for application with dry sowing but also sowing at the onset of the rainy season might have advantages.

The last question is then, what the real mechanisms are, that contribute to the success of seedballs. Are these exclusively nutrient factors or are other effects involved? One could hypothesize that seedballs - as they have a finer texture than the surrounding soil matrix - are attracting water due to a higher water suction. In combination with enhanced rooting density, this property can support survival in early drought periods, since more water is available to the plant, less energy is needed to extract this water from the surroundings and more nutrients are transported towards the plant that are otherwise potentially leached. In fact, certain plants can manipulate their rhizosphere under poor soil physiological status to increase nutrient availability (Neumann and Römheld, 2007), but to date, this is not proven for pearl millet. Therefore, seedballs might be a management option that can act as a substitute for this disability, particularly in the chemically infertile Sahelian *Arenosols*.

Another advantage of seedballs is that the incorporated seeds are hardly accessible to predators such as birds, small mammals or ants until the suitable germination conditions are met (Kelt et al., 2004). A known number of seeds can be inserted into seedballs. It is important to identify this number in a participatory manner with farmers, since the number of existing plants per pocket does not only play a role as yield component but also to counteract harmful erosion events. Under Sahelian conditions, at the onset of the rainy season, strong convective storm events regularly occur (Lamers, 1995). The saltating sand grains during these events can impact on pearl millet seedlings to such an extent that they die. Therefore in one sowing pocket more seedlings need to be established than is necessary only for the yield aspect. In a sowing pocket the outer plants protect the inner ones against erosion effects. With conventional manual sowing under Sahelian conditions, an unknown seed amount is incalculably inserted into the soil. Seed wastage is most prominent when children do the sowing.

They tend to increase the seed amount per pocket when they become tired. And this effect can be massive. Klaij and Hoogmoed (1993) report insertion of up to 300 seeds per pocket as conventional practice. Consequently, irrespective of who does the sowing with seedballs, sowing can become more economical from the perspectives of required seed amount and labor. With respect to the latter seedballs can reduce the demand for thinning activities and in case of efficient emergence for replanting. All these benefits would support, in particular, women farmers who have the lowest resource availability.

2.8. Constraints to adoption

Only a few research findings on enhanced pearl millet production technologies have passed on to the Sahelian farmers during the last decades. This is partly caused by lacking skills and financial resources of farmers but also by lacking extension services and the top-down attitude in the researcher-extensionist-farmer continuum. Buerkert and Schlecht (2013) state that there are three pre-requisites for success of agricultural innovations in Sudano-Sahelian West Africa. These are (i) enhanced farmers' access to markets (ii) low cost innovations, and (iii) limited risk of no return on investment. Herrmann et al. (2013) call for a paradigm change in research, pledging for more participation of and giving more responsibility to farmers. They state that the empowerment of farmers leads to faster progress with respect to innovation testing, adaptation and sustainable adoption. For local framers, adapting and adopting innovations is a complex process that involves risk considerations. Technologies are easier adopted if they relate to the knowledge background of the farmers and when they can be observed and evaluated (e.g. in demonstration plots) before they enter into on-farm testing. Cropping risks related to a technology and its handling need to be made explicit. Adaptation – that means change of a technology according to the needs and capacities of a farmer needs to be accepted by the researchers, and become a regular concept in their activities.

Several workshops held with the Sahelian smallholder pearl millet farmers revealed that the application of seedballs has no disadvantages in the Sahel region (Biegert, 2013). In fact, it was reported (i) that the indigenous local material components of seedballs are freely available (ii) that all gender can easily produce seedballs, and (iii) that seedballs application might be economical due to low financial demand and rational use of seeds. Neither religious beliefs nor other habits hinder potential adoption of seedballs.

2.9. Conclusions, open questions and research demands

Reviewing what was discussed above, it appears possible that the seedball technology has advantages under Sahelian conditions since it is a cheap technology based on locally available resources that does not disadvantage any sex. However, it is also clear that this technology needs to be adapted and optimized. A panicle yield increment of about 30 % in pearl millet was observed in several on-farm trials in 2016 planting season in Maradi region, Niger Republic. In fact, seedball technology is interesting for other semi-arid areas such as Rajasthan in India, Punjab and Sindh in Pakistan. However, it is of scientific interest to know which mechanisms contribute to the success of the technology in order to refine recommendations and to develop the technology further.

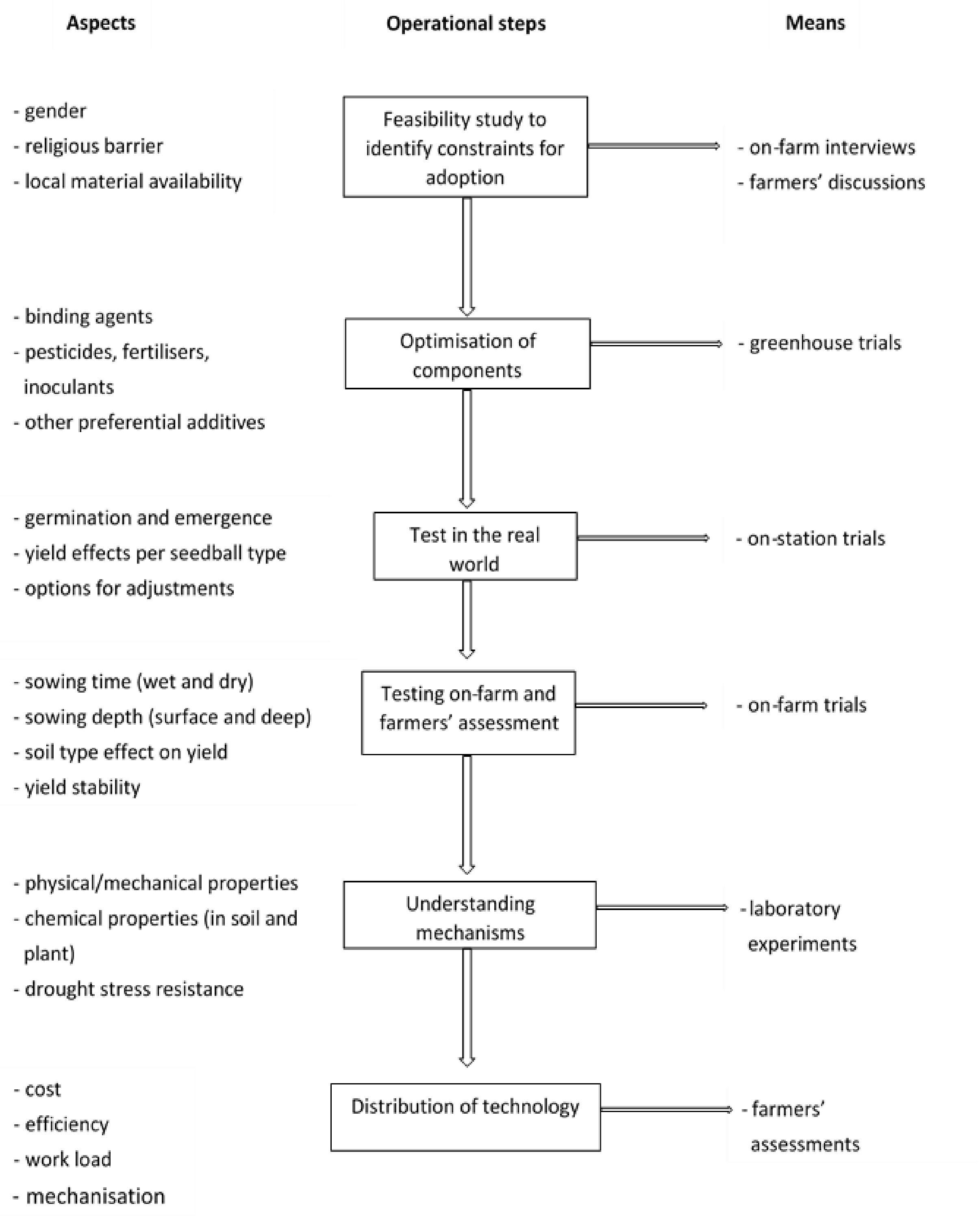

Figure 1: Proposed operational scheme for the development of the seedball technology in the Sahelian smallholder context.

In order to make it operational, the following scheme appears reasonable. First of all, farmers in different regions need to be interviewed with respect to potential constraints for adoption. If no major barriers are revealed, the mechanical and chemical optimisation can start. This is best to be done in greenhouse trials, considering aspects like optimal binding agent, nutrients and pesticides as additives. For the latter, care must be taken that local farmers might be able to apply those chemical compounds in a reasonable and comprehensive manner. Once greenhouse trials show the defined performance (e.g. with respect to germination rates or biomass indicators) first trials can be performed under field conditions in the Sahel. Optimally, one starts with researcher controlled trials in order to avoid too many uncertainties with respect to interpretation of trial results (e.g. non-communicated additional farmer treatments). If these on-station trials are performing, the test phase with demonstration plots in different villages can start. These can yield additional information on necessary adaptation to local conditions and in particular, gender preference, and labor demand. Finally, farmers are free to experiment with the technology only reporting which additional management measures have been taken. Again, this information can help to improve the performance of the technology and to develop a final technical sheet for extension purposes.

With respect to the Sahelian conditions in particular, Schlecht et al. (2006) and Fowler and Rockstrom (2001) reclaim (i) to develop a simple–to–understand technique (ii) which can increase resource use efficiency (iii) and that is compatible with the socio–economic level of the target rural farmers. Therefore, the seedball technology should use freely available, and inexpensive local materials such as sand, loam, termite mound material, charcoal, animal dung or wood ash. With respect to NPK as nutrient additive in the seedballs, only minute amounts per hectare (i.e. several kg) are required; these are available and affordable to smallholder WAS farmers in particular.

Finally, research on socio–economic advantages in the target Sahelian region is mandatory before this technology can be massively distributed to the farmers. Additionally, a proper assessment of gender equality, adoption scenarios, and mechanization for mass production at low labor cost appear meaningful.

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

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3.1. 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.

3.2. 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 P (Rebafka, 1993; Muehlig-Versen et al., 2003), N 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 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.

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.

3.3. 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.

3.3.1. 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.

3.3.2. 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 2mm mesh to remove over-sized particles.

3.3.3. Laboratory analyses

The pH, EC, soluble cations, total P and N as well as C_{org} 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). EC (1:20 H_2O) was measured using a portable EC 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 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.

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

Component	**pH**$_{1:20\ H_20}$	**EC** $_{1:20}$ (µS 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 fertilizer	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 fertilizer**
N$_{total}$	326	151100
P$_{total}$	1880	67200
K^{+}	65100	152500
Ca^{2+}	683	27500
Mg^{2+}	860	7430
Na^{+}	2190	2470

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.

3.3.4. 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 3.3.2 (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.

3.3.5. 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 furtherwater 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 $pHCaCl_2$ 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).

3.3.6. 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 $mgkg^{-1}$ 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.

3.3.7. 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.

3.4. 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.

3.4.1. Experiments 1 and 2: Chemical and mechanical optimisation of seedballs

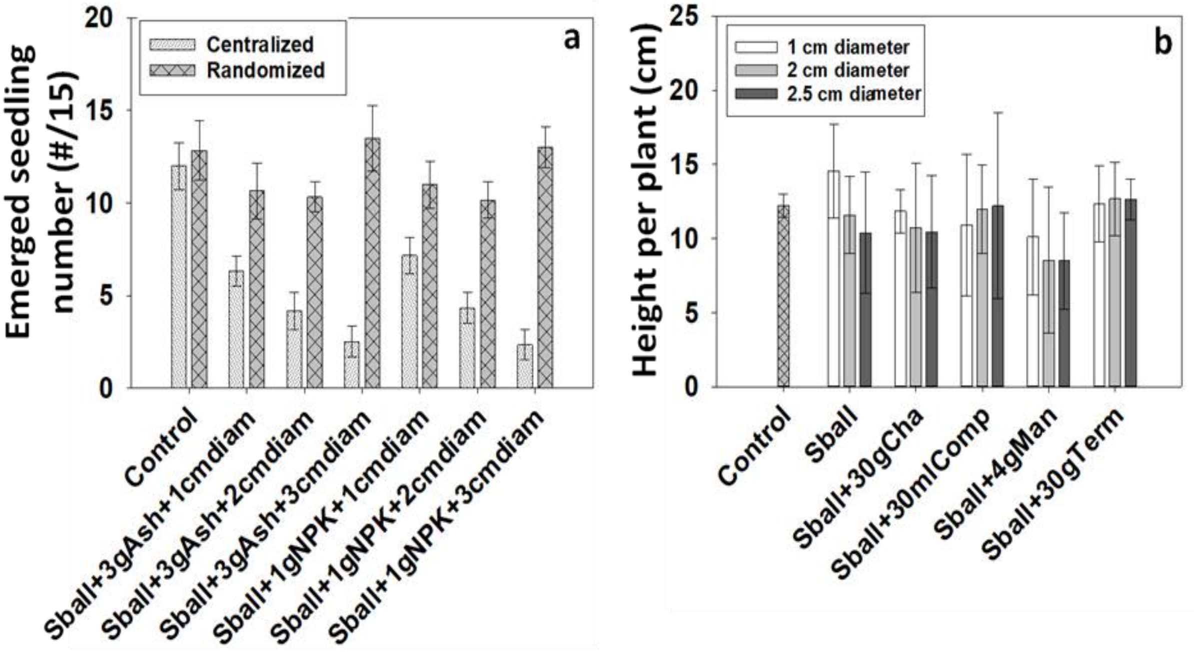

Figure 2: Treatment effects on pearl millet: (a) number of plants at day 7 after sowing, (b) plant height at day 9 after sowing at the greenhouse of ISRA/CNRA research station, Bambey, Senegal. Symbols show arithmetic means (n = 6) and error bars indicate standard deviations (±). Control = non-pelleted 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.

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. 2a). 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. 2b). 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. 3).

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. 4a). 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 (4b and 4c). 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. 4d). 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. 4e). Sball+3gAsh, Sball+0.5gCNT and Sball+1gNPK treatments showed 82 %, 440 % and 193 % more P uptake, respectively, than the control (Fig. 4f). The total nutrient uptake is more indicative than the nutrient content. The former shows the already known pattern for all three investigated nutrients (Fig. 4f). 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. 4f). 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.

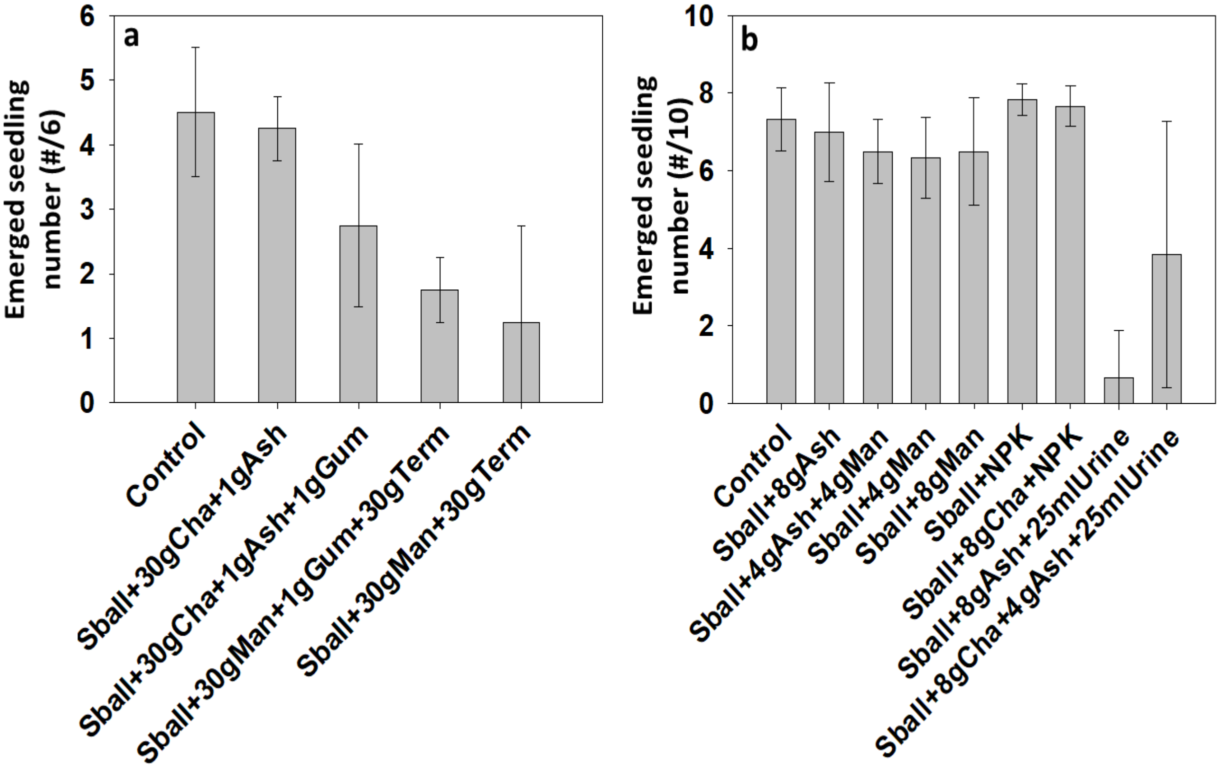

Figure 3: Treatment effects on pearl millet seedling number at the 7th day after sowing for (a) six and (b) ten seeds per seedball, observed at the greenhouse of University of Hohenheim, Germany. Bars represent arithmetic means (n =6) and error bars indicate standard deviations (±). Control = non-pelleted 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.

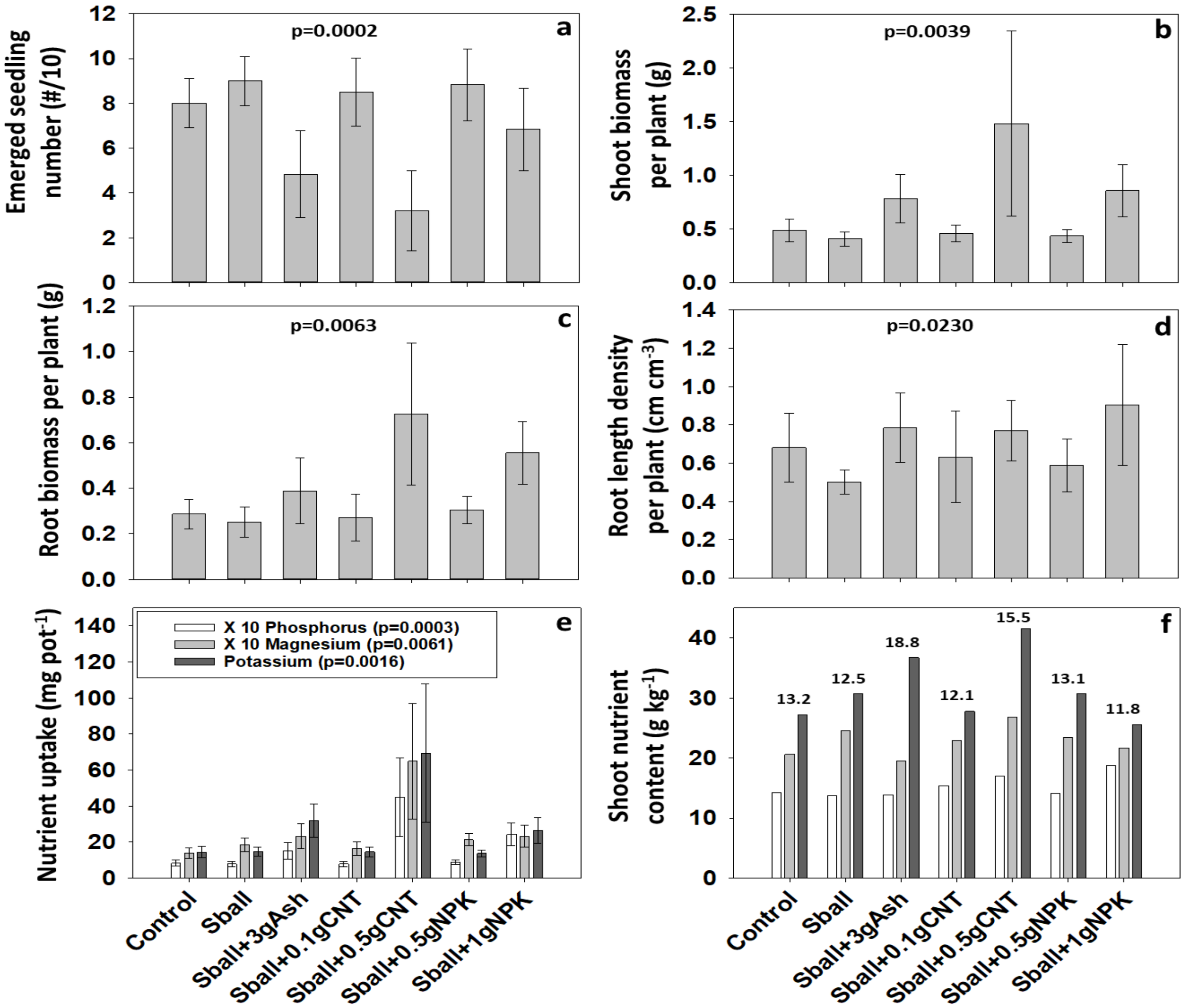

Figure 4: Treatment effects on pearl millet (a) emergence at 7th DAP, and (b) shoot biomass (c) root biomass (d) root length density (e) shoot nutrient content as well as (f) total nutrient uptake, at 28th DAP, observed at the greenhouse of University of Hohenheim, Germany. Numbers in (e) indicate the 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.

3.4.2. 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. 5a). Within 24th 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. 5b).

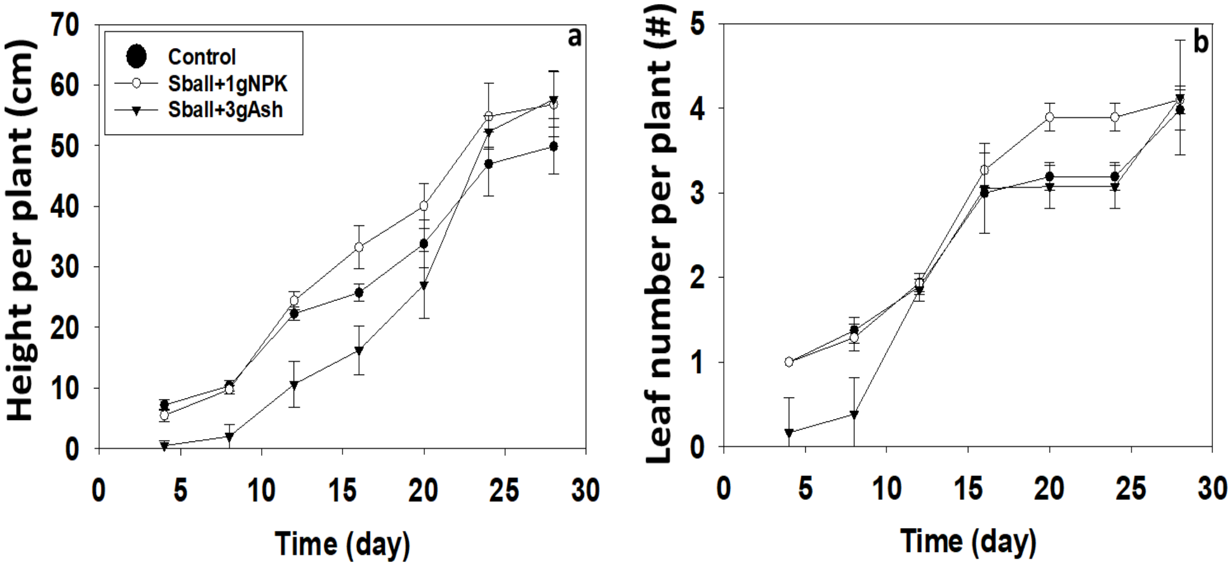

Figure 5: Pearl millet (a) shoot height and (b) leaf number development for different treatments at the greenhouse of University of Hohenheim, Germany. Symbols show arithmetic means (n = 6) and error bars indicate standard deviations (±). Control = non-pelleted seeds, Sball = 2 cm diameter sized-seedball made from a mixture of = 80 g sand + 50 g loam + 25 ml water, Ash = wood ash, and NPK = 15:15:15 mineral fertiliser.

Seedlings emergence slightly declined in Sball+3gAsh and Sball+1gNPK treatments after about six weeks of storage (Fig. 6). 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 observed for all treatments. The seedlings of Sball+3gAsh and Sball+1gNPK treatments in particular were more vigorous than those of the conventional sowing.

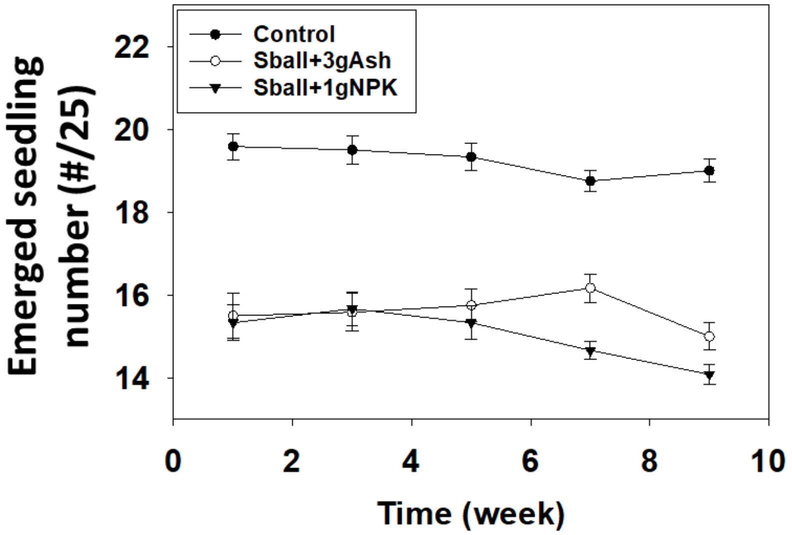

Figure 6: Absolute number of emerged pearl millet seedlings 8 DAP for three treatments as affected by storage time at the greenhouse of University of Hohenheim, Germany. Symbols show arithmetic means (n = 20) and error bars indicate standard deviations (±). Control = non-pelleted seeds, Sball = 2 cm 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.

3.5. Discussion

3.5.1. 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.

3.5.2. 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. 2a). With respect to the diameter, the biomass experiment did not provide a final argument (Fig. 2b). 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.

3.5.3. Experiment 2: Chemical optimisation of seedballs

The negative effect of gum arabic on seedlings emergence (Fig. 3a) 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. 3b), 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 $mgkg^{-1}$) of ammonia (Hebel, 1995).

The probable reasons for failed emergence in the wood ash and CNT amended seedballs (Fig. 4a) 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 (CT) (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 P.

On the other hand, seedlings K content could be increased by ash and CNT application. While the ash effect can be explained by the high content of water soluble K in the ash itself, the CNT effect must be indirect, i.e. by better extraction of K from the soil mediated by a longer root network (Fig. 4c). The same argument can be applied for Mg, since the 0.5 g CNT application yields highest content for Mg as well. The K in the plant can contribute to biomass production (Fig. 4b 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 mgkg^{-1}) and the NPK fertiliser (7430 mgkg^{-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. 4b 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.

3.5.4. Experiment 3: Seedball storage effects and on-station

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. 6). 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.

3.6. 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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4. Seedball-induced changes of root growth and physico-chemical properties – a case study with pearl millet

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4.1. Abstract

Seedball is a cheap ‘‘*seed-pelleting-technique*’’ that combines local materials, seeds and optionally additives such as mineral fertilizer to enhance pearl millet (*Pennisetum glaucum* (L.) R. Brown) early growth under poor soil conditions. The major objective here was to study the mechanisms behind positive seedball effects. Chemical effects in the rhizosphere and early root development of seedball-derived pearl millet seedlings were monitored using micro-suction-cups to extract soil solutions and X-ray tomography to visualize early root growth. Pearl millet (single seedling) was grown in soil columns in a sandy soil substrate. Root and shoot biomass were sampled. X-ray tomography imaging revealed intense development of fine roots within the nutrient-amended seedball. Seedball and seedball+NPK treatments, respectively, were 65 % and 165 % higher in shoot fresh weight, and 108 % and 227 % higher in shoot dry matter than the control treatment. Seedball+NPK seedlings showed promoted root growth in the upper compartment and 105 % and 30 % increments in root fresh and dry weights. Soil solution concentrations indicate that fine root growth ass stimulated by release of nutrients from the seedballs to their direct proximity. Under real field conditions, the higher root length density and finer roots could improve seedlings survival under early drought conditions due to better ability to extract water and nutrients from a greater soil volume.

Keywords: seedball technology, rhizosphere dynamics, pearl millet roots, seedling establishment, early crop growth, Sahel, arid and semi-arid areas, dry sowing.

4.2. Introduction

Pearl millet [*Pennisetum glaucum* (L.) R. Brown] is one of the major staple crops produced grown on nutrient-poor sandy soils of the African Sahel (FAO, 1986; Herrmann et al., 1994). Poor seedling establishment arising from low N and P availability (De Rouw, 2004) is still a challenging factor limiting the yield. The use of mineral fertilizers (Bationo et al., 1993; Pandey et al., 2001), seed treatment (Rebafka et al., 1993; Raj et al., 2004; Karanam and Vadez, 2010) or irrigation (Fox and Rockstro¨m, 2003) have proven to potentially increase crop yield in semi-arid areas such as the Sahel. However, lack of skills and financial resources disallow the Sahelian smallholder farmers to use these options (Corbeels et al., 2014; Brick and Visser, 2015).

A prerequisite for adoption of any technology in the smallholder context is that it is cheap, simple, based on locally available resources, and does not interfere with peak labor demands (Fowler and Rockstrom, 2001). Seedballs are such a kind of seed-pelleting-technique. It combines sand as matrix, loam as binding agent, and supportive additives in small amounts such as fertilizer, wood ash, or pesticides. Moreover, seedballs can be prepared in the dry seasons when labor is not a limiting factor. The technology was developed in the framework of permaculture in Japan (Fukuoka, 1978) and used for revegetation of semi-arid areas in South Australia (Atkinson, 2003). However, little is known about the mechanisms by which plant establishment is improved. Scientific studies and literature on this topic are missing. Due to its materials and properties, seedballs appear suitable in particular for fine-grained seeds such as pearl millet. Application to dry sowing – as frequently practiced in the dry and drought prone Sahelian environment – is a particular option, since the dry state of hard seedballs protects the seeds against predators and might postpone germination to suitable conditions (avoiding unwanted germination under too low rainfall). In addition, additives, such as fertilizers or fungicides, might positively influence crop establishment as well as favor early plant vigor.

The aim of this study was to evaluate the mechanisms behind seedball-mediated positive effects in the root zone of pearl millet seedlings. It is to be expected that seedballs physically and chemically influence soil conditions at a micro-scale (several cm). The main objective was to measure physico-chemical effects spatially close to the seedballs compared to conventional sowing. We hypothesized that seedballs influence (1) available nutrient distribution in the rhizosphere and (2) early root and consequently shoot development of pearl millet within the first 21 days after planting (DAP). In order to test these hypotheses, soil column experiments were conducted, and root growth and soil solution composition were monitored in situ. In addition, soil solution was sampled and chemically analyzed as well as plant biomass (root and shoot) determined.

4.3. Materials and methods

4.3.1. Preparation of soil samples and seedballs

The experiment was conducted in the climate chamber of Helmholtz Centre for Environmental Research, Halle, Germany. Sandy subsoil material was collected from Rastatt (48°49'N, 8°11'E) in Germany, intended to mimic typical Sahelian pearl millet sites. The soil material was air-dried and passed through a 2 mm sieve to remove coarser particles. The soil is characterized by > 90 % sand, a pH$CaCl_2$ of 4.5, less than 1 % organic matter, a carbon : nitrogen ratio of 23, a potential cation exchange capacity of 39 mmol kg^{-1}, and 33 mg kg^{-1} plant-available P (P_{Bray1}). Further properties of this soil can be accessed from Stahr et al. (2009). Apart from the available P content, these properties are similar to those of Sahelian *Arenosol* materials that serve as major pearl millet cropping sites (Herrmann, 1996).

Seedballs made of 80 g sand, 50 g loam, 25 mL water, and with or without 1.0 g NPK (see below) of 2.0 cm diameter size, each, were produced manually. At ambient temperature (20–25 °C), the formed seedballs were air dried in less than 24 h to avoid unwanted seed germination. Each seedball as well as the control treatment contained two pearl millet [*Pennisetum glaucum* (L.) R. Brown] seeds and were thinned to one seedling per germination column on the 5th DAP, owing to the friable nature of sand substrate. The seeds were from local variety collected from farmers in Bambey (Senegal) shortly after harvest in November 2015. Therefore, one seedling (a single plant per germination column) was used throughout the experiment. The seeds were stored for 3 months and 2 weeks at an average temperature of 25 °C prior to this experiment. Three treatments were established: (1) conventional sowing without seedballs served as absolute control, (2) seedballs with no nutrient additive served as seedball control, and (3) mineral fertilizer-containing seedballs represented the intended formula for later application in the field (seedball+NPK). The used mineral fertilizer was NPK 15:15:15. It had 2–5 mm granular size, was white-colored, and contained less than 2 % water.

Unpublished results of preceding experiments revealed that ammonium fertilizers and urea as nutrient additives inhibited germination. For this reason, nitrate was chosen as N fertilizer. Sowing depth for all treatments was 3.0 cm, measured from the soil surface (Fig. 7). A fertilized conventional treatment was not intended, since growth chamber resources were restricted and positive effects of the micro-dosing technology are known (Hayashi et al., 2008). The expected advantage of seedballs versus non-seedball micro-dosing is the lower fertilizer amount required and the lower risk of crop performance failure due to osmotic effects when farmers, as frequently practiced to reduce labor demand, mix fertilizer and seeds during conventional sowing.

4.3.2. Soil column setup and experimental conditions

Columns were 7.0 cm in diameter and 25.0 cm in height. Transparent polycarbonate pipes were used.

The columns were carefully filled with sieved sand, using a simultaneous filling and compacting method aiming at a homogenous bulk density (1.6 g cm^{-3}). At the bottom of each column, a nylon mesh of 30 mm pore size was installed to allow free drainage at the lower boundary. The complete randomized experimental design comprised six replications of the three treatments: control, seedball, and seedball+NPK. For each treatment, ten columns were initially prepared. After germination, the six most identical plants with respect to height and leaf number were selected for the experiment. All columns were wrapped in aluminum foil to prevent light exposure of the soil that triggers algal bloom (Linkous et al., 2000). The gravimetric water content of each column was adjusted to 16.3 %.

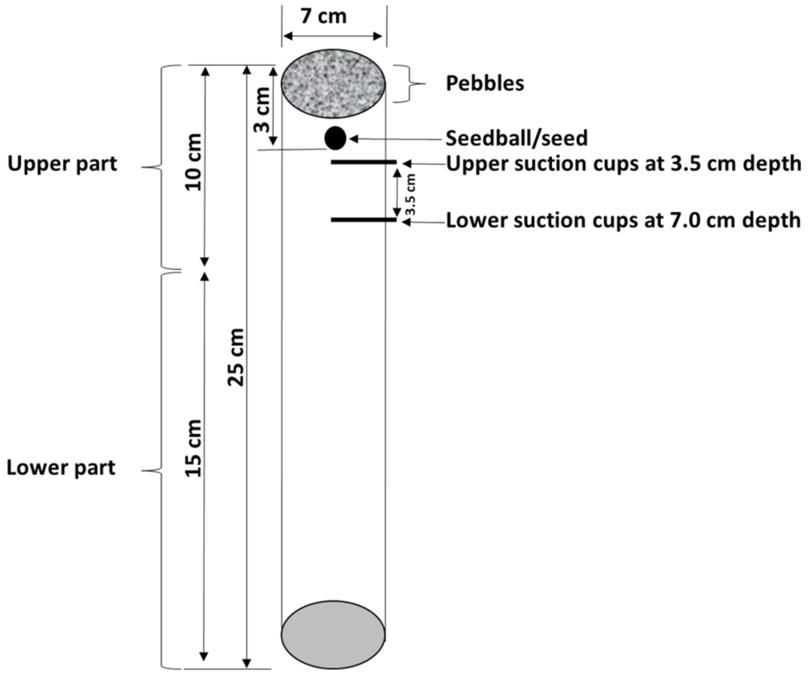

Figure 7: Sketch of a soil column displaying position of micro-suction cups in relation to seedball and definition of the upper and lower part of the column for the determination of root parameters.

About 2.5 mm-sized gravel covered the topmost 2.0 cm of the columns to minimize water loss via evaporation. Through weighing, soil moisture content was daily adjusted until harvest. Day length of

12 h was ensured with 350 mmol m^{-2} s^{-1} photosynthetic active radiation. Day and night temperatures of 30 and 25 °C, respectively, with a relative air humidity of 65 % were maintained throughout. The seedlings were harvested on the 22nd DAP. Root weight, root length, and root diameter, as well as shoot weight were separately assessed. In addition, the soil columns were segmented into an upper (0.0–10.0 cm) and lower (10.1–25.0 cm) part as shown in Fig. 7.

4.3.3. Computer tomography and soil solution

X-ray tomography (CT) was performed with an industrial µCT (XT H 225, Nikon Metrology) with 140 kV, 286 µA (equals 40 W), and 500 ms exposure time to obtain raw images from the upper and lower root zones of the germination columns. Each scan was performed with 1000 projections and one frame per projection, resulting in an exposure time of 8.5 min per scan. A copper filter with 0.5 mm thickness was used to reduce the beam hardening artefact and the amount of low energized radiation. Distance between X-ray source and sample was about 13 cm. The spatial resolution of the X-ray tomogram was 40 mm. The calculated dose rate for these settings is 480 R h^{-1}, equal to 4.2 Gy h^{-1}. The dose was calculated with the RadProCalculator Version 3.26 (www.radprocalculator.com). For this study, we only considered the CT data for visual examination regarding early root growth. Further quantitative analyses of CT data for all time points were out of scope for the present study. All image processing steps were carried out with the Fiji software (Schindelin et al., 2012). Noise was removed with a non-local means filter (Buades et al., 2005) and roots were segmented using hysteresis thresholding with user-defined thresholds as implemented in the 3D Image suite (Ollion et al., 2013). Ex ante, CT image analyses showed that the soil columns were homogeneously filled with the growth substrate, and that seedballs and suction cups did not change their position within the columns (not shown).

As for CT, soil solution sampling took place every week from each soil column. MicroRhizon samplers from Rhizosphere Research Products B.V., The Netherlands (https://www.rhizosphere.com/microrhizons), 1.0 mm in diameter and a mean pore size of 0.15 mm, six per soil column (three per layer), were installed in 3.5 and 7.0 cm depth as described by Vetterlein and Jahn (2004). Soil solution sampling was carried out at a suction of 390 (–15) hPa for less than 4 h. In general, three samples per depth were measured and arithmetic means reported here. In cases in which sample volume was too small, soil solution was pooled for one sampling depth in the same soil column. EC, pH, and P concentration were measured. The first two variables were immediately measured after sampling, using a Mettler-Toledo Seven Excellence® with automatic temperature correction. These measurements were conducted at a room temperature of 20 ℃. The remaining soil solutions were frozen and stored for P determination applying the molybdenum blue and ascorbic acid method. The absorbance of the complex was measured at 710 nm using a Varian ‘‘Cary 50 Conc’’ UV-VIS spectrophotometer. Details of the methods used to determine the P concentration of the solutions can be found in Rodriguez et al. (1994).

4.3.4. Shoot and root parameters

Plant height and leaf number as shoot development parameters were recorded after each CT-scan. After harvest (22 DAP), fresh weights (biomass) of the shoot and root systems were directly measured. The dry matter was obtained after drying in an oven at 68 ℃ for 36 h. The upper and lower parts of the column were separated at harvest. Roots were obtained by washing the material through a sieve (2 mm mesh size). The roots were cut to lengths of about 1.0 cm using a clean pair of scissors to avoid root inter-twisting during scanning. Inter-twisted roots often lead to errors in root diameter as well as root length measurement. Half of each sample was used for dry matter determination, the other half for determination of root length in different root diameter classes. Root length and root diameter were measured using WinRhizo® V2009c software (Regent Instruments, Nepean, Canada).

4.3.5. Statistical analysis

Gauss distribution and variance homogeneity were tested using 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). Proc MIXED was performed for repeated measurements (e.g., H^+ concentration of soil solution). The treatment means were compared for significant differences (P < 5 %). Results are presented as treatment means (– standard deviations) of the measured variables. All analyses were performed with SAS version 9.4, while Sigma Plot version 13.0 was used to plot all graphs.

4.4. Results

4.4.1. Temporal development of root and shoot parameters

Germination for all replicates occurred between the 3rd and 5th DAP. Plant height as a parameter for shoot development over time differed between treatments as early as 7 DAP. It was consistently and significantly higher for all seedball treatments throughout the experiment, compared to the control (Fig. 8a). Likewise, leaf number developed more rapidly in seedball+NPK (Fig. 8b), but there was no significant difference.

Root development was monitored with CT 7, 14, and 21 DAP. Visualization of roots and seedballs was possible (Fig. 9), but not all root segments could be segmented from the CT data. The given resolution (voxel size 40 mm) was too low in relation to the root diameter class dominating in pearl millet (compare Fig. 11) to conduct automated complete segmentation. Hence, only two representative examples (selection based on WinRhizo results) were selected for detailed image processing.

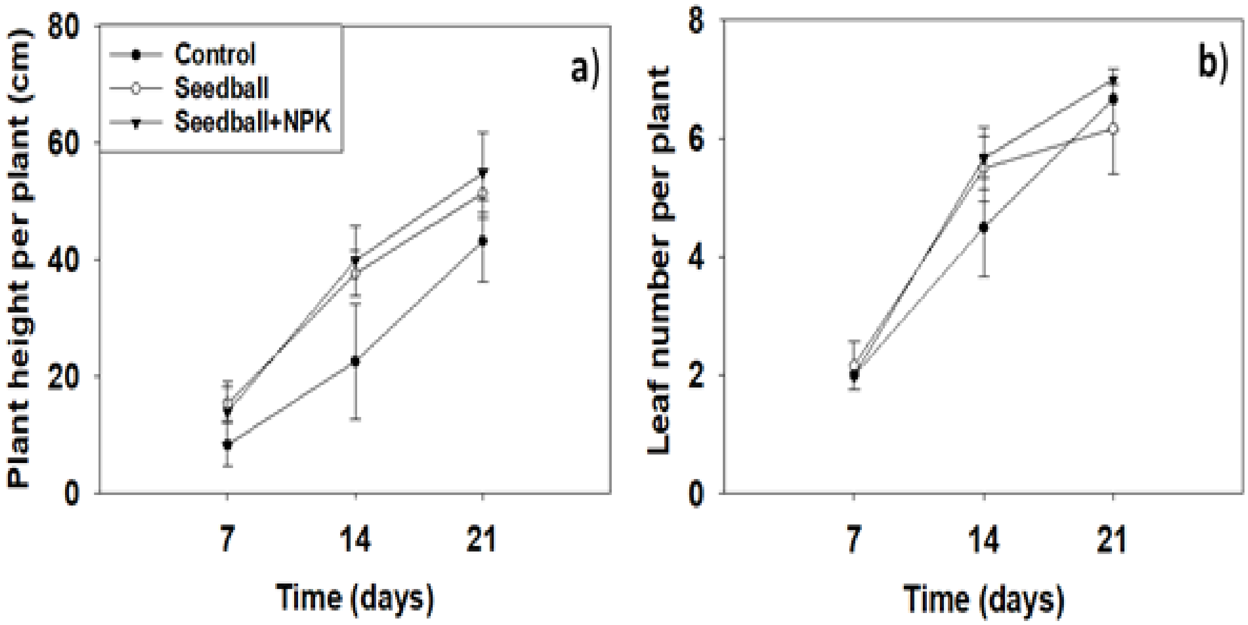

Figure 8: Pearl millet shoot development after planting as indicated by (a) plant height and (b) leaf number for the three treatments. Symbols show arithmetic means (n = 6) and error bars indicate standard deviations (–).

The comparison of control and seedball+NPK clearly shows that fine root growth (red color in Fig. 9b) was strongly promoted within the seedball.

The seedball itself is clearly visible within the surrounding soil matrix. With respect to a qualitative screening of all CT scans, a tendency towards a higher total fine root development in the upper column parts in the seedball treatments was observed, while conventionally sown plants developed stronger roots faster to greater depth.

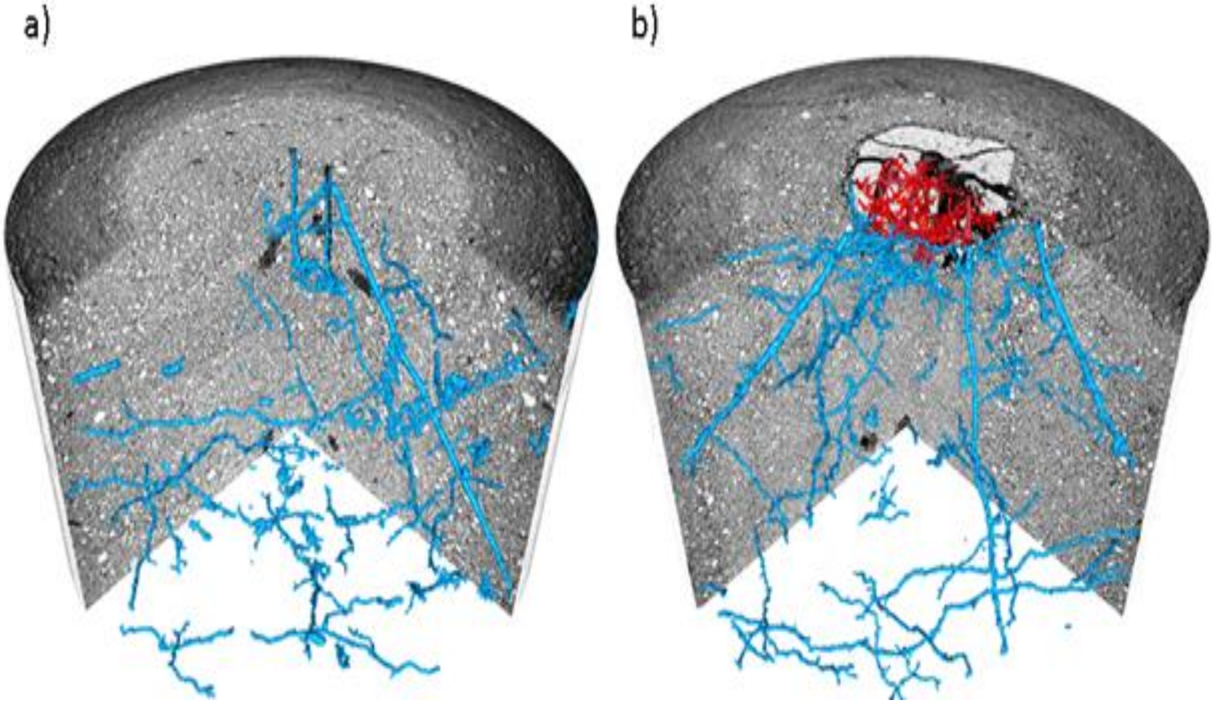

Figure 9: 3D representation of the segmented root system within the upper part of the soil column on day 21 within the spatial context of the soil–seedball structure. Roots within the seedball are colored in red, roots outside the seedball are colored in blue. The soil-seedball structure is presented in grey, with dark colors representing material with low electron density, i.e., air-filled pores and light colors representing high electron density, i.e., quartz grains. (a) Control treatment, (b) seedball+NPK. Voxel side length is 40 mm, hence roots in the lowest diameter class (0–200 mm) could only partially be segmented.

4.4.2. Shoot and root biomass at harvest

Shoot fresh and dry weights as well as root fresh weight at harvest showed the same response pattern as already reported for the biomass indicators during the experiment. For example, seedball and seedball+NPK treatments, respectively, were 65 % and 165 % higher in shoot fresh weight, and 108 % and 227 % higher in shoot dry matter than the control treatment (Fig. 10a). Seedball+NPK seedlings showed 105 % and 30 % increments in root fresh and dry weights, compared to the control (Fig. 10b).

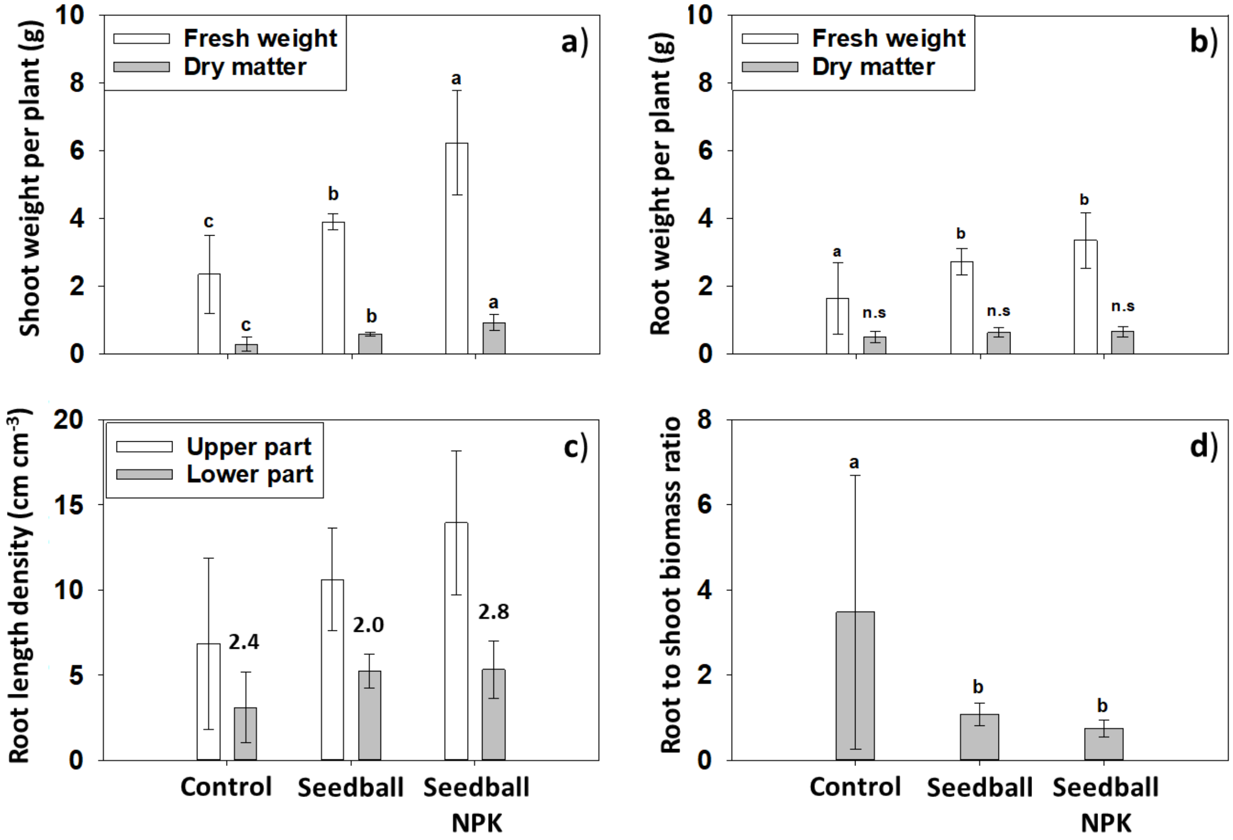

Figure 10: Fresh and dry weights of pearl millet (a) shoot (b) root biomass, as well as (c) root length density and (d) root:shoot biomass ratio 21 d after planting for the three treatments. Numbers in (c) indicate the ratio of root length density between upper and lower part of the columns. Lower-case letters on top of bars indicate significant differences of means, n.s = not significant. Arithmetic means (n = 6) are shown and error bars indicate standard deviations (–).

In seedball treatments, higher root density was detected in particular for the upper part (Fig. 10c). In particular, for treatment seedball+NPK root growth was promoted more strongly within the upper compartment. This is reflected by the ratio of root length density in the upper versus the lower compartment (Fig. 10c). The root : shoot biomass ratio (Fig. 10d) clearly shows that despite the local promotion of fine root growth within the seedball (Fig. 9), overall shoot growth increased more than root growth in the seedball treatments. The control plants invested relatively more into root development, compared to those in the seedball treatments, as indicated by the root:shoot dry matter ratio (Fig. 10d).

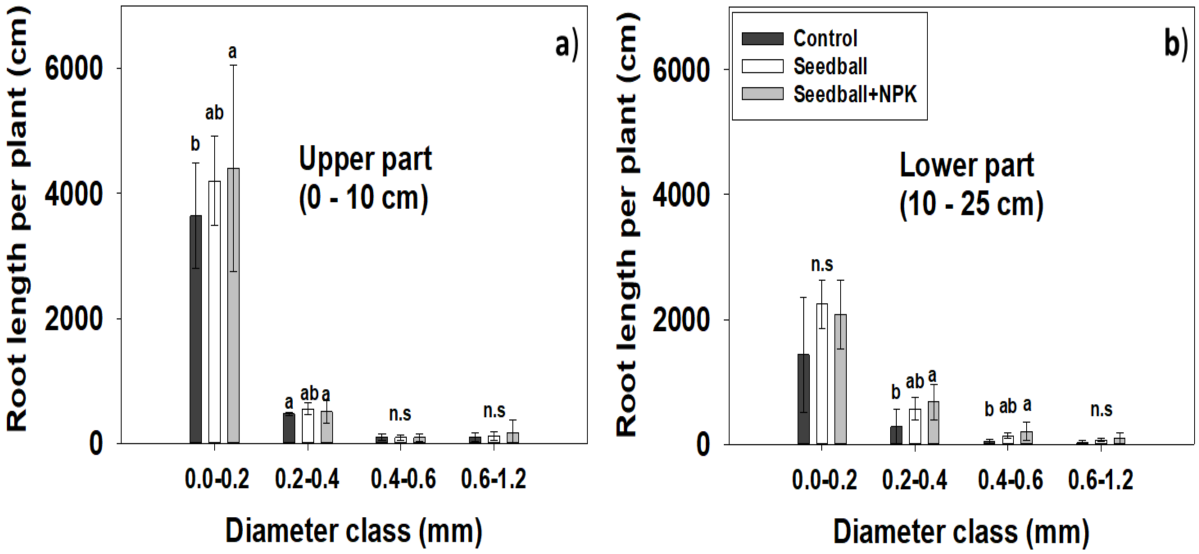

Figure 11: Pearl millet root length within different diameter classes 21 days after planting for the three treatments. Data are provided separately for the (a) upper and (b) lower part of the columns. Lower-case letters on top of bars indicate significant differences of means, whereas n.s. indicates non-significant differences. Arithmetic means (n = 6) are shown and error bars indicate standard deviations (–).

In all treatments, the largest share of the root length (about 83 %) was found in the diameter class < 200 mm (Fig. 11). In the upper part, this diameter class was more dominant than in the lower part. The highest root length in diameter class < 200 mm was found for treatment seedball+NPK.

4.4.3. Soil solution composition

Soil solution EC decreased with time in both sampling depths for all treatments, indicating depletion of salts in soil solution by plant nutrient uptake (Fig. 12c, d).

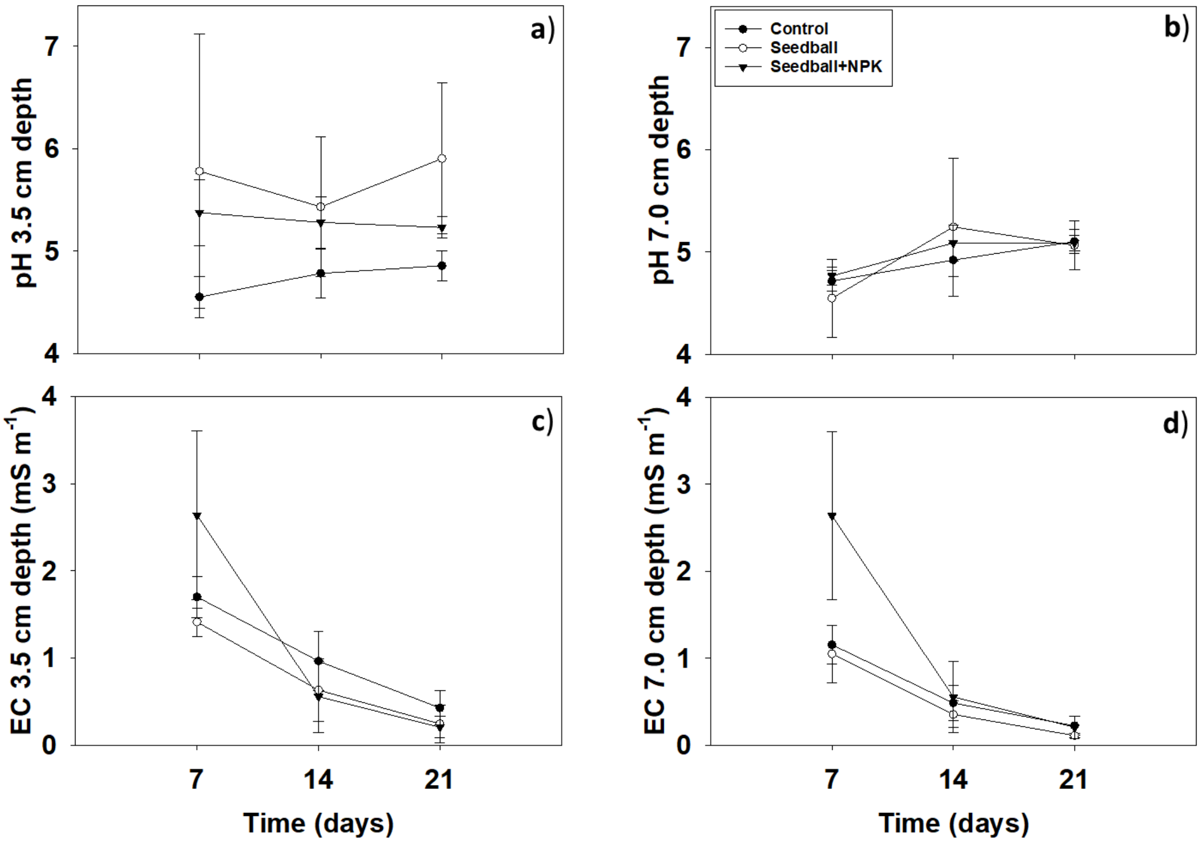

Figure 12: Change of pH and EC at 3.5 and 7.0 cm depth for the three treatments throughout the 21 d growth period of pearl millet. Symbols show arithmetic means (n = 6) and error bars indicate standard deviations (–).

This was observed in particular for "seedball+NPK", which initially (7th DAP) showed the highest values. In general, values were higher in 3.5 cm depth (vicinity of seedball; Fig. 12c) than in 7 cm depth (Fig. 12d). This effect is in part due to a slight gradient in water content induced by gravity, but the main driver is suspected to be nutrient release from the seedball, in particular in the Seedball+NPK treatment.

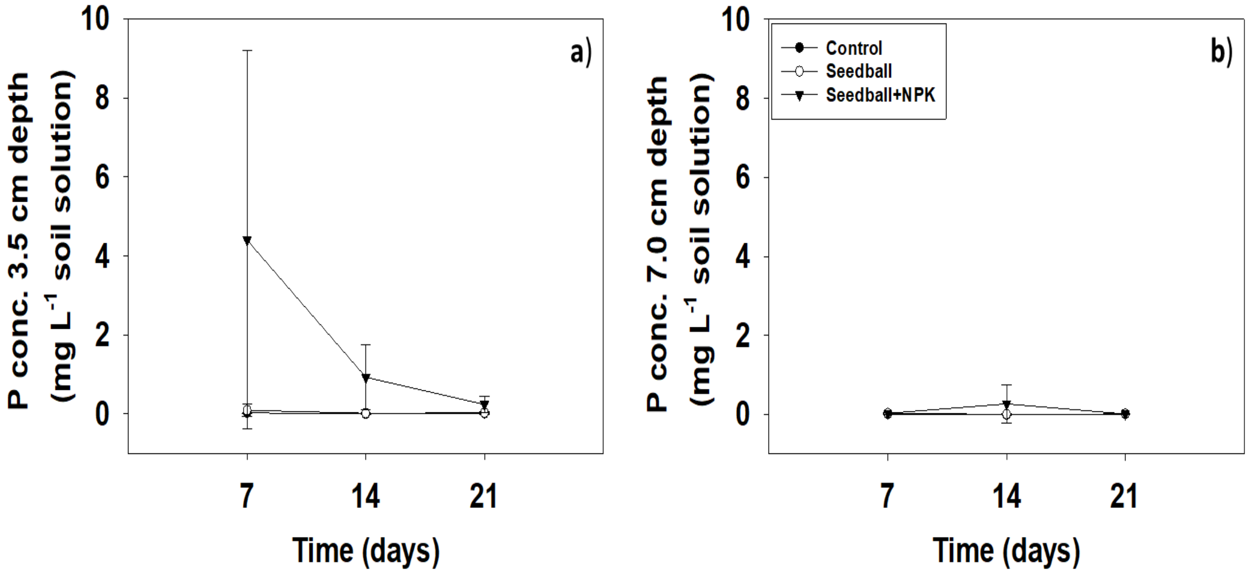

Figure 13: Change of soil solution phosphorus concentration in (a) 3.5 and (b) 7 cm depth for the three treatments throughout the 21 d growth period of pearl millet. Symbols show arithmetic means (n = 6) and bars indicate standard deviation (–).

Soil pH was higher in the seedball treatments close to the seedball (3.5 cm depth). The seedball+NPK treatment showed a P concentration in the soil solution one order of magnitude higher than the other treatments, with a decline in P concentration over time (Fig. 13a). In 7.5 cm depth, P concentrations were low in all treatments (Fig. 13b).

4.5. Discussion

4.5.1. Effects of seedballs on growth and development of pearl millet seedlings

Seedballs did not hamper germination due to the fact that a large number of pre-trials were conducted in order to find the right formula with respect to seedball size, constituents, and seed number (Nwankwo et al., unpublished). It is well described in the literature that coating pearl millet seeds with nutrients in high concentration, e.g., P (Rebafka et al., 1993), binders, or other coating products

(Peske and Novembre, 2011) can inhibit germination. In particular, Arabic gum showed a partly negative influence on germination when used as binding agent in seedballs (Muehlena, 2013). Therefore, it is necessary to understand the effects of any additive (e.g., urea or other organic fertilizers) with respect to nutrient and water availability, as well as toxic effects in the vicinity of the germinating primary roots (Pan et al., 2016).

In regard to the early growth, seedballs showed their efficiency within the first 3 weeks after planting, exactly the time span for which they were expected to be supportive. This is true in particular when mineral fertilizer is used as a nutrient additive. Positive effects were also obtained in other experiments when replacing NPK by wood ash that is a locally available natural fertilizer and contains water-soluble P and K compounds (Nwankwo et al., unpublished). It appears that the NPK fertilizer is available to the plants from the beginning and its concentration was such that no negative osmotic effects were observed. Similar growth-stimulating effects were reported for pearl millet when seeds were coated with P alone (Rebafka et al., 1993; Valluru et al., 2010). This appears reasonable since P is often seen as the major limiting nutrient in Sahelian sandy soils (Rebafka, 1993; Bationo and Buerkert, 2001).

Enhanced root proliferation, particularly within the seedball, was detected through CT-scanning in seedball+NPK treatments. Further fine root analysis with WinRhizo confirmed a large fraction of fine roots in particular in the upper part of the treatment seedball+NPK. This is in line with high P concentration in soil solution in this treatment (Fig. 13). Local increase in P concentration is known to promote root branching (Kretzschmar et al., 1991; Hafner et al., 1993; Rebafka et al., 1994), particularly at seedlings stage. A significant increase in overall pearl millet yield (panicle and stover biomass) has been reported in the Sahelian soil characterized as low-P soil (Karanam and Vadez, 2010). The main factor responsible for this yield increment was the early nutrient supply to the seedlings at emergence stage (Rebafka et al., 1993; Valluru et al., 2010). Seedballs have the potential to yield similar results in Sahelian subsistence pearl millet production systems if properly produced and applied.

Seedball seedlings developed more homogeneously than the more erratically behaving control (see error bars in Fig. 10). Growth variability is a common characteristic in Sahelian pearl millet stands (Gerard and Buerkert, 2001). However, since the material in the soil columns was homogeneous, the varying response of seedlings in the control are likely explained by non-homogeneity of seed quality (e.g., size or nutrient content in the kernel) which is of particular relevance if external nutrient supply is low. In the Sahelian context, landraces are widely cropped that are, by definition, genetically non-uniform (Haussmann et al., 2012). This can be suspected for the local Senegalese variety, too.

Root length density was lowest in the control treatment (Fig. 10c) and at the same time, root to shoot dry matter ratio was highest (Fig. 10d). These facts indicate that the control plants needed to invest relatively more into the root system in order to collect nutrients, since water was not a limiting factor in the experimental setup. CT scans indicated that seedball+NPK favored root growth in particular within the seedball and more general in the upper part. While this strategy is adequate for exploiting the fertilizer applied, it might result in an increased risk in the incidence of drought stress. In particular, in combination with the decrease in root:shoot ratio, a larger transpirational demand has to be satisfied. On the other hand, the higher root density in the upper centimeters allows exploiting water resources that are otherwise lost by evaporation. Additionally, the K supply by the fertilizer might result in higher water use efficiency. In the African Sahel, where drought is often inevitable particularly at early pearl millet growth stages, crop water management is crucial. This implies that fast development of the seedlings will be advantageous if the growth season is shortened by drought, but not if drought occurs early in the season.

One question that remains is why the seedballs without nutrient addition had a positive effect. Most likely, the loam added as filler contained nutrients that could be efficiently used by the small seedlings. Loam constitutes 35–40 % of the seedball matrix. The loam hardly contains available N if the source is subsoil material – as in this case. In the Sahel zone, termite mound material can as well serve as binding agent. Large termite mounds can contain as much as 230 mg kg^{-1} nitrate (Herrmann et al., 1994). Since termite mound material in sandy soils contains regularly more clay particles, it could be used where loam is otherwise not available. The measured pH of the seedball treatment was 5.1, i.e., pH was shifted closer to the optimum for the availability of soil P. As a consequence, P availability was likely increased. However, this was not reflected in the soil P concentration. There are two factors influencing the pH change: the loam and the fertilizer components. In the case of the seedball treatment, the loam component alone increased the soil solution pH to 5.5–5.9. This effect is probably due to the low buffering capacity of the pure sand that was used as matrix in the growth columns. The pH value of the used fertilizer for the seedball+NPK treatment was 4.8. Therefore, as expected, the loam effect was reduced resulting in a pH of 5.2–5.3. The control (4.5–4.9) more or less reflected the bulk soil pH (4.5). In principle, soil solution pH is influenced by the form of the N source applied, acidic or alkaline for NH_4^+ or NO_3^-, respectively (Smiley, 1974; Nye, 1981; Gijsman, 1990). However, the temporal trends are too small in the nutrient-amended seedball treatment to be interpreted in this respect.

Seedball+NPK had an effect on the EC and P concentration of the soil solution in the immediate environment (several centimeters). The effect is only visible in the first DAP and vanishes rather fast. With respect to the decreasing order in the measured EC (seedball+NPK > seedball > control), again mineral fertilizer and the loam component can be made responsible. The fertilizer has water-soluble compounds and the loam contains exchangeable ions. These differences were clear on 7th DAP for the nutrient-amended seedballs, but decreased in the following to non-significant differences. The temporal trend to decreasing values can be explained by the nutrient uptake of the seedlings, reducing the ion concentration in the soil solution. Osmolarity of the solution showed similar trends (data not presented). Due to the small soil solution volumes sampled, only P could be analyzed with respect to nutrients. On 7th DAP, the P concentration in the nutrient-amended seedball treatment was over 160-times higher, compared to the control (Fig. 13a), in the upper rhizosphere. At 7 cm depth, the small concentration fluctuations of extreme low values hardly allow for any interpretation. Therefore, the spatial effect of seedballs in this respect is rather small. This is probably due to two reasons: (1) the nutrient amount in seedballs is, absolutely, small and (2) the roots absorb this resource rather fast from the soil solution.

4.6. Conclusion

Seedballs positively influence biomass variables of pearl millet seedlings in particular within the first three weeks of establishment. The higher root length density and biomass of seedlings developed from seedballs might increase the survival rate under Sahelian field conditions in the case of drought occurring late in the season. The small amounts of nutrients that can be added to seedballs only have a short-duration effect on plant performance. The soil solution data indicate that the nutrient concentration is only higher in the seedball environment during the first week. Whether this improved seedling establishment is sufficient to promote plant growth throughout the season needs to be tested under field condition.

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5. Discussion: Are seedballs a reliable technology for pearl millet subsistence farming in the sandy West African Sahelian belt?

Poor seedlings establishment continues to be the major cause of low panicle yield in the WAS smallholder pearl millet production system (Rebafka et al., 1993; Karanam and Vadez, 2010). The nutrient-deficient *Arenosols* characterizing this region (IUSS, 2014), the micro-variability of the soil (Brouwer et al., 1993; Herrmann et al., 1994), and early seasonal drought arising from the erratic rainfall, in particular, at the beginning of the season (Sivakumar, 1988) have been strongly linked to poor seedlings establishment. Coating of pearl millet seeds with pure P (Rebafka et al., 1993; Karanam and Vadez, 2010), soaking of seeds in *Pseudomonas fluorescens* isolates i.e. seed priming (Raj et al., 2004) and mineral fertilization (Badiane et al., 2001; Pandey et al., 2001) have been generally accepted as lasting solutions to enhance seedlings establishment in the WAS region. However, the adoption of these techniques by the local farmers is uncertain due to lack of skills to practise seed treatments and lack of financial resources to acquire NPK, coupled with the unavailability of the specific recommended fertilizers in the market (Van der Pol and Traore, 1993). According to Fowler and Rockstrom (2001), the factors that increase innovation adoption in the context of the African smallholder farmers in particular are (i) the use of local materials (ii) simple applicability, and (iii) affordability. Consequently, the main goals of this study were to improve pearl millet seedlings establishment in WAS environment using a local material-based innovation – i.e. seedball technology, understand its enhancement mechanisms, and determine its agronomic benefits for the smallholder farmers. Hence, the main findings of this study were:

(1) The seedball technology totally conforms to the agronomic practices of the WAS smallholder farmers. The farmers can independently produce and apply seedballs with freely available resources – i.e. sand and loam. Gender and religion seem not to pose a barrier to seedball applicability in this

region. In addition, the involvement of the farmers as early as the seedball development stage was crucial to increase its adoption by the local farmers.

(2) The optimized seedball technology enhanced the performance of pearl millet seedlings under WAS conditions i.e. early seasonal drought and P-deficient soils. Wood ash and NPK as nutrient additives are crucial to increase pearl millet early biomass. Ammonium fertilizers as well as animal urine as nutrient additives, however, inhibited germination. The 2 cm diameter sized seedballs with randomly placed seeds allowed for optimum seedlings establishment.

(3) The root and shoot enhancement of pearl millet seedlings by the seedball seemed to be triggered by an increased nutrient release, in particular P into the root zone. However, the nutrients released by the seedball were depleted after three weeks of planting by plant uptake. From this moment onward, nutrient supplementation is mandatory e.g. through organic manuring to further support the growth of the well-established seedlings.

(4) The seedball technology seemed to be beneficial to the WAS local farmers. Seed usage at sowing was minimized. In addition, there are hints that seedball sowing is simple on the sandy soils in particular. However, the farmers needed more time to produce the seedballs relative to using the conventional seeds.

5.1. Optimization and further tasks

Confirming to our hypothesis, pearl millet seedlings establishment was enhanced soon after emergence by seedballs, in particular when NPK and wood ash were used as nutrient additives. Our study revealed the best recipe for making seedball dough (Sball), at which germination is not hampered, was derived from a mixture of 80 g sand + 50 g loam + 25 ml water + 2.5 g pearl millet seeds. Exactly, 10 to 11 seedballs of 2 cm diameter size can be produced from this gravimetric base dough mixture. Random seed placement inside the seedball showed good germination performance relative to central seed placement. The diameter size and sowing depth from the soil surface for seedball were optimum at 2 cm and 3 cm, respectively (Chapter 3). The poor germination performance observed in the centrally placed seeds probably resulted from the autotoxic water-soluble compounds produced by pearl millet roots during emergence, which declined germination at higher concentration (Saxena et al., 1996). This assumption is based on the fact that the pearl millet seeds were tightly clustered in our seedballs. The poor emergence observed in seedball sown at > 3 cm depth could be linked to mechanical impedance, which resists small seeded species from breaking through substrates, in particular at > 3 cm sowing depths. Chen and Maun (1999) investigated the effect of sand burial on seed germination and seedling emergence in ten *Calligonum species*, and pointed out that the deeper the seeds in sand, the lower the germination. A major advantage of recommended seed placement relative to central seed placement is time saving during seedball production; the task of allocating a certain number of pearl millet seeds per seedball is minimized since the seeds can be directly mixed with loam, sand and water during base dough preparation.

Sball+3gAsh and Sball+0.5gCNT treatments reduced seedlings emergence by about 40 % and 60 %, respectively. High osmotic pressure can be suspected for the reduced emergence, since these same water-soluble compounds at lower concentration in the seedball did not reduce seed germination. Reduced seed germination is often associated with seed coating. For instance, Rebafka et al. (1993) observed the same in pearl millet when seeds were coated with pure P at higher concentration. However, it is possible to increase seed number in the seedballs when necessary (Chapter 3). Considering the local farmers ability to make the seedballs by themselves, unlike seed coating with pure P, the challenge of reduced seedlings emergence in seedball can be tackled by increasing the seed content per seedball. A recommendation is to investigate the solubility of wood ash gotten from different sources since wood ash greatly varies in components, depending on the burnt materials, combustion process and ash conditioning (Augusto et al., 2008). Ammonium fertilizer, cow urine and arabic gum totally inhibited seed germination in the seedball. This observation is consistent with the reports of Pan et al. (2016) on the toxic effect of ammonium compounds on cereal seed germination, particularly for ammonium fertilizer and urine. Therefore, these compounds and fertilizers that contain NH_4^+ exclusively are not recommended as additives in seedballs; choice of fertilizer is crucial. Other tested potential nutrient additives in the seedball such as ruminant dung and compost manure showed insignificant effects on early biomass development at concentrations in the seedballs that did not hamper germination due to their NH_4^+ content. This is contrary to the purpose of the seedball; hence, animal dung and compost manure were considered unsuitable as seedball nutrient additives.

Seedball amendment with 1 g of NPK (Sball+1gNPK), 0.5 g CNT (Sball+0.5gCNT) and 3 g (Sball+3gAsh) significantly enhanced the early biomass indicators in pearl millet seedlings. The observed overall root length, root length density, root biomass as well as the root dry matter were greatly enhanced. Likewise, seedlings height, leaf development obtained through leaf counting, shoot biomass as well as shoot dry matter were enhanced. These observations are consistent with the reports of Karanam and Vadez (2010) and Valluru et al. (2010) when P in particular was supplied to pearl millet as early as seedlings emergence in P-deficient sandy soils. N supply increased leaf development (Coaldrake, 1985) as well as dry matter (Coaldrake and Pearson, 1985) in pearl millet. Thus, our findings corroborate the hypothesis that seedballs increase early P supply to produce, in turn, healthy pearl millet seedlings during the establishment phase. P content of the seeds often serve as nutrient source during seedlings emergence (Hall and Hodges, 1966). Hypothetically, seedball will show less enhancement effects with greater grain sizes due to higher P stock per single grain. The thousand grain weight of pearl millet varies only between 14 to 44 g per 1000 grains (Baryeh, 2002).

Thus, a suggestion is to experimentally test the effect of pearl millet grain size on the early biomass indicators.

Seedballs did not significantly enhance P, K and Mg nutrients content in pearl millet. Nevertheless, total nutrient uptake, as a product of biomass and nutrient content, was significantly enhanced by Sball+1gNPK, Sball+3gAsh and Sball+0.5gCNT treatments (Chapter 3). Poor P and K supply results in poor nutrient uptake in pearl millet (Scott-Wendt et al., 1988). In the WAS, where P content of the soil can be as low as 1 mg kg^{-1} (Manu et al., 1991), the seedball technology can be an alternative, for early nutrient supply, to the local farmers who cannot afford other sophisticated seed treatment options. The use of wood ash as nutrient additive to the seedball by the farmers would be one way of increasing P availability and uptake by plants. Wood ash has been shown to release P as well as ameliorate low soil pH (Nkana et al., 2002). The poor seedlings establishment effects of the acidic as well as low plant available P soils of the Sahel (Scott-Wendt et al., 1988) on pearl millet can be potentially minimized through the seedball technology. In addition, the enhanced K uptake in seedball-derived pearl millet seedlings can potentially increase drought resilience in the Sahel, where early seasonal drought is sometimes inevitable (Sivakumar, 1988). Higher K uptake in pearl millet is positively associated with drought resistance (Ashraf et al., 1994). However, to clear these suspicious advantages of the seedball technology, field trials in the WAS environment are recommended since our experiment was conducted in pots as well as climate-controlled environments.

5.2. Exploring mechanisms and open questions

Previous studies of seed coating with pure P by Rebafka et al. (1993) as well as priming by Raj et al. (2004) and mineral fertilization (Badiane et al., 2001), obviously, increased pearl millet seedlings establishment and panicle yield under WAS conditions. However, a major critic to these options remains their inaccessibility to the WAS subsistence pearl millet farmers in particular. In this study, the chemically (osmotic effect reduction, nutrient content) and physically (right diameter size, random seed placement) optimized seedball technology clearly enhanced pearl millet seedlings establishment. The investigated mechanisms behind this positive enhancement revealed that seedballs released nutrients that most likely improved the physico-chemical properties in the pearl millet root zone, compared to traditional sowing system (Chapter 4).

As observed through the CT-scan, Sball+1gNPK in particular showed early (first 7 days), fine as well as intense root development in pearl millet seedlings, compared to the control. The ex-situ nutrient analysis of the soil solution sampled from the root zone, revealed Sball+1gNPK treatment triggered P nutrient release as well as cations and anions, observed through EC measurement. As a result, suspected nutrient uptake enhanced root development in pearl millet. The increased EC as influenced by the seedball in the root zone is an indicator for other nutrients (cations and anions) availability. According to Ho et al. (2005), deep rooting systems in plants increased P uptake. Adequate P content in plants is associated with drought tolerance (Zegada-Lizarazu and Iijima, 2005). Thus, the increased root density, as observed in our seedball, can be an important adaptation of plants for P uptake (Lynch, 2011). Low P availability constrains food production particularly for smallholder farmers in the Sahel (Verde and Matusso, 2014). A worse scenario is the loss of plant available P and other nutrients through plant harvest (Heckman et al., 2003), especially when both grain and stover (as animal feed) are harvested as often done in the Sahel. In this context, the seedball technology can be crucial at enhancing P, cations and anions availability as well as uptake.

The non-nutrient amended seedball also had some positive effects (Chapter 4). However, does this positive effect make the addition of nutrient additives to the seedballs invalid? No, seedball needs nutrient additives because they are crucial to enhance the early biomass indicators. The seedlings enhancement effect of non-nutrient amended seedball (see Chapter 4) may be linked to zerocompetition for nutrient due to the fact that a single seedling was grown per germination column, coupled with the cations supply by the 35 – 40 % loam as component of the seedballs. Loam has a higher cation exchange capacity relative to sand (Lorenz, 1999). The WAS sandy soil, in general, is low in effective cation exchange capacity (Bationo and Mokwunye, 1991), coupled with its micro-variability nature (Herrmann et al., 1994) often associated with poor pearl millet growth (Barron et al., 1999). These WAS adverse conditions apparently qualify the addition of nutrient additives to the seedball. This is particularly important since 14 - 20 seedlings could emerge from the seedball. The competition for scarce nutrients has to be kept to a minimum.

In spite of the positive effect of the seedball on pearl millet seedlings, there are needs for further investigation on the root development as affected by the seedball. Does the seedball increase root distribution several cm away from its placement? Does the seedball influence root architecture of pearl millet? How far away (in cm) can the seedball-released nutrients be transported in the root zone? And how will the seedling roots react after 3-4 weeks of establishment i.e. when soil nutrients are depleted?

5.3. Reasons for biomass increment in the field

In small seeded species, P seed reserves were often exhausted as early as 14-18 DAP (Williams, 1948; Krigel, 1967). The observation of Williams (1948) showed that grain was the first source of P in cereal seeds. Hence, P- deficiency is often the consequence in particular when the growth medium is P deficient. Seed P reserves were translocated to the developing roots and shoot as early as 8 DAP (Hall and Hodges, 1966). In support of this, a review by Williams (1955) revealed more than 90 % of N and P uptake accumulated when the dry matter was just 25 % of the final weight in cereals. The accumulated nutrients served as reserve on which all later growth depended. Consequently, the level of this nutrient accumulation determined the final yield in cereals. These observations indicate that the seeds of small-seeded species need nutrient supplementation as early as seedlings emergence stage. Particularly, when the substrate is P-deficient, as in the WAS sandy soil.

Pearl millet seeds are generally small, weighing 7–10 mg per grain. As a result, its nutrient stock is low. A single pearl millet grain has a seed P reserve of about 20 μg, which apparently qualifies it for an external P supply soon after seedling emergence (Rebafka et al., 1993). Several works have demonstrated that higher grain yields could be attained if the seedlings were nutritionally and physiologically enhanced as early as the emergence (Rebafka, 1993; Rebafka et al., 1993; Karanam and Vadez, 2010; Valluru et al., 2010) in particular under WAS conditions. Exactly, this is the primary function of the seedball technology; to supply the targeted nutrients to pearl millet seedlings as early as seedlings emergence (Chapters 3 and 4). Valluru et al. (2010) observed that P supply to pearl millet seedlings later than 19 DAS had no effect on the plant biomass. These results indicate that enhanced seedlings soon after emergence are a pre-requisite for higher grain yield in WAS pearl millet production. Likewise, seedballs produce nutritionally and physiologically (root and shoot biomass) enhanced pearl millet seedlings relative to the traditional sowing system (Chapters 3 and 4). In turn, seedballs can potentially increase pearl millet grain yield.

Now that the potential of the seedball technology is known, long-term (> 7 years, if possible) on-farm trials in the Sahelian environment are highly recommended, especially under different seasonal conditions. This is particularly important since the Sahelian weather conditions are highly unpredictable as well as vary with huge differences (Sivakumar, 1988; D'amato and Lebel, 1998; Cooper et al., 2008; Herrmann et al., 2013; Salack et al., 2014).

5.4. Pre-conditions for adoption

Farmers' perception of the risk and benefits (Sofoluwe et al., 2011), the social, economic, and cultural status as well as the characteristic (simple or complicated, cheap or expensive) of an agricultural innovation (Pannell et al., 2006) greatly influence its adoption. Obviously, the already existing seed treatment (Rebafka et al., 1993; Raj et al., 2004; Karanam and Vadez, 2010) as well as mineral fertilization (Badiane et al., 2001; Twomlow et al., 2010; Aune and Ousman, 2011) options, though effective, were not developed for the smallholder farmers. Lack of skills (Brick and Visser, 2015) to practise the seed treatments as well as financial resources (Cooper et al., 2008) to acquire the NPK often disallow these local farmers. Consequently, the adoption of these options is low. Several authors (Fowler and Rockstrom, 2001; Schlecht et al., 2006; Twomlow et al., 2010; Vanlauwe et al., 2010; Ayuke et al., 2011) suggested that innovations targeting the smallholder farmers in particular, should (i) be simple to understand (ii) depend on local resources (iii) minimize cropping risks as well (iv) be compatible with the social and economic status of the farmers. Based on these criteria, the seedball technology is a valid option. The technology is simple to understand, uses locally available as well as low-cost materials, and enhanced pearl millet seedlings establishment under WAS conditions. During the training of the farmers on seedball production, both female and male farmers as well as farmers of different spiritual beliefs participated. These facts indicate that the technology is not hampered by any gender or religious barrier of any kind. Thus, the seedball technology is for every farmer at will.

In research for development, as done in this study, Herrmann et al. (2013) suggested to involve the target farmers as early as the development stage of an innovation. Exactly, the Sahelian farmers were involved during the seedball technology development (Chapter 3). An in-depth review as well as farmer training workshops (conducted in Louga, Senegal and Maradi, Niger Republic) revealed that the seedball technology absolutely conforms to the agronomic management practices for pearl millet production in the WAS. The local farmers of the FUMA Gaskiya farmers federation along with the researchers of INRAN learned the importance as well as the production of seedballs. The increment in number from 45 to more than 1600 during the three years of this project is a hint that seedball adoption is feasible. During seedball development, the necessary changes for adaptations were discussed among the farmers during the training workshops.

The seedball technology fits to dry and hand sowing. Dry sowing, to date, remains a major practice in the WAS agricultural system (Mulvaney et al., 2014). Farmers believe, it prolongs the vegetative period of the plant as well as increases the seasonal rainfall utilization. However, two major setbacks of dry sowing practice in the WAS are high crop failure (Salack et al., 2014) and seeds exposure to pests such as birds and ants (Nwanze and Sivakumar, 1990). Already, it is evident that seedballs minimized pest predation (Overdyck et al., 2013). Seedballs remain in the soil without germinating till sufficient germination conditions are met (Fukuoka, 1978). With respect to sowing, seedballs can be hand-sown the same way as conventional seeds.

5.5. Summary of achievements

This study has proven that the underutilized local resources such as wood ash, sand and loam can be used to enhance pearl millet seedlings establishment in the WAS through the seedball technology. The right mixture for making the seedball base dough was clearly identified as 80 g sand + 50 g loam + 25 ml water + 2.5 g seeds. In addition, the suitable features that enhance optimum performance of the seedball were identified. E.g., diameter size of 2 cm, nutrient additives of either 1 g NPK or 3 g wood ash, random seed placement, and sowing depth of 3 cm. In addition, the seedball could be stored for up to 8 weeks without significantly reducing its germination.

The seedball technology seems to save seeds. Seeds are the most important resources to a smallholder farmer at the season's onset in particular (Diouf, oral comm.). For the WAS pearl millet production system, 4 kg ha^{-1} is often recommended. Note that this amount could be more when children do the sowing and become exhausted; as high as 300 seeds per planting pocket was observed by Klaij and Hoogmoed (1993). In contrast, the seedball contains a relative fixed number of seeds, usually 20–25 per seedball. Thus, seed wastage is minimized irrespective of who does the sowing. With the seedball technology, farmers, who consistently obtain pearl millet seeds from their own harvest or buy from seed dealers (Ndjeunga, 2002), can save seeds as well as financial resources for other purposes.

Again, there are hints that sowing is easier with the seedballs on the dominant sandy soils of the Sahel, compared to the conventional pearl millet seeds. Farmers can simply drop the seedball and step on it; thus, making holes with an auger is not required. Nevertheless, it is important to note that time is invested during the production of the seedballs from gathering the materials, especially the loam that could be fetched far from the homestead, till drying the seedballs.

Another important achievement of the seedball technology project is networking between the local farmers, and their Universities as well as national scientists. This is particular evident in the Maradi region of Niger Republic, where pearl millet serves as the major staple cereal. The emphasis of such networks between farmers could play a crucial role in capacity building to address other challenges facing pearl millet production, as well as enhance farmers' indigenous knowledge exchange. Contrary to other seed treatment technologies, the seedball technology seems to be more beneficial to the female farmers. The women apply the seedball through dry sowing when labour demand is less, thereby creating time to help their husbands at season's on-set.

In summary, the seedball technology will be particularly useful in the WAS as a simple and cheap innovation that enhances pearl millet seedlings establishment. The technology seems promising with respect to early biomass increment as well as its adoption by the local farmers. In addition, there were no identified barriers (gender or religious) of any kind in our study.

5.6. Open questions and further tasks

The next steps will be to take the technology to the WAS smallholder farmers through experimentally designed long-term field trials as well as demonstration plots. The trials should aim at assessing the yield increment potential of the technology on pearl millet panicle under different Sahelian conditions. Another suggestion is to experimentally test whether other market-available NPK in the WAS, apart from NPK 15:15:15, can serve as effective nutrient additive in the seedball.

Seedball enhanced biomass production of pearl millet seedlings (Chapters 3 and 4). Hypothetically, it has to be pointed out that the high biomass production could expose the well-developed seedlings to drought stress through higher overall water consumption. High root biomass can lead to greater exploitation of soil water volume. Therefore, further research needs to evaluate water consumption by transpiration. Cereals vary in P uptake. E.g., pearl millet has genetic variability for P uptake, usage and grain yield under P deficient conditions (Gemenet et al., 2016). Therefore, it might be interesting to, experimentally, test P uptake in different breeds of seedball-derived vs traditional pearl millet seedlings in a climate-controlled environment.

Again, the overall socio-economic status of the local farmers as well as the farmers’ perception of seedball as an innovation necessitate investigation. The time investment from gathering all the seedball components to producing the seedball may play a crucial role in the adoption of the seedball technology. A potential hindrance factor to some farmers could be lack of loam in certain villages of the African Sahel (Abass, oral comm.). Clearly, loam is not as rampant as sand in the WAS; some farmers may need to travel up to 5 km away from their homestead in search of loam; hence, a toilsome workload.

Pesticides, in larger trials, can be applied to seedballs. Diseases as well as pests that attack pearl millet seedlings need suitable treatments as the seedball technology developed in this study is not a solution to all problems. Therefore, in working towards alleviating the challenges of seedlings establishment in the WAS regions, there is no particular solution that fits in all challenges. The Sahelian famers produce sorghum next to pearl millet. Fonio (*Digitalia spp*) has similar size to pearl millet; it is an important crop often neglected in the Sahel. It is therefore recommended to explore the yield improvement potential of the seedball technology on sorghum and fonio crops. The exploration should start under climate chamber controlled conditions, and in case of success, extend to the field for validation under different Sahelian weather conditions.

5.6.1. References

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Summary (in English)

The objectives of this study were to review the potential of the local material-based innovation – i.e. the seedball technology, at enhancing pearl millet seedlings establishment under Sahelian conditions, identify its potential constraints as well as applicability, chemically and mechanically optimize the seedball, and validate its performance under Sahelian field conditions. Seedball is a local seed pelleting techniques that aims at improving seedlings performance and to stabilize yield.

First, the potential local materials such as sand, loam, wood ash, gum arabic, termite soil, charcoal as well as animal dung as the seedball components were identified and reviewed. These materials were selected based on their affordability to the local farmers. Potential constraints to seedball applicability as well as adoption in the Sahel were evaluated, and options for adaptation were discussed with the farmers. Afterwards, mechanical and chemical optimization of the seedball technology in several greenhouse experiments were conducted, followed by a germination test of the optimized seedball in the Sahelian field. Lastly, the mechanism of pearl millet seedlings root and shoot enhancement was investigated using micro-suction cup and computer tomography.

Our evaluation showed that the materials needed for seedball production are locally available at affordable costs. The seedball technology totally conforms to the agronomic management practices in the African Sahel. In addition, the socio-economic status as well as cultural practices seemed not to reduce the chances of seedball technology adoption in this region. Our greenhouse studies showed that the seedball base dough, from which about ten 2 cm diameter-sized seedballs can be produced, is derived from the combination of 80 g sand + 50 g loam + 25 ml water. Either 1 g mineral fertilizer or 3 g wood ash can be added as nutrient additive to enhance early biomass of pearl millet seedlings. With respect to nutrient additives, ammonium fertilizers and urea hampered seedlings emergence. Wood ash amended (Sball+3gAsh) and mineral fertilizer-amended seedballs (Sball+1gNPK)

enhanced shoot biomass by 60 % and 75-160 %, root biomass by 36 % and 94 %, and root length density of pearl millet by 14 % and 28 %, respectively, relative to the control. Again, the mineral fertilizer amended seedball in particular enhanced root dry matter by 227 %, compared to the control. Although the shoot nutrient content was not clearly enhanced by the seedball, nutrient extraction, calculated as the product of biomass yield and nutrient content, was higher in the nutrient-amended seedballs, compared to the conventional sowing. In Senegal, optimized seedballs showed over 95 % emergence in an on-station trial, indicating its viability in the Sahel region. With respect to seedball enhancement mechanism, the mineral fertilizer-amended seedball in particular promoted root growth within the vicinity of the seedball as early as 7 days after planting. The analysis of the sampled soil solution revealed that P as well as other cations and anions, observed through EC measurement, were released by the seedball in direct proximity of the seedball. Most likely, the nutrient release by the seedball triggered the observed fine root growth and overall higher root biomass of pearl millet seedlings. However, due to nutrient depletion in the root zone, nutrient supplementation was needed after three weeks after sowing to further promote growth of the well-established seedlings.

At the Sahelian field, where seedlings enhancement is decisive for higher panicle yield in pearl millet, nutrient amended seedballs can potentially increase panicle yield under subsistence production. The seedball technology is cheap, and seems to have favorable conditions for adoption in the Sahel, coupled with its minimal seed usage and simple sowing on the sandy soil. A recommendation will be to conduct long-term, on-farm as well as on-station field trials, testing the seedball technology under different seasonal weather conditions. Pearl millet and sorghum are the major Sahelian staple crops. Fonio (*Digitaria spp*) is often neglected despite its high nutritional values. It is, therefore, recommended to test the seedball technology on the other fine-grained cereal crops.

Zusammenfassung (in German)

Im Rahmen dieser Arbeit wurde das Potential von Saatkugeln, einer auf lokalen Ausgangs-materialen basierenden Aussaattechnologie, untersucht, um den Perlhirseanbau, insbesondere die Auflaufphase, unter den Bedingungen der Sahelzone zu verbessern. Die möglichen Einsatzbeschränkungen wurden identifiziert, die Saatkugeln bezüglich ihrer chemischen und physikalischen Eigenschaften optimiert und die Anwendbarkeit unter Feldbedingungen der Sahelzone validiert. Saatkugeln stellen eine lokale Pelletiertechnik dar, die Sand, Lehm sowie Holzasche oder einen geringen Anteil an Mineraldünger verwendet, um das Auflaufverhalten zu verbessern.

Zunächst wurden die potentiellen lokalen Ausgangsmaterialien zur Herstellung der Saatkugeln wie zum Beispiel Sand, Lehm, Holzasche, Termitenhügelsubstrat, Gummi arabikum, Holzkohle, sowie Kompost identifiziert und charakterisiert. Diese Materialien wurden anhand ihrer Bezahl- und Verfügbarkeit für die lokalen Bauern ausgewählt. Potentielle Einschränkungen des Einsatzes der Saatkugeln, sowie die Adaption an die Bedingungen der Sahelzone wurden unter Einbeziehung der lokalen Landwirte diskutiert und evaluiert. Anschließend wurden verschiedene Gewächshausexperimente durchgeführt, um die physikalischen und chemischen Eigenschaften der Saatkugeln zu optimieren. Darauf folgte ein Keimungstest der optimierten Saatkugeln unter Feldbedingungen der Sahelzone. Abschließend wurden mittels Mikrosaugkerzen und Computertomographie die Mechanismen des Keimlingswurzelwachstums und des Sprosswachstums der Perlhirsekeimlinge untersucht.

Unsere Evaluation zeigte, dass die Ausgangsmaterialien für die Saatkugelherstellung vor Ort zu niedrigen Kosten verfügbar sind. Die Saatkugeltechnologie entspricht den landwirtschaftlichen Verfahrensweisen in der afrikanischen Sahelzone und kann daher leicht angewandt werden. Außerdem scheinen der sozioökonomische Status und die kulturellen Praktiken der Landbevölkerung

einem Einsatz der Saatkugeltechnologie in dieser Region nicht negativ entgegenzustehen. Die Gewächshausexperimente zeigten, dass eine Mischung aus 80 g Sand, 50 g Lehm und 25 ml Wasser die optimale Zusammensetzung der Saatkugeln darstellt. Aus dieser Menge können zehn Saatkugeln mit einem Durchmesser von 2 cm hergestellt werden. Zusätzlich wurden sowohl 1 g Mineraldünger als auch 3 g Holzasche als Nährstoffquelle hinzugefügt, um die frühe Biomassenproduktion der Perlhirsenkeimlinge zu verbessern.

Der Einsatz der Stickstoffverbindungen Ammonium und Harnstoff hemmte das Auflaufen der Keimlinge. Die Nährstoffadditive Holzasche bzw. Mineraldünger führten zu einer Zunahme der Sprossbiomasse um 60 % bzw. 75 - 160 %, der Wurzelbiomasse um 36 % bzw. 94 % und der Wurzellängendichte der Perlhirse um 14 % bzw. 28 %, relativ zur Kontrolle. Die Mineraldünger enthaltende Saatkugel erhöhte insbesondere die Wurzeltrockenmasse um 227 % im Vergleich zur Kontrolle. Der Nährstoffgehalt des Sprosses nach Anwendung der Saatkugel-Technologie war nicht eindeutig erhöht. Jedoch war die Nährstoffextraktion, berechnet als Produkt aus Biomasseertrag und Nährstoffgehalt, bei den mit Nährstoffen angereicherten Saatkugeln, höher als bei herkömmlicher Aussaat.

In Senegal zeigten die optimierte Saatkugeln in einem Stationsversuch eine Auflaufrate von über 95 %. Die Mineraldüngervariante zeigte bereits 7 Tage nach der Aussaat eine Steigerung des Wurzelwachstum in der Nähe der Saatkugel. Die Leitfähigkeitsmessung der Bodenlösung im Rhizotronversuch zeigte, dass Nährstoffe aus der Saatkugel herausdiffundierten. Höchstwahrscheinlich löste die Nährstofffreisetzung aus der Saatkugel das beobachtete Feinwurzelwachstum und die positive Gesamtwurzelentwicklung der Perlhirsesämlinge aus. Aufgrund der Nährstoffverarmung in der Wurzelzone drei Wochen nach der Keimung wird jedoch eine weitere Nährstoffgabe erforderlich, um das Wachstum der etablierten Sämlinge weiter zu fördern.

Auf den Arenosolen der Sahelzone können Saatkugeln mit zugesetzten Nährstoffen den Biomasseertrag in der Subsistenzlandwirtschaft erhöhen. Die Saatkugeltechnologie ist kostengünstig und es scheint keine soziokulturellen Gründe zu geben, die gegen ein Anwendung sprächen. Die Technologie ist mit einem minimalen Saatgutverbrauch bei einfacher Aussaat auf sandigem Boden verbunden. Als weiterer Schritt sollten mehrjährige Freilandversuche unter realen Bedingungen auf Subsistenzbetrieben in der Sahelzone durchgeführt werden. Perlhirse und Sorghum sind die Grundnahrungsmittel. Fonio (*Digitaria spp*.) wird trotz seiner hohen Nährwerte oft vernachlässigt. Es wird empfohlen, die Saatkugel-Technologie mit Sorghum- und Fonio-Kulturen zu testen.

Dedication

This work is fully dedicated to the entire smallholder pearl millet farmers in the African Sahel.

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Appendix

Publications related to this thesis within the period of doctoral studies

- Nwankwo, C. I., and Herrmann, L. (2018). Viability of the seedball technology to improve pearl millet seedlings establishment under Sahelian conditions – a review of pre-requisites and environmental conditions. IJAIR 6, 261-268
- Nwankwo, C. I., Mühlena, J., Biegert, K., Butzer, D., Neumann, G., Sy, O., and Herrmann, L. (2018). Physical and chemical optimisation of the seedball technology addressing pearl millet under Sahelian conditions. Journal of Agriculture and Rural Development in the Tropics and Subtropics, 119, 67-79
- Nwankwo, C. I., Blaser, S. R., Vetterlein, D., Neumann, G., and Herrmann, L. (2018). Seedball-induced changes of root growth and physico-chemical properties – a case study with pearl millet. Journal of Plant Nutrition and Soil Science, 181, 768-776

Conference contributions (oral presentations related to this thesis)

- Herrmann, L., Sy, O., Nouri, M., Oumarou, H. M., Aminou, A. and Nwankwo, C. I. (2015). Optimisation of the seedball technology for pearl millet, and agronomic and socio-economic evaluation in the context of smallholder farmers in Senegal and Niger. *Sorghum and Millet Innovation Lab*, March 2015, Niamey, Niger Republic
- Herrmann, L., Nwankwo, C. I., Mühlena, J., Butzer, D., Biegert, K. and Neumann, G. (2015). Saatkugeln als Managementoption zur Verbesserung des Auflaufverhaltens von Perlhirse (*Pennisetum glaucum*) auf sandigen Böden im Sahel. Deutsche Forschungsgemeinschaft, September 2015, Munich, Germany
- Herrmann, L., Sy, O., Nouri, M., Oumarou, H. M., Dieng, C. T., Aminou, A. and Nwankwo,

C. I. (2016). Optimisation of seedball technology in the context of smallholder farmers in the African Sahel - Niger and Senegal as the target countries. *Sorghum and Millet Innovation Lab,* March 2016, Senegal

- Herrmann, L., Sy, O., Nouri, M., Oumarou, H. M., Aminou, A. and Nwankwo, C. I. (2017). Optimisation of the seedball technology for pearl millet, and agronomic and socio-economic evaluation in the context of smallholder farmers in Senegal and Niger *Sorghum and Millet Innovation Lab,* March 2017, Saly, Senegal
- Nwankwo, C. I., Herrmann, L., Vetterlein, D. and Blaser, S. R. G. A. (2017). Seedball-induced changes of root growth and physico-chemical properties in the rhizosphere of pearl millet seedlings. *Tropentag*, September, 2017, Bonn, Germany

Poster presentations (related to this thesis)

- Nwankwo, C. I., Herrmann, L., Rennert, T. and Neumann, G. (2015). Optimisation of seedball technology for pearl millet (*Pennisetum glaucum*) production in the Sahel. *Tropentag* September 2015, Berlin, Germany
- Nwankwo, C. I., Herrmann, L., Neumann, G. Aminou, A. M., Oumarou, H. M., Nouri, M. K. and Sy, O. (2017). Seedball technology improves pearl millet yield in Sahelian production systems. *Tropentag,* September 20 - 22, 2017, Bonn, Germany
- Nwankwo, C. I., Maman, N. K., Moussa, H., Sy, O., Maman, A. A., Neumann, G. and Herrmann, L. (2016). Seedball fabrication guide: Harnessing the potential of local materials through seedball technology. *Sorghum and Millet Innovation Lab,* March 2016, Saly, Senegal
- Nwankwo, C. I., Maman, N. K., Moussa, H., Sy, O., Maman, A. A., Neumann, G. and Herrmann, L. (2016). Mechanisation of seedball production: Increasing pearl millet

production efficiency through a simple tool. *Sorghum and Millet Innovation Lab,* March 2016, Saly, Senegal

- Nwankwo, C. I., Herrmann, L. and Neumann, G. (2017). Assessment of morpho-physiological traits associated with drought stress tolerance in seedball pearl millet seedlings. *Sorghum and Millet Innovation Lab,* March 2017, Saly, Senegal
- Herrmann, L., Sy, O., Nouri, M., Oumarou, H. M., Aminou, A. and Nwankwo, C. I. (2017). Optimisation of seedball technology for pearl millet; agronomic and socio-economic evaluation in the context of smallholder farmers in Senegal and Niger. *Sorghum and Millet Innovation Lab,* March 2017, Saly, Senegal

Publications not related to this thesis

- Ayenan, M. A. T., Sodedji, K. A. F., Nwankwo, C. I., Olodo, K. F., & Alladassi, M. E. B. Harnessing genetic resources and progress in plant genomics for fonio (Digitaria spp.) improvement. *Genetic Resources and Crop Evolution*, 65, 373 - 386
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- Neumann G., Jauß H., Asim M., Nwankwo C. I. (2014): Gesucht – Gefunden. Signalwirkungen von Nährstoffen und ihre Bedeutung für Düngung und Wurzelentwicklung von *Raps*, 34, 34 - 37
- Neumann G., Jauß H., Ken F., Kremer I., Nwankwo C. I. (2014): Bedeutung Funktion und Biologie der Rapswurzel *Raps*, 32, 30 - 32

Seedball Technology Fact Sheet 2017

A. Introduction

The seedball as technology was born in the frame of the permaculture movement in Japan to cultivate in areas normally unsuitable for cropping. It was then adapted in Australia for rangeland amelioration and finally adopted by the “guerrilla gardening” community and is distributed today for this purpose by organisations like Greenpeace.

B. Background

With respect to natural resources the semi-arid Sahelian environment is characterised by high climatic variability in space and time. The growing season is short (approximately 3 months), its beginning unpredictable and early season droughts after sowing common. Cropping risk is further increased by sandy soils with low nutrient status and low water holding capacity. Farmers are mainly subsistence oriented smallholders with low investment capital. Due to the short cropping season timely sowing is crucial in order to capture the yield potential. Every day of later sowing is decreasing the yield potential. That is why dry sowing before the season is commonly practiced. However dry sowing has its risks including predation of the seeds e.g. by rodents or birds and crop loss due to early droughts after minimal rains that led to seed germination.

C. The seedball concept

Seedballs are simply a mixture of soil materials that stick together, water, seeds and additives that improve plant performance. The latter can be nutrients, pesticides or anti-rodent components. In the framework of the SMIL-programme emphasis was on optimisation of the nutrient content. The principle idea followed was that the seedballs should be based on local materials that are affordable for subsistence farmers.

Hypotheses why seedballs should work in the Sahelian context:

1. They conserve the seed under dry sowing against rodents, birds and other pests by physical protection.

2. Seeds do not germinate under too low rainfall.

3. In the soil they attract water due to a higher matric potential resulting in faster germination.

4. Seedballs deliver constraining nutrients in the early growing phase.

5. Subsequent better root establishment and K delivery lead to better water use efficiency and in turn a higher survival rate in case of early drought.

6. Better root establishment allows to catch nutrients otherwise leached.

7. Higher root density leads to higher total nutrient uptake and early biomass production.

D. Seedball optimisation

Decisive for the seedball success is an optimal germination rate. Therefore, first the physical properties needed to be optimised. Seedballs with a diameter of 1.5-2cm diameter showed the best responses in this respect.

In the next step nutrient content needed to be maximised without hampering the germination rate. For this purpose NPK fertiliser and woodash as a locally available multicomponent fertiliser were tested.

E. The final seedball recipe 2nd phase: On-farm testing

In 2016 more than 150 on-farm tests were conducted in the Maradi region of Niger. Out of those 53 could be used to determine the statistical difference to conventional sowing since they included the information on the panicle yield of the control.

Table 3: On-farm panicle yield difference of the seeball technology compared to conventional farmers' sowing practice in the Maradi region of Niger 2016 given in %

All treatments	Sandy soils	Loamy soils
+29 (n=58, p=0.02)	+27 (n=30, p=0.06)	+32 (n=20, p=0.24)

F. Laboratory results on the mechanisms behind seeball success

Laboratory and greenhouse trials showed in 2016 and 2017 that nutrient amended seedballs lead to better root development (density and distribution) and higher nutrient uptake particularly in the first two weeks after sowing. Then the nutrients provided by the seedballs are exhausted and additional fertilisation needs to take place.

G. The way forward

In 2017 on-farm trials are conducted in the Maradi region of Niger. More than 1000 volunteer participants were recorded by the local farmer organisation, Fuma Gasikya. In addition, greenhouse trials shall evaluate the response of seedballs to early drought conditions. In future, mechanisation of seeball production needs to be improved in order to attract the attention of male farmers.

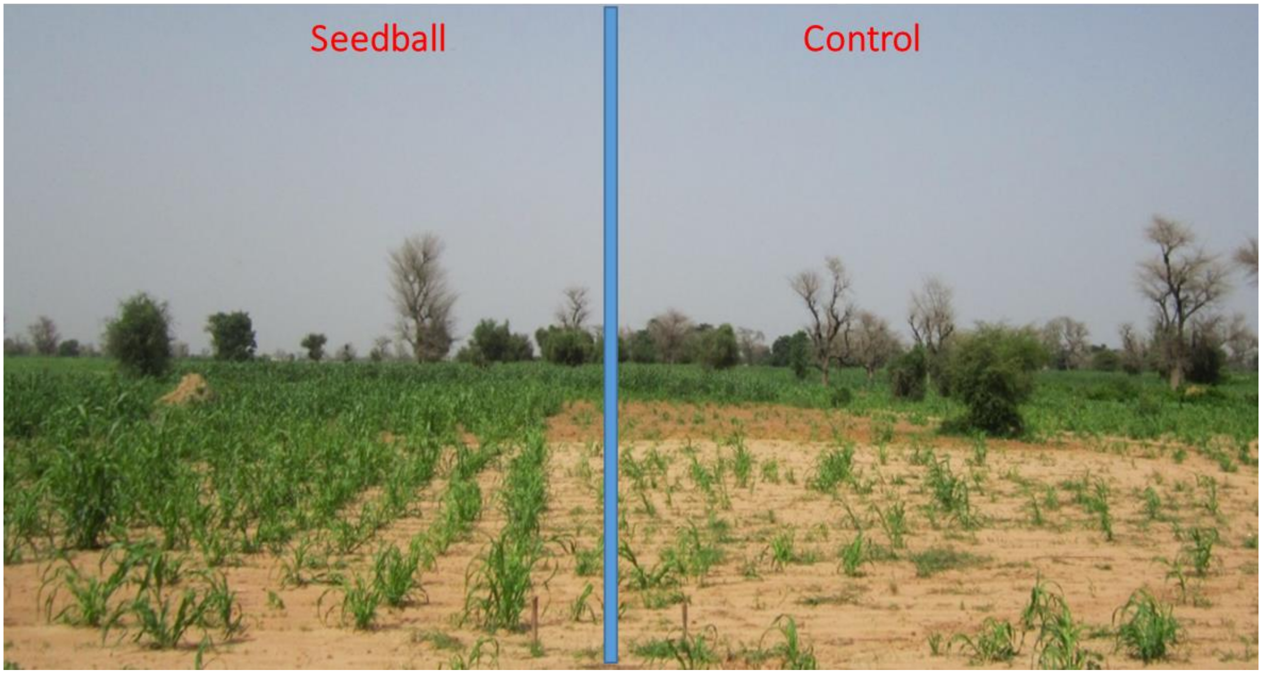

Figure 14: Influence of seedball on pearl millet seedlings establishment in an on-farm trial at three weeks after planting in Maradi region, Niger.

Seedball dataset

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

Table 4: The effect of treatment and seedball diameter size (Sball_diam) on pearl millet germination (Germ), height and leaf development 9 days after sowing at the greenhouse of ISRA/CNRA research station, Bambey, Senegal. Treatment (n = 6) column shows Control = non-pelleted seeds, Sball = 80 g sand + 50 g loam + 25 ml water, NPK = 15:15:15 mineral fertilizer, Cha = charcoal, Comp = compost, Term = termite soil and Man = manure.

Treatment	**Rep**	**Sball_diam (cm)**	**Germ (#/20)**	**Height (cm)**	**Leaf (#)**
Control	1	1	18	12	2
Control	2	1	19	14	2
Control	3	1	12	12	2
Control	4	1	12	13	2
Control	5	1	13	13	2
Control	6	1	14	12	2
Sball	1	1	1	14	2
Sball	2	1	2	12	3
Sball	3	1	.	.	.
Sball	4	1	.	.	.
Sball	5	1	.	.	.
Sball	6	1	1	18	3
Sball+30gCha	1	1	1	10	2
Sball+30gCha	2	1	1	10	2
Sball+30gCha	3	1	6	14	3
Sball+30gCha	4	1	4	12	2
Sball+30gCha	5	1	3	14	2
Sball+30gCha	6	1	2	13	2
Sball+30mlComp	1	1	.	.	.
Sball+30mlComp	2	1	1	6	1
Sball+30mlComp	3	1	5	16	2
Sball+30mlComp	4	1	2	14	2
Sball+30mlComp	5	1	.	.	.
Sball+30mlComp	6	1	4	8	2

Sball+4gMan	1	1	3	13	2
Sball+4gMan	2	1	1	13	2
Sball+4gMan	3	1	1	4	1
Sball+4gMan	4	1	9	12	2
Sball+4gMan	5	1	.	.	.
Sball+4gMan	6	1	1	10	2
Sball+30gTerm	1	1	4	15	2
Sball+30gTerm	2	1	3	10	2
Sball+30gTerm	3	1	.	.	.
Sball+30gTerm	4	1	.	.	.
Sball+30gTerm	5	1	.	.	.
Sball+30gTerm	6	1	7	12	2
Control	1	2	18	12	2
Control	2	2	19	14	2
Control	3	2	12	12	2
Control	4	2	12	13	2
Control	5	2	13	13	2
Control	6	2	14	12	2
Sball	1	2	1	14	2
Sball	2	2	6	12	2
Sball	3	2	5	13	2
Sball	4	2	2	7	2
Sball	5	2	8	13	2
Sball	6	2	.	.	.
Sball+30gCha	1	2	3	12	3
Sball+30gCha	2	2	6	16	2
Sball+30gCha	3	2	2	10	3
Sball+30gCha	4	2	1	4	2
Sball+30gCha	5	2	1	9	2
Sball+30gCha	6	2	8	14	3
Sball+30mlComp	1	2	.	.	.
Sball+30mlComp	2	2	6	14	2
Sball+30mlComp	3	2	1	15	3
Sball+30mlComp	4	2	2	9	2
Sball+30mlComp	5	2	.	.	.
Sball+30mlComp	6	2	2	11	2
Sball+4gMan	1	2	1	3	1
Sball+4gMan	2	2	4	10	2
Sball+4gMan	3	2	2	13	2
Sball+4gMan	4	2	.	.	.
Sball+4gMan	5	2	.	.	.

Sball+4gMan	6	2	.	.	.
Sball+30gTerm	1	2	8	15	2
Sball+30gTerm	2	2	8	13	2
Sball+30gTerm	3	2	4	13	2
Sball+30gTerm	4	2	.	.	.
Sball+30gTerm	5	2	3	9	2
Sball+30gTerm	6	2	.	.	.
Control	1	3	18	12	2
Control	2	3	19	14	2
Control	3	3	12	12	2
Control	4	3	12	13	2
Control	5	3	13	13	2
Control	6	3	14	12	2
Sball	1	3	2	3	1
Sball	2	3	1	11	2
Sball	3	3	15	12	3
Sball	4	3	7	11	2
Sball	5	3	4	15	3
Sball	6	3	5	12	2
Sball+30gCha	1	3	1	14	2
Sball+30gCha	2	3	5	8	2
Sball+30gCha	3	3	2	3	1
Sball+30gCha	4	3	14	13	2
Sball+30gCha	5	3	11	11	3
Sball+30gCha	6	3	10	14	3
Sball+30mlComp	1	3	.	.	.
Sball+30mlComp	2	3	1	5	2
Sball+30mlComp	3	3	3	16	3
Sball+30mlComp	4	3	5	15	2
Sball+30mlComp	5	3	.	.	.
Sball+30mlComp	6	3	.	.	.
Sball+4gMan	1	3	1	12	2
Sball+4gMan	2	3	1	5	2
Sball+4gMan	3	3	2	6	1
Sball+4gMan	4	3	2	11	2
Sball+4gMan	5	3	.	.	.
Sball+4gMan	6	3	.	.	.
Sball+30gTerm	1	3	10	11	2
Sball+30gTerm	2	3	6	12	2
Sball+30gTerm	3	3	3	13	2
Sball+30gTerm	4	3	.	.	.

Sball+30gTerm	5	3	8	14	3
Sball+30gTerm	6	3	1	14	3

Table 5: Effect of seed position in the seedball on pearl millet germination 7 days after sowing for different treatments factors at the greenhouse of ISRA/CNRA research station, Bambey, Senegal. The treatment (n = 6) column shows Control = non-pelleted seeds, Sball = 80 g sand + 50 g loam + 25 ml water, Ash = wood ash, NPK = 15:15:15 mineral fertiliser, diam = seedball diameter size in cm. GermCentralized = seed placement at the core centre of the seedball and GermRandomized = scattered seed placement in seedball.

Treatment	Rep	GermCentralized (#/15)	GermRandomized (#/15)
Control	1	13	14
Sball+3gAsh+1cmdiam	1	7	12
Sball+3gAsh+2cmdiam	1	5	11
Sball+3gAsh+3cmdiam	1	3	15
Sball+1gNPK+1cmdiam	1	8	12
Sball+1gNPK+2cmdiam	1	5	11
Sball+1gNPK+3cmdiam	1	3	14
Control	2	13	14
Sball+1gNPK+1cmdiam	2	8	12
Sball+3gAsh+1cmdiam	2	7	12
Sball+1gNPK+2cmdiam	2	5	11
Sball+3gAsh+2cmdiam	2	5	11
Sball+1gNPK+3cmdiam	2	3	14
Sball+3gAsh+3cmdiam	2	3	15
Control	3	12	13
Sball+1gNPK+1cmdiam	3	7	11
Sball+3gAsh+1cmdiam	3	6	9
Sball+1gNPK+2cmdiam	3	4	9
Sball+3gAsh+2cmdiam	3	4	10
Sball+1gNPK+3cmdiam	3	2	12
Sball+3gAsh+3cmdiam	3	3	11
Control	4	10	10
Sball+1gNPK+1cmdiam	4	6	9
Sball+3gAsh+1cmdiam	4	6	9
Sball+1gNPK+2cmdiam	4	4	10

Sball+3gAsh+2cmdiam	4	3	10
Sball+1gNPK+3cmdiam	4	2	12
Sball+3gAsh+3cmdiam	4	2	12
Control	5	13	14
Sball+1gNPK+1cmdiam	5	8	12
Sball+3gAsh+1cmdiam	5	7	12
Sball+1gNPK+2cmdiam	5	5	11
Sball+3gAsh+2cmdiam	5	5	11
Sball+1gNPK+3cmdiam	5	3	14
Sball+3gAsh+3cmdiam	5	3	15
Control	6	11	12
Sball+1gNPK+1cmdiam	6	6	10
Sball+3gAsh+1cmdiam	6	5	10
Sball+1gNPK+2cmdiam	6	3	9
Sball+3gAsh+2cmdiam	6	3	9
Sball+1gNPK+3cmdiam	6	1	12
Sball+3gAsh+3cmdiam	6	1	13

Table 6: Treatment effects on pearl millet survival (GermSurv) after germination, germination number (MaxGerm) as well as time (MxGermTime) 7 days after sowing at the greenhouse of University of Hohenheim, Germany. Treatment (n = 6) column shows Control = non-pelleted seeds, Seedball = 2 cm diameter sized-seedball made from a mixture of 80 g sand + 50 g loam + 25 ml water, Ash = wood ash, NPK = 25 ml 17:17:17 mineral fertiliser and CNT = calcium nitrate tetrahydrate.

Treatment	Rep	GermSurv (#/10)	MaxGerm (#/10)	MxGermTime (day)
Control	1	9	9	3
Sball	1	9	9	5
Sball+1gNPK	1	8	9	6
Sball+3gAsh	1	2	3	8
Sball+0.1gCNT	1	10	10	5
Sball+0.5gNPK	1	10	10	6
Sball+0.5gCNT	1	3	3	3
Control	2	8	9	6
Sball	2	7	7	4
Sball+1gNPK	2	6	6	5

Sball+3gAsh	2	5	6	8
Sball+0.1gCNT	2	8	8	4
Sball+0.5gNPK	2	9	10	6
Sball+0.5gCNT	2	1	2	6
Control	3	8	8	4
Sball	3	9	9	4
Sball+1gNPK	3	6	6	5
Sball+3gAsh	3	8	8	8
Sball+0.1gCNT	3	6	6	5
Sball+0.5gNPK	3	8	9	6
Sball+0.5gCNT	3	1	1	5
Control	4	6	8	4
Sball	4	8	10	4
Sball+1gNPK	4	4	4	5
Sball+3gAsh	4	3	3	11
Sball+0.1gCNT	4	10	10	5
Sball+0.5gNPK	4	6	6	6
Sball+0.5gCNT	4	.	.	.
Control	5	8	8	4
Sball	5	9	9	6
Sball+1gNPK	5	8	8	6
Sball+3gAsh	5	4	4	8
Sball+0.1gCNT	5	9	9	5
Sball+0.5gNPK	5	7	10	5
Sball+0.5gCNT	5	3	5	6
Control	6	5	6	3
Sball	6	9	10	6
Sball+1gNPK	6	8	8	7
Sball+3gAsh	6	4	5	8
Sball+0.1gCNT	6	8	8	6
Sball+0.5gNPK	6	8	8	6
Sball+0.5gCNT	6	5	5	5

Table 7: Treatment effects on pearl millet root length (Rootlen), root dry matter (Rootdrymat), shoot biomass (Shootbio), shoot dry matter (Shootdrymat), root biomass (Rootbio) and root length density (Rootden) 28 days after sowing at the greenhouse of University of Hohenheim, Germany. Treatment (n = 6) column shows Control = non-pelleted seeds, Seedball = 2 cm diameter sized-seedball made from a mixture of 80 g sand + 50 g loam + 25 ml water, Ash = wood ash, NPK = 25 ml 17:17:17 mineral fertiliser and CNT = calcium nitrate tetrahydrate.

Treatment	Rep	Rootlen (cm)	Rootdrymat (g)	Shootbio (g)	Shootdrymat (g)	Rootbio (g)	Rootden (cm cm^{-3})
Control	1	808	0.04	0.36	0.07	0.21	0.52
Sball	1	639	0.03	0.33	0.06	0.17	0.41
Sball+1gNPK	1	1272	0.07	0.66	0.12	0.46	0.81
Sball+3gAsh	1	1611	0.07	1.07	0.17	0.52	1.03
Sball+0.1gCNT	1	684	0.04	0.40	0.08	0.26	0.44
Sball+0.5gNPK	1	779	0.05	0.39	0.07	0.34	0.50
Sball+0.5gCNT	1	1370	0.04	1.03	0.16	0.54	0.88
Control	2	917	0.04	0.49	0.09	0.26	0.59
Sball	2	920	0.06	0.52	0.11	0.33	0.59
Sball+1gNPK	2	1865	0.11	0.99	0.20	0.75	1.19
Sball+3gAsh	2	1102	0.06	0.65	0.13	0.34	0.71
Sball+0.1gCNT	2	942	0.05	0.45	0.10	0.27	0.60
Sball+0.5gNPK	2	609	0.03	0.34	0.07	0.19	0.39
Sball+0.5gCNT	2	.	.	2.49	0.42	1.27	.
Control	3	981	0.04	0.47	0.08	0.25	0.63
Sball	3	773	0.04	0.40	0.08	0.28	0.49
Sball+1gNPK	3	1427	0.07	0.90	0.19	0.44	0.91
Sball+3gAsh	3	786	0.04	0.46	0.09	0.22	0.50
Sball+0.1gCNT	3	1707	0.07	0.61	0.13	0.47	1.09
Sball+0.5gNPK	3	828	0.04	0.42	0.07	0.30	0.53
Sball+0.5gCNT	3	.	.	2.35	0.27	0.68	.
Control	4	1506	0.05	0.58	0.11	0.36	0.96
Sball	4	825	0.03	0.44	0.08	0.27	0.53
Sball+1gNPK	4	2075	0.14	1.25	0.28	0.71	1.33
Sball+3gAsh	4	1355	0.09	0.95	0.16	0.41	0.87
Sball+0.1gCNT	4	983	0.03	0.39	0.08	0.25	0.63
Sball+0.5gNPK	4	1146	0.05	0.49	0.07	0.36	0.73
Sball+0.5gCNT	4	.	.	.	.	.	.

Control	5	864	0.04	0.41	0.08	0.28	0.55
Sball	5	715	0.02	0.37	0.06	0.16	0.46
Sball+1gNPK	5	1081	0.05	0.59	0.11	0.46	0.69
Sball+3gAsh	5	1140	0.03	0.69	0.10	0.26	0.73
Sball+0.1gCNT	5	720	0.03	0.45	0.08	0.17	0.46
Sball+0.5gNPK	5	1011	0.04	0.49	0.09	0.32	0.65
Sball+0.5gCNT	5	921	0.06	0.88	.	0.52	0.59
Control	6	1320	0.06	0.65	0.14	0.36	0.84
Sball	6	839	0.04	0.38	0.07	0.30	0.54
Sball+1gNPK	6	751	0.07	0.75	0.16	0.51	0.48
Sball+3gAsh	6	1360	0.17	0.89	0.17	0.59	0.87
Sball+0.1gCNT	6	893	0.03	0.46	0.09	0.21	0.57
Sball+0.5gNPK	6	1148	0.07	0.49	0.10	0.32	0.73
Sball+0.5gCNT	6	1314	0.08	0.67	0.12	0.62	0.84

Table 8: Pearl millet height and leaf development per plant for different treatments at the greenhouse of University of Hohenheim, Germany. Treatment (n = 6) column shows 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.

Treatment	**Rep**	**Time (day)**	**Height (cm)**	**Leaf (#)**
Control	1	4	7	1
Sball	1	4	5	1
Sball+1gNPK	1	4	6	1
Sball+3gAsh	1	4	.	.
Sball+0.1gCNT	1	4	6	1
Sball+0.5gNPK	1	4	.	.
Sball+0.5gCNT	1	4	8	1
Control	2	4	8	1
Sball	2	4	6	1
Sball+1gNPK	2	4	5	1
Sball+3gAsh	2	4	.	.
Sball+0.1gCNT	2	4	5	1
Sball+0.5gNPK	2	4	.	.
Sball+0.5gCNT	2	4	.	.
Control	3	4	7	1

Sball	3	4	8	1
Sball+1gNPK	3	4	5	1
Sball+3gAsh	3	4	2	1
Sball+0.1gCNT	3	4	4	1
Sball+0.5gNPK	3	4	.	.
Sball+0.5gCNT	3	4	.	.
Control	4	4	8	1
Sball	4	4	8	1
Sball+1gNPK	4	4	7	1
Sball+3gAsh	4	4	.	.
Sball+0.1gCNT	4	4	5	1
Sball+0.5gNPK	4	4	.	.
Sball+0.5gCNT	4	4	.	.
Control	5	4	7	1
Sball	5	4	5	1
Sball+1gNPK	5	4	6	1
Sball+3gAsh	5	4	.	.
Sball+0.1gCNT	5	4	5	1
Sball+0.5gNPK	5	4	.	.
Sball+0.5gCNT	5	4	4	1
Control	6	4	6	1
Sball	6	4	5	1
Sball+1gNPK	6	4	4	1
Sball+3gAsh	6	4	.	.
Sball+0.1gCNT	6	4	4	1
Sball+0.5gNPK	6	4	.	.
Sball+0.5gCNT	6	4	4	1
Control	1	8	11	1
Sball	1	8	8	1
Sball+1gNPK	1	8	10	1
Sball+3gAsh	1	8	.	.
Sball+0.1gCNT	1	8	1	1
Sball+0.5gNPK	1	8	8	1
Sball+0.5gCNT	1	8	12	1
Control	2	8	10	2
Sball	2	8	8	1
Sball+1gNPK	2	8	9	1
Sball+3gAsh	2	8	.	.
Sball+0.1gCNT	2	8	10	1
Sball+0.5gNPK	2	8	7	1
Sball+0.5gCNT	2	8	3	1

Control	3	8	11	1
Sball	3	8	11	1
Sball+1gNPK	3	8	11	1
Sball+3gAsh	3	8	5	1
Sball+0.1gCNT	3	8	12	2
Sball+0.5gNPK	3	8	6	1
Sball+0.5gCNT	3	8	3	1
Control	4	8	11	1
Sball	4	8	11	1
Sball+1gNPK	4	8	10	1
Sball+3gAsh	4	8	.	.
Sball+0.1gCNT	4	8	9	1
Sball+0.5gNPK	4	8	6	1
Sball+0.5gCNT	4	8	.	.
Control	5	8	9	1
Sball	5	8	7	1
Sball+1gNPK	5	8	9	1
Sball+3gAsh	5	8	.	.
Sball+0.1gCNT	5	8	8	1
Sball+0.5gNPK	5	8	7	1
Sball+0.5gCNT	5	8	8	1
Control	6	8	10	2
Sball	6	8	9	1
Sball+1gNPK	6	8	9	1
Sball+3gAsh	6	8	3	1
Sball+0.1gCNT	6	8	7	1
Sball+0.5gNPK	6	8	6	1
Sball+0.5gCNT	6	8	7	2
Control	1	12	24	2
Sball	1	12	19	2
Sball+1gNPK	1	12	23	2
Sball+3gAsh	1	12	8	2
Sball+0.1gCNT	1	12	19	2
Sball+0.5gNPK	1	12	21	2
Sball+0.5gCNT	1	12	25	2
Control	2	12	23	2
Sball	2	12	22	2
Sball+1gNPK	2	12	25	2
Sball+3gAsh	2	12	13	2
Sball+0.1gCNT	2	12	25	2
Sball+0.5gNPK	2	12	21	2

Sball+0.5gCNT	2	12	14	2
Control	3	12	22	2
Sball	3	12	22	2
Sball+1gNPK	3	12	27	2
Sball+3gAsh	3	12	15	2
Sball+0.1gCNT	3	12	24	2
Sball+0.5gNPK	3	12	16	2
Sball+0.5gCNT	3	12	10	2
Control	4	12	22	2
Sball	4	12	24	2
Sball+1gNPK	4	12	24	2
Sball+3gAsh	4	12	6	2
Sball+0.1gCNT	4	12	23	2
Sball+0.5gNPK	4	12	18	2
Sball+0.5gCNT	4	12	.	.
Control	5	12	22	2
Sball	5	12	22	2
Sball+1gNPK	5	12	23	2
Sball+3gAsh	5	12	8	2
Sball+0.1gCNT	5	12	21	2
Sball+0.5gNPK	5	12	21	2
Sball+0.5gCNT	5	12	16	2
Control	6	12	21	2
Sball	6	12	19	2
Sball+1gNPK	6	12	25	2
Sball+3gAsh	6	12	14	2
Sball+0.1gCNT	6	12	20	2
Sball+0.5gNPK	6	12	21	2
Sball+0.5gCNT	6	12	18	2
Control	1	16	27	3
Sball	1	16	27	3
Sball+1gNPK	1	16	32	4
Sball+3gAsh	1	16	12	3
Sball+0.1gCNT	1	16	23	3
Sball+0.5gNPK	1	16	24	3
Sball+0.5gCNT	1	16	29	2
Control	2	16	26	3
Sball	2	16	23	3
Sball+1gNPK	2	16	35	3
Sball+3gAsh	2	16	19	3
Sball+0.1gCNT	2	16	32	3

Sball+0.5gNPK	2	16	23	3
Sball+0.5gCNT	2	16	20	3
Control	3	16	27	3
Sball	3	16	24	3
Sball+1gNPK	3	16	38	3
Sball+3gAsh	3	16	22	3
Sball+0.1gCNT	3	16	30	3
Sball+0.5gNPK	3	16	21	3
Sball+0.5gCNT	3	16	11	3
Control	4	16	26	3
Sball	4	16	26	3
Sball+1gNPK	4	16	32	4
Sball+3gAsh	4	16	13	4
Sball+0.1gCNT	4	16	24	3
Sball+0.5gNPK	4	16	21	3
Sball+0.5gCNT	4	16	.	.
Control	5	16	23	3
Sball	5	16	27	3
Sball+1gNPK	5	16	28	3
Sball+3gAsh	5	16	13	3
Sball+0.1gCNT	5	16	24	3
Sball+0.5gNPK	5	16	24	3
Sball+0.5gCNT	5	16	19	3
Control	6	16	26	3
Sball	6	16	20	3
Sball+1gNPK	6	16	36	3
Sball+3gAsh	6	16	19	4
Sball+0.1gCNT	6	16	24	3
Sball+0.5gNPK	6	16	25	3
Sball+0.5gCNT	6	16	29	3
Control	1	20	28	3
Sball	1	20	33	4
Sball+1gNPK	1	20	38	4
Sball+3gAsh	1	20	19	4
Sball+0.1gCNT	1	20	31	4
Sball+0.5gNPK	1	20	26	3
Sball+0.5gCNT	1	20	38	3
Control	2	20	36	3
Sball	2	20	29	3
Sball+1gNPK	2	20	44	4
Sball+3gAsh	2	20	31	3

Sball+0.1gCNT	2	20	40	4
Sball+0.5gNPK	2	20	26	3
Sball+0.5gCNT	2	20	31	4
Control	3	20	38	3
Sball	3	20	30	3
Sball+1gNPK	3	20	45	4
Sball+3gAsh	3	20	31	3
Sball+0.1gCNT	3	20	37	3
Sball+0.5gNPK	3	20	26	3
Sball+0.5gCNT	3	20	22	4
Control	4	20	35	3
Sball	4	20	27	3
Sball+1gNPK	4	20	39	4
Sball+3gAsh	4	20	26	3
Sball+0.1gCNT	4	20	33	3
Sball+0.5gNPK	4	20	23	2
Sball+0.5gCNT	4	20	.	.
Control	5	20	30	3
Sball	5	20	31	3
Sball+1gNPK	5	20	35	4
Sball+3gAsh	5	20	23	3
Sball+0.1gCNT	5	20	35	3
Sball+0.5gNPK	5	20	26	3
Sball+0.5gCNT	5	20	34	4
Control	6	20	36	3
Sball	6	20	22	2
Sball+1gNPK	6	20	40	4
Sball+3gAsh	6	20	34	3
Sball+0.1gCNT	6	20	33	3
Sball+0.5gNPK	6	20	28	3
Sball+0.5gCNT	6	20	27	2
Control	1	24	43	3
Sball	1	24	38	4
Sball+1gNPK	1	24	56	4
Sball+3gAsh	1	24	50	4
Sball+0.1gCNT	1	24	48	4
Sball+0.5gNPK	1	24	44	3
Sball+0.5gCNT	1	24	67	3
Control	2	24	55	3
Sball	2	24	48	3
Sball+1gNPK	2	24	54	4

Sball+3gAsh	2	24	51	3
Sball+0.1gCNT	2	24	45	4
Sball+0.5gNPK	2	24	40	3
Sball+0.5gCNT	2	24	60	4
Control	3	24	46	3
Sball	3	24	40	3
Sball+1gNPK	3	24	63	4
Sball+3gAsh	3	24	49	3
Sball+0.1gCNT	3	24	49	3
Sball+0.5gNPK	3	24	47	3
Sball+0.5gCNT	3	24	50	4
Control	4	24	50	3
Sball	4	24	44	3
Sball+1gNPK	4	24	55	4
Sball+3gAsh	4	24	55	3
Sball+0.1gCNT	4	24	41	3
Sball+0.5gNPK	4	24	52	2
Sball+0.5gCNT	4	24	.	.
Control	5	24	40	3
Sball	5	24	41	3
Sball+1gNPK	5	24	46	4
Sball+3gAsh	5	24	55	3
Sball+0.1gCNT	5	24	46	3
Sball+0.5gNPK	5	24	41	3
Sball+0.5gCNT	5	24	50	4
Control	6	24	48	3
Sball	6	24	45	2
Sball+1gNPK	6	24	55	4
Sball+3gAsh	6	24	54	3
Sball+0.1gCNT	6	24	44	3
Sball+0.5gNPK	6	24	43	3
Sball+0.5gCNT	6	24	50	2
Control	1	28	47	4
Sball	1	28	41	4
Sball+1gNPK	1	28	56	4
Sball+3gAsh	1	28	56	5
Sball+0.1gCNT	1	28	48	4
Sball+0.5gNPK	1	28	48	4
Sball+0.5gCNT	1	28	68	4
Control	2	28	57	4
Sball	2	28	50	4

Sball+1gNPK	2	28	54	4
Sball+3gAsh	2	28	56	3
Sball+0.1gCNT	2	28	45	5
Sball+0.5gNPK	2	28	45	4
Sball+0.5gCNT	2	28	69	5
Control	3	28	46	4
Sball	3	28	44	4
Sball+1gNPK	3	28	63	4
Sball+3gAsh	3	28	50	3
Sball+0.1gCNT	3	28	50	4
Sball+0.5gNPK	3	28	47	4
Sball+0.5gCNT	3	28	53	5
Control	4	28	54	4
Sball	4	28	48	3
Sball+1gNPK	4	28	60	4
Sball+3gAsh	4	28	62	4
Sball+0.1gCNT	4	28	45	4
Sball+0.5gNPK	4	28	52	4
Sball+0.5gCNT	4	28	.	.
Control	5	28	46	4
Sball	5	28	47	4
Sball+1gNPK	5	28	48	4
Sball+3gAsh	5	28	62	4
Sball+0.1gCNT	5	28	50	4
Sball+0.5gNPK	5	28	46	4
Sball+0.5gCNT	5	28	53	5
Control	6	28	49	4
Sball	6	28	45	3
Sball+1gNPK	6	28	60	4
Sball+3gAsh	6	28	60	5
Sball+0.1gCNT	6	28	47	4
Sball+0.5gNPK	6	28	43	4
Sball+0.5gCNT	6	28	52	5

Table 9: Pearl millet seedlings emergence 8 days afer sowing for three treatments as affected by storage time at the greenhouse of University of Hohenheim, Germany. Treatment (n = 20) column shows 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.

Treatment	**Rep**	**Time (week)**	**Germination (#/20)**
Control	1	1	19
Control	2	1	18
Control	3	1	19
Control	4	1	20
Control	5	1	18
Control	6	1	21
Control	7	1	19
Control	8	1	20
Control	9	1	21
Control	10	1	20
Control	11	1	19
Control	12	1	21
Sball+3gAsh	1	1	14
Sball+3gAsh	2	1	18
Sball+3gAsh	3	1	15
Sball+3gAsh	4	1	14
Sball+3gAsh	5	1	18
Sball+3gAsh	6	1	14
Sball+3gAsh	7	1	15
Sball+3gAsh	8	1	14
Sball+3gAsh	9	1	14
Sball+3gAsh	10	1	18
Sball+3gAsh	11	1	14
Sball+3gAsh	12	1	18
Sball+1gNPK	1	1	14
Sball+1gNPK	2	1	18
Sball+1gNPK	3	1	16
Sball+1gNPK	4	1	14
Sball+1gNPK	5	1	18
Sball+1gNPK	6	1	14
Sball+1gNPK	7	1	15
Sball+1gNPK	8	1	16
Sball+1gNPK	9	1	14

Sball+1gNPK	10	1	15
Sball+1gNPK	11	1	16
Sball+1gNPK	12	1	14
Control	1	3	18
Control	2	3	19
Control	3	3	20
Control	4	3	18
Control	5	3	21
Control	6	3	19
Control	7	3	20
Control	8	3	21
Control	9	3	20
Control	10	3	19
Control	11	3	21
Control	12	3	18
Sball+3gAsh	1	3	14
Sball+3gAsh	2	3	17
Sball+3gAsh	3	3	14
Sball+3gAsh	4	3	15
Sball+3gAsh	5	3	17
Sball+3gAsh	6	3	18
Sball+3gAsh	7	3	14
Sball+3gAsh	8	3	17
Sball+3gAsh	9	3	16
Sball+3gAsh	10	3	17
Sball+3gAsh	11	3	14
Sball+3gAsh	12	3	14
Sball+1gNPK	1	3	14
Sball+1gNPK	2	3	17
Sball+1gNPK	3	3	18
Sball+1gNPK	4	3	14
Sball+1gNPK	5	3	14
Sball+1gNPK	6	3	17
Sball+1gNPK	7	3	16
Sball+1gNPK	8	3	14
Sball+1gNPK	9	3	15
Sball+1gNPK	10	3	16
Sball+1gNPK	11	3	16
Sball+1gNPK	12	3	17
Control	1	5	18
Control	2	5	19

Control	3	5	18
Control	4	5	18
Control	5	5	20
Control	6	5	20
Control	7	5	18
Control	8	5	20
Control	9	5	21
Control	10	5	20
Control	11	5	19
Control	12	5	21
Sball+3gAsh	1	5	18
Sball+3gAsh	2	5	15
Sball+3gAsh	3	5	16
Sball+3gAsh	4	5	14
Sball+3gAsh	5	5	15
Sball+3gAsh	6	5	14
Sball+3gAsh	7	5	15
Sball+3gAsh	8	5	16
Sball+3gAsh	9	5	17
Sball+3gAsh	10	5	18
Sball+3gAsh	11	5	15
Sball+3gAsh	12	5	16
Sball+1gNPK	1	5	15
Sball+1gNPK	2	5	15
Sball+1gNPK	3	5	14
Sball+1gNPK	4	5	17
Sball+1gNPK	5	5	15
Sball+1gNPK	6	5	17
Sball+1gNPK	7	5	18
Sball+1gNPK	8	5	14
Sball+1gNPK	9	5	14
Sball+1gNPK	10	5	15
Sball+1gNPK	11	5	14
Sball+1gNPK	12	5	16
Control	1	7	20
Control	2	7	18
Control	3	7	18
Control	4	7	20
Control	5	7	18
Control	6	7	19
Control	7	7	20

Control	8	7	18
Control	9	7	18
Control	10	7	19
Control	11	7	18
Control	12	7	19
Sball+3gAsh	1	7	14
Sball+3gAsh	2	7	18
Sball+3gAsh	3	7	17
Sball+3gAsh	4	7	16
Sball+3gAsh	5	7	16
Sball+3gAsh	6	7	15
Sball+3gAsh	7	7	18
Sball+3gAsh	8	7	16
Sball+3gAsh	9	7	17
Sball+3gAsh	10	7	16
Sball+3gAsh	11	7	16
Sball+3gAsh	12	7	15
Sball+1gNPK	1	7	14
Sball+1gNPK	2	7	15
Sball+1gNPK	3	7	14
Sball+1gNPK	4	7	15
Sball+1gNPK	5	7	15
Sball+1gNPK	6	7	14
Sball+1gNPK	7	7	16
Sball+1gNPK	8	7	14
Sball+1gNPK	9	7	15
Sball+1gNPK	10	7	14
Sball+1gNPK	11	7	16
Sball+1gNPK	12	7	14
Control	1	9	19
Control	2	9	18
Control	3	9	18
Control	4	9	19
Control	5	9	18
Control	6	9	18
Control	7	9	19
Control	8	9	20
Control	9	9	21
Control	10	9	19
Control	11	9	19
Control	12	9	20

Sball+3gAsh	1	9	14
Sball+3gAsh	2	9	15
Sball+3gAsh	3	9	18
Sball+3gAsh	4	9	14
Sball+3gAsh	5	9	15
Sball+3gAsh	6	9	14
Sball+3gAsh	7	9	16
Sball+3gAsh	8	9	15
Sball+3gAsh	9	9	15
Sball+3gAsh	10	9	15
Sball+3gAsh	11	9	15
Sball+3gAsh	12	9	14
Sball+1gNPK	1	9	13
Sball+1gNPK	2	9	14
Sball+1gNPK	3	9	13
Sball+1gNPK	4	9	13
Sball+1gNPK	5	9	15
Sball+1gNPK	6	9	14
Sball+1gNPK	7	9	15
Sball+1gNPK	8	9	14
Sball+1gNPK	9	9	14
Sball+1gNPK	10	9	15
Sball+1gNPK	11	9	15
Sball+1gNPK	12	9	14

Table 10: Pearl millet plant nutrient uptake 28 days after sowing at the greenhouse of University of Hohenheim, Germany. Treatment (n = 6) column shows 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, NPK= 15:15:15 mineral fertiliser and CNT = calcium nitrate tetrahydrate.

Treatment	**Rep**	**Phosphorus (mg pot^{-1})**	**Magnesium (mg pot^{-1})**	**Potassium (mg pot^{-1})**
Control	1	0.6	1.0	10.6
Sball	1	0.6	1.4	11.6
Sball+1gNPK	1	1.9	1.8	20.5
Sball+3gAsh	1	2.0	3.1	43.4
Sball+0.1gCNT	1	0.7	1.5	12.8
Sball+0.5gNPK	1	0.9	2.1	12.3

Sball+0.5gCNT	1	3.2	4.6	48.5
Control	2	0.8	1.3	14.2
Sball	2	1.0	2.4	18.8
Sball+1gNPK	2	3.0	2.8	31.4
Sball+3gAsh	2	1.3	1.9	26.4
Sball+0.1gCNT	2	0.8	1.6	14.1
Sball+0.5gNPK	2	0.7	1.5	10.7
Sball+0.5gCNT	2	7.7	11.1	117.0
Control	3	0.8	1.3	13.8
Sball	3	0.8	1.9	14.7
Sball+1gNPK	3	2.3	2.3	26.5
Sball+3gAsh	3	0.9	1.3	18.5
Sball+0.1gCNT	3	1.1	2.4	19.9
Sball+0.5gNPK	3	0.9	2.1	13.1
Sball+0.5gCNT	3	5.8	8.6	104.9
Control	4	1.0	1.7	17.1
Sball	4	0.8	2.0	15.9
Sball+1gNPK	4	3.4	3.3	37.7
Sball+3gAsh	4	1.8	2.7	38.1
Sball+0.1gCNT	4	0.7	1.4	12.5
Sball+0.5gNPK	4	1.0	2.4	15.2
Sball+0.5gCNT	4	.	.	.
Control	5	0.7	1.2	12.1
Sball	5	0.7	1.5	12.9
Sball+1gNPK	5	1.8	1.7	18.7
Sball+3gAsh	5	1.2	1.9	27.5
Sball+0.1gCNT	5	0.7	1.4	13.5
Sball+0.5gNPK	5	1.0	2.3	15.2
Sball+0.5gCNT	5	2.9	4.1	42.1
Control	6	1.1	1.8	19.0
Sball	6	0.8	1.9	14.3
Sball+1gNPK	6	2.2	2.1	23.4
Sball+3gAsh	6	1.9	2.9	37.2
Sball+0.1gCNT	6	0.8	1.5	14.2
Sball+0.5gNPK	6	1.0	2.3	15.4
Sball+0.5gCNT	6	2.8	4.0	34.6

Seedball-induced changes of root growth and physico-chemical properties

Table 11: Height and leaf development of pearl millet seedlings 22 days after sowing as affected by three treatments at UFZ climate chamber, Halle, Germany. Treatment (n = 6) column shows Control = non-pelleted seeds, Seedball = 80 g sand + 50 g loam + 25 ml water whereas NPKSeedball = Seedball + 1 g 15:15:15 NPK mineral fertiliser.

Treatment	**Rep**	**Time (day)**	**Height (cm)**	**Leaf (#)**
Control	1	7	9	2
Control	2	7	6	2
Control	3	7	14	2
Control	4	7	3	2
Control	5	7	10	2
Control	6	7	7	2
Seedball	1	7	12	2
Seedball	2	7	17	2
Seedball	3	7	18	3
Seedball	4	7	17	2
Seedball	5	7	11	2
Seedball	6	7	16	2
NPKSeedball	1	7	11	2
NPKSeedball	2	7	5	2
NPKSeedball	3	7	18	2
NPKSeedball	4	7	13	2
NPKSeedball	5	7	19	2
NPKSeedball	6	7	17	2
Control	1	14	25	5
Control	2	14	19	5
Control	3	14	39	5
Control	4	14	9	3
Control	5	14	24	5
Control	6	14	19	4
Seedball	1	14	35	5
Seedball	2	14	37	6
Seedball	3	14	37	6
Seedball	4	14	44	5
Seedball	5	14	33	5
Seedball	6	14	40	6

NPKSeedball	1	14	39	6
NPKSeedball	2	14	31	5
NPKSeedball	3	14	48	6
NPKSeedball	4	14	40	6
NPKSeedball	5	14	36	6
NPKSeedball	6	14	44	5
Control	1	21	43	7
Control	2	21	46	7
Control	3	21	53	7
Control	4	21	33	6
Control	5	21	46	7
Control	6	21	38	6
Seedball	1	21	50	6
Seedball	2	21	47	7
Seedball	3	21	48	6
Seedball	4	21	59	5
Seedball	5	21	53	7
Seedball	6	21	52	6
NPKSeedball	1	21	58	7
NPKSeedball	2	21	54	7
NPKSeedball	3	21	62	7
NPKSeedball	4	21	52	7
NPKSeedball	5	21	43	7
NPKSeedball	6	21	60	7

Table 12: Treatment effect on the extracted soil solution at the upper part (3.5 cm depth) of germination column on phosphorus concentration (Upper_P), pH (Upper_pH) and electrical conductivity (Upper_EC) throughout the 21 days growth period of pearl millet. Treatment (n = 6) column shows Control = non-pelleted seeds, Seedball = 80 g sand + 50 g loam + 25 ml water, and NPKSeedball = Seedball + 1 g 15:15:15 NPK mineral fertiliser, whereas b.d. for phosphorus concentration indicates below detection level.

Treatment	**Rep**	**Upper_P (mg l^{-1})**	**Upper_pH**	**Upper_EC (mS μS^{-1})**
Control	1	0.02	4.8	1891
Control	2	0.02	4.5	1821
Control	3	b.d.	4.3	1236

Control	4	0.05	4.7	1693
Control	5	0.04	4.3	1762
Control	6	0.03	4.7	1796
Seedball	1	0.01	7.3	1488
Seedball	2	0.01	4.9	1507
Seedball	3	b.d.	5.7	1399
Seedball	4	0.38	4.5	1510
Seedball	5	0.01	4.7	1475
Seedball	6	0.15	7.6	1093
NPKSeedball	1	10.64	5.8	4133
NPKSeedball	2	0.79	5.4	1968
NPKSeedball	3	10.18	5.7	2733
NPKSeedball	4	3.35	5.2	2689
NPKSeedball	5	b.d.	4.9	1279
NPKSeedball	6	1.44	5.3	3017
Control	1	b.d.	5.1	382
Control	2	0.02	4.6	1389
Control	3	b.d.	4.9	854
Control	4	b.d.	4.8	1021
Control	5	b.d.	4.5	1005
Control	6	b.d.	4.8	1132
Seedball	1	0.05	6.8	376
Seedball	2	0.01	5.4	507
Seedball	3	b.d.	5.3	356
Seedball	4	0.01	5.2	1211
Seedball	5	0.04	4.9	941
Seedball	6	0.01	5.1	401
NPKSeedball	1	1.67	5.3	449
NPKSeedball	2	1.43	5.3	1325
NPKSeedball	3	0.29	5.3	227
NPKSeedball	4	1.85	5.7	444
NPKSeedball	5	b.d.	5.1	236
NPKSeedball	6	0.33	5.0	657
Control	1	b.d.	5.0	169
Control	2	0.02	4.8	762
Control	3	b.d.	4.8	468
Control	4	0.02	5.1	467
Control	5	0.02	4.7	326
Control	6	0.03	4.9	372
Seedball	1	0.02	7.1	282
Seedball	2	0.07	5.2	43

Seedball	3	b.d.	6.0	43
Seedball	4	0.04	6.1	553
Seedball	5	.	5.0	.
Seedball	6	.	6.1	308
NPKSeedball	1	0.23	5.1	174
NPKSeedball	2	.	.	.
NPKSeedball	3	0.55	5.3	423
NPKSeedball	4	0.31	5.4	106
NPKSeedball	5	0.01	5.3	194
NPKSeedball	6	0.09	5.2	140

Table 13: Treatment effect on the extracted soil solution at the lower part (3.5 cm depth) of germination column on phosphorus concentration (Lower_P), pH (Lower_pH) and electrical conductivity (Lower_EC) throughout the 21 days growth period of pearl millet. Treatment (n = 6) column shows Control = non-pelleted seeds, Seedball = 80 g sand + 50 g loam + 25 ml water, and NPKSeedball = Seedball + 1 g 15:15:15 NPK mineral fertiliser, whereas b.d. for phosphorus concentration indicates below detection level.

Treatment	**Rep**	**Lower_P (mg l^{-1})**	**Lower_pH**	**Lower_EC (mS µS^{-1})**
Control	1	0.01	4.7	859
Control	2	b.d.	4.5	1205
Control	3	0.03	4.7	1199
Control	4	b.d.	4.8	1047
Control	5	0.01	4.7	1097
Control	6	b.d.	4.8	1527
Seedball	1	0.01	4.7	1339
Seedball	2	0.03	4.9	1059
Seedball	3	b.d.	5.0	549
Seedball	4	0.02	4.2	872
Seedball	5	0.03	4.0	1473
Seedball	6	0.04	4.6	1011
NPKSeedball	1	0.04	4.8	1496
NPKSeedball	2	0.03	4.8	1797
NPKSeedball	3	b.d.	4.6	1515
NPKSeedball	4	0.06	4.7	1628
NPKSeedball	5	0.02	4.9	757

NPKSeedball	6	0.01	4.8	1503
Control	1	b.d.	5.0	339
Control	2	b.d.	4.8	555
Control	3	b.d.	5.2	261
Control	4	b.d.	4.9	487
Control	5	b.d.	4.7	434
Control	6	b.d.	4.9	837
Seedball	1	0.01	4.9	285
Seedball	2	0.02	5.2	228
Seedball	3	b.d.	5.0	214
Seedball	4	b.d.	5.0	334
Seedball	5	b.d.	4.8	458
Seedball	6	b.d.	6.6	614
NPKSeedball	1	1.20	5.2	460
NPKSeedball	2	0.01	5.0	755
NPKSeedball	3	0.35	5.4	450
NPKSeedball	4	0.01	5.1	335
NPKSeedball	5	0.02	5.1	195
NPKSeedball	6	b.d.	4.9	584
Control	1	0.01	5.2	106
Control	2	0.02	4.9	186
Control	3	0.01	5.2	115
Control	4	0.01	5.1	261
Control	5	0.02	5.1	320
Control	6	0.02	5.1	363
Seedball	1	b.d.	4.8	129
Seedball	2	0.01	5.2	87
Seedball	3	0.01	5.2	111
Seedball	4	0.02	5.3	96
Seedball	5	0.01	4.8	158
Seedball	6	b.d.	5.1	96
NPKSeedball	1	0.01	5.0	161
NPKSeedball	2	0.01	5.1	177
NPKSeedball	3	0.01	5.0	110
NPKSeedball	4	b.d.	5.2	110
NPKSeedball	5	0.02	5.1	130
NPKSeedball	6	0.01	5.2	107

Table 14: Shoot biomass (Shootbio), dry matter (Shootdry), upper 3.5 cm part root biomass (Upperrootbio) as well as lower 7.0 cm part root biomass (Lowerrootbio) and total root biomass (Totrootbio) of pearl millet 21 days after sowing for the three treatments. Treatment (n = 6) column shows Control = non-pelleted seeds, Seedball = 80 g sand + 50 g loam + 25 ml water, and NPKSeedball = Seedball + 1 g 15:15:15 NPK mineral fertiliser.

Treatment	**Rep**	**Shootbio (g)**	**Shootdry (g)**	**Upperrootbio (g)**	**Lowerrootbio (g)**	**Totrootbio (g)**
Control	1	2.64	0.40	1.07	0.98	2.05
Control	2	2.63	0.26	1.55	0.76	2.31
Control	3	3.96	0.58	1.76	1.24	3.00
Control	4	0.95	0.03	0.31	0.17	0.48
Control	5	2.87	0.37	0.59	1.03	1.62
Control	6	1.04	0.06	0.26	0.06	0.32
Seedball	1	3.65	0.55	1.36	1.58	2.94
Seedball	2	3.92	0.58	1.89	1.49	3.38
Seedball	3	3.74	0.60	1.24	1.27	2.51
Seedball	4	4.16	0.69	1.24	1.33	2.57
Seedball	5	3.69	0.54	0.87	1.40	2.27
Seedball	6	4.20	0.58	1.50	1.15	2.65
NPKSeedball	1	6.80	1.00	2.13	2.62	4.75
NPKSeedball	2	4.82	0.71	1.49	1.25	2.74
NPKSeedball	3	7.80	1.12	1.34	1.67	3.01
NPKSeedball	4	7.03	1.08	1.62	2.21	3.83
NPKSeedball	5	3.87	0.58	1.75	0.82	2.57
NPKSeedball	6	7.06	1.07	1.80	1.41	3.21

Table 15: Total root dry matter (Totrootdrym), root length (Totrootlen) as well as density (Rootden) of pearl millet 21 days after sowing for three treatments. Treatment (n = 6) column shows Control = non-pelleted seeds, Seedball = 80 g sand + 50 g loam + 25 ml water i.e. seedball without nutrient additive, and NPKSeedball = Seedball + 1 g 15:15:15 NPK mineral fertiliser i.e. seedball with nutrient additive.

Treatment	**Rep**	**Totrootdrym (g)**	**Totrootlen (cm)**	**Rootden (cm cm^{-1})**
Control	1	0.67	5524	5.74
Control	2	0.56	5936	6.17
Control	3	0.68	7932	8.24
Control	4	0.28	988	1.03
Control	5	0.51	4886	5.08
Control	6	0.31	1317	1.37
Seedball	1	0.74	7248	7.53
Seedball	2	0.74	9750	10.13
Seedball	3	0.79	8119	8.44
Seedball	4	0.51	6131	6.37
Seedball	5	0.50	5088	5.29
Seedball	6	0.50	6381	6.63
NPKSeedball	1	0.92	12146	12.62
NPKSeedball	2	0.66	5957	6.19
NPKSeedball	3	0.76	7687	7.99
NPKSeedball	4	0.53	7438	7.73
NPKSeedball	5	0.52	7764	8.07
NPKSeedball	6	0.57	9670	10.05

Table 16: Root length of pearl millet within different diameter classes, in mm, 21 days after planting for the three treatments. Treatment (n = 6) column shows Control = non-pelleted seeds, Seedball = 80 g sand + 50 g loam + 25 ml water i.e. seedball without nutrient additive, and NPKSeedball = Seedball + 1 g 15:15:15 NPK mineral fertiliser i.e. seedball with nutrient additive.

Treatment	**Rep**	**Location**	**0-0.2mm (cm)**	**0.2-0.4mm (cm)**	**0.4-0.6mm (cm)**	**0.6-0.8mm (cm)**	**0.8-1.0mm (cm)**
Control	1	upper	2807.5	483.3	110.4	88.8	78.1
Control	2	upper	3615.3	448.1	49.5	46.5	45.0
Control	3	upper	4493.9	496.5	150.6	29.3	13.0
Control	4	upper	474.3	43.2	7.7	5.5	2.7
Control	5	upper	1156.7	262.4	29.0	14.5	12.2
Control	6	upper	697.4	102.9	20.2	8.1	5.2
Seedball	1	upper	3503.2	465.0	52.7	24.3	37.7
Seedball	2	upper	4932.2	549.7	133.9	108.9	72.2
Seedball	3	upper	4174.5	653.4	108.4	52.4	33.3
Seedball	4	upper	2569.7	360.0	53.5	30.7	21.0
Seedball	5	upper	2492.6	293.5	56.5	22.6	22.7
Seedball	6	upper	3107.2	400.5	65.8	21.7	25.7
NPKSeedball	1	upper	6302.3	723.3	159.8	180.7	194.6
NPKSeedball	2	upper	3260.5	389.1	54.3	21.7	20.2
NPKSeedball	3	upper	3642.4	408.6	72.9	34.2	28.2
NPKSeedball	4	upper	3277.9	558.5	59.9	18.2	19.2
NPKSeedball	5	upper	4793.2	827.2	172.1	84.4	41.5
NPKSeedball	6	upper	5612.3	879.0	109.5	72.1	67.7
Control	1	lower	1809.6	113.3	17.9	1.1	.
Control	2	lower	1376.0	272.6	46.2	15.6	7.6
Control	3	lower	2373.5	326.2	42.2	5.4	.
Control	4	lower	324.7	96.6	20.6	8.1	3.5
Control	5	lower	2364.8	832.2	114.9	45.5	39.7
Control	6	lower	367.7	76.1	22.4	7.7	3.3
Seedball	1	lower	2504.2	468.3	119.4	30.0	14.3
Seedball	2	lower	2867.9	756.9	189.8	45.5	41.3
Seedball	3	lower	2234.1	612.4	145.3	46.1	33.1
Seedball	4	lower	2058.4	743.8	182.8	52.6	18.7
Seedball	5	lower	1802.6	279.0	69.5	20.0	16.9
Seedball	6	lower	2007.7	533.3	143.3	26.6	20.1
NPKSeedball	1	lower	2599.5	1158.5	498.2	158.5	81.1
NPKSeedball	2	lower	1632.0	419.2	106.8	19.1	12.6

NPKSeedball	3	lower	2540.7	681.6	165.2	43.8	35.9
NPKSeedball	4	lower	2404.1	819.5	196.1	45.7	13.0
NPKSeedball	5	lower	1207.5	410.7	142.5	36.7	18.5
NPKSeedball	6	lower	2098.0	576.2	157.7	34.2	24.4