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Review article

Biological nitrogen fixation and socioeconomic factors for legume production in sub-Saharan Africa: a review

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Abstract – Low crop productivity is a general problem facing most farming systems in sub-Saharan Africa (SSA). These low yields are pronounced in grain legumes and are often associated with declining soil fertility and reduced N_2-fixation due to biological and environmental factors. Unfortunately, the majority of African small farmers are now unable to afford the high mineral fertilizer prices. More than 75% of the fertilizers used in Africa are imported, putting pressure on foreign exchange. Low cost and sustainable technical solutions compatible with the socioeconomic conditions of small farmers are needed to solve soil fertility problems. Biological nitrogen fixation (BNF), a key source of N for farmers using little or no fertilizer, constitutes one of the potential solutions and plays a key role in sustainable grain legumes (e.g., soybean) production. Given the high cost of fertilizer in Africa and the limited market infrastructure for farm inputs, current research and extension efforts have been directed to integrated nutrient management, in which legumes play a crucial role. Inoculation with compatible and appropriate rhizobia may be necessary where a low population of native rhizobial strains predominates and is one of the solutions which grain legume farmers can use to optimize yields. It is critical for sustained yield in farmlands deficient in native rhizobia and where N supply limits production. Research on use of *Rhizobium* inoculants for production of grain legumes showed it is a cheaper and usually more effective agronomic practice for ensuring adequate N nutrition of legumes, compared with the application of N fertilizer. Here, we review past and on-going interventions in *Rhizobium* inoculation (with special reference to soybean) in the farming systems of SSA with a view to understanding the best way to effectively advise on future investments to enhance production and adoption of BNF and inoculant technologies in SSA. The major findings are: (1) complete absence of or very weak institutions, policy and budgetary support for biotechnology research and lack of its integration into wider agricultural and overall development objectives in SSA, (2) limited knowledge of inoculation responses of both promiscuous and specifically nodulating soybean varieties as well as the other factors that inhibit BNF, hence a weak basis for decision-making on biotechnology issues in SSA, (3) limited capacity and lack of sustainable investment, (4) poorly developed marketing channels and infrastructure, and limited involvement of the private sector in the distribution of inoculants, and (5) limited farmer awareness about and access to (much more than price) inoculants. The lessons learned include the need: (1) to increase investment in *Rhizobium* inoculation technology development, and strengthen policy and institutional support, (2) for public private partnership in the development, deployment and dissemination of BNF technologies, (3) to develop effective BNF dissemination strategies (including participatory approach) to reach farmers, (4) for greater emphasis on capacity building along the BNF value chain, and (5) for partnership between universities in SSA and those in the North on BNF research.

low soil fertility / N_2 fixation / inoculants / soybean / adoption drivers / sub-Saharan Africa

Contents

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List of abbreviations

ASK	Agricultural Society of Kenya
BCR	Benefit Cost Ratio
BNF	Biological Nitrogen Fixation
CAN	Calcium Ammonium Nitrate
CIAT	Centro Internacional Agricultura de Tropical
DAP	Di-Ammonium Phosphate
DR-Congo	Democratic Republic of Congo
FAO	Food and Agriculture Organization of the United Nation
FYM	Farmyard manure
IAEA	International Atomic Energy Agency
IITA	International Institute of Tropical Agriculture
IFDC	International Fertilizer Development Center
INM	Integrated Nutrient Management
ISAR	Institut des Sciences Agronomique du Rwanda
KARI	Kenya Agricultural Research Institute
KIOF	Kenya Institute of Organic Farming
KShs	Kenya Shillings
LSD	Least Significant Difference
MIRCEN	Microbiological Resources Center
MRR	Marginal Rate of Returns
N	Nitrogen
NGO	Non-governmental organization
NPK	Nitrogen Phosphorus Potassium
OMMN	Organic Matter Management Network
P	Phosphorus
R&D	Research and Development
SPRL	Soil Productivity Research Laboratory
SSA	Sub-Saharan Africa
SUA	Sokoine University of Agriculture
TGx	Tropical Glycine crosses
UNEP	United Nations Environment Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
US$	United States of America Dollar

1. INTRODUCTION

Smallholder farming systems in sub-Saharan Africa (SSA) are constrained by low crop productivity. Grain legumes are being seen as the "meat for the poor" due to their rich protein content and the low prices of pulses compared with meat. High productivity of pulses becomes vital as most poor people in SSA depend on pulses for protein supply to meet their food, nutritional and health needs. The average yields of grain legumes have remained very low (e.g., about 622 kg/ha for common bean) under farmers' conditions compared with research station yields (e.g., over 1500 kg/ha for common beans) (Mushi, 1997). Low yields are associated with declining soil fertility due to continuous cropping without soil replenishment and reduced N_2-fixation due to various biological and environmental factors (Dakora and Keya, 1997). This becomes more severe as farmers expand into marginal lands in response to population pressure. Arid and semiarid marginal lands are generally deficient in nitrogen (N), required to raise crop production (Mugabe, 1994).

Methods to enhance cost-effective soil nutrient supplies to small farmers have remained a challenge to scientists working to improve agricultural productivity in SSA. In the highland agricultural ecozones of SSA, N supply is also a key limiting factor in crop production for 35–45% of the farmers (Odame, 1997). Soybean is estimated to fix 80% of its N needs (Smaling et al., 2008). Many SSA countries have a growing need for mineral fertilizers to enhance crop yields (Mugabe, 1994; Morris et al., 2007; World Bank, 2008). However, the majority (about 60%) of African smallholder farmers are unable to afford the high prices of mineral fertilizers (Yanggen et al., 1998). A farmer has to sell about 10 kg of maize or 5 kg of common bean to buy 1 kg of N or P in the form of mineral fertilizers (Odame, 1997). This high conversion (crop to sell to purchase a unit of mineral fertilizer) ratio implies a low incentive to use fertilizers, and is largely explained by the high average farm gate prices of fertilizer in SSA. More than 75% of the mineral fertilizers used in Africa are imported (Mugabe, 1994), leading to reduced foreign exchange. For example, in the 1990s, Kenya spent over 30% of its foreign exchange annually on fertilizer importation (Mugabe, 1994).

Although grain legume yields can be improved by use of moderate levels of mineral fertilizers, legumes (unlike cereals) are rarely fertilized by farmers, probably due to the high cost of fertilizers and low awareness of the associated economic returns, or both (Ndakidemi et al., 2006). Supplementing legumes with soil nutrients has been shown to double yields (Dakora, 1984; da Silva et al., 1993), and increase plant growth and N_2-fixation compared with the unfertilized control (Ndakidemi et al., 2006). *Rhizobium* inoculation also helps to boost the yield of grain legumes, leading to land savings, and has been described as a cheap insurance for higher yields (Ndakidemi et al., 2006). However, despite its potential to address low N and its cost effectiveness, the demand for inoculants by farmers in SSA remains low (Kannaiyan, 1993). The reasons included poor quality, and inadequate and inefficient marketing outlets, as well as inadequate extension services covering inoculant use (Kannaiyan, 1993; Odame, 1997).

Given the high cost of fertilizer in Africa and the limited market infrastructure for agro-inputs, current research and extension efforts have been directed to integrated nutrient management (INM), in which leguminous crops, shrubs and trees play a key role (Chianu and Tsujii, 2005; Mafongoya et al., 2007). BNF is a key source of N for farmers who use little or no fertilizer, especially for legumes such as soybean (Smaling et al., 2008). Rinnofner et al. (2008) described BNF, in the context of legume catch crops, as an additional benefit. Based on the studies of Zotarelli et al. (1998), Alves et al. (1999, 2005), Hungria et al. (2006) and Araujo et al. (2006), it has been widely shown that up to 80% of the above-ground N accumulation in soybean is due to N fixation by rhizobia. A study carried out in Uganda shows that BNF contributes 22% of nitrogen inflows for perennial crops and 44% for annual crops (Nkonya et al., 2008). It is estimated that about 11.1 million metric tons of nitrogen is fixed annually through BNF in developing countries (Hardarson et al., 2003). If supplied through mineral fertilizers, about twice this amount will be required to achieve the same crop yield level (Hardarson et al., 2003). Most African countries could reduce expenditures on fertilizer imports through a full exploitation of BNF (Mugabe, 1994). It is estimated that *Rhizobium* alone could provide more than 50% of the fertilizer required for crop production in most of the marginal lands of Kenya, Zimbabwe and Tanzania (Mugabe, 1994). This underscores the importance of BNF in ensuring sustainable and low cost production by smallholder farmers in SSA. However, several constraints (socioeconomic, environmental, production, etc.) need to be addressed to tap the full benefits of BNF (Bohlool et al., 1992; Amijee and Giller, 1998; Date, 1999). The most serious problems affecting nodulation and N fixation in tropical cropping systems are limited skills, low quality inoculants, acid soils and high soil temperatures, among others.

The overall BNF history, especially in SSA, indicates that holistic studies addressing the challenges facing the use of inoculants by farmers have been rare. This contributes to limited knowledge and approaches on how to stimulate widespread use of BNF. Most studies on rhizobial inoculants have tended to address the biophysical components and the science of *Rhizobium* production (Amijee and Giller, 1998). Some research has also been carried out on the economic productivity of inoculants under experimental studies (Ndakidemi et al., 2006). Only a few studies have examined the socioeconomic and policy constraints affecting household adoption and utilization of inoculants by farmers. Meanwhile, lack of knowledge by farmers is a key factor explaining the low adoption, use and retention of inoculant technologies (Date, 1999).

Here, we review past and on-going interventions in *Rhizobium* inoculation (with special reference to soybean) in SSA in order to understand how best to effectively advise on future investments to popularize soybean enterprises and enhance production and adoption of BNF and inoculant technologies to improve the farming systems, household nutrition, income and overall welfare in SSA. We hypothesize that soybean inoculation significantly enhances the sustainability and productivity of farming systems in SSA and as a result, leads to reduction in poverty, and improvements in farm income and the overall welfare of farm families.

2. PRODUCTION AND MARKETING OF INOCULANTS IN SSA

BNF and N-inoculants have had a long history in Africa, starting with the colonial agricultural research efforts to develop N-inoculants for pasture legumes aimed at increasing the productivity of exotic cattle (Odame, 1997). To promote BNF in developing countries, UNESCO established a number of Microbiological Resource Centers (MIRCENs) across five continents with support from the UNEP and the FAO (Odame, 1997). The broad responsibilities of MIRCENs in Africa (located in Dakar, Cairo and Nairobi) include the collection, identification, maintenance and testing of strains as well as preparing inoculants and distributing cultures compatible with local crops. Others are the deployment of local *rhizobia* inoculant technology, promotion of research, and the provision of advice, training and guidance to individuals and institutions engaged in rhizobiology research. For instance, the Nairobi MIRCEN project promoted and transferred BNF technologies (including inoculants of pulses, pasture legumes and trees) to researchers and other agricultural stakeholders in Kenya and all of east Africa. The Nairobi MIRCEN also diversified into screening *Rhizobium* strains for tolerance to abiotic stress (e.g., high temperatures, soil acidity, drought, etc.), especially given the numerous environmental stresses that affect the success of BNF and since two-thirds of Kenya's agricultural land suffers from these. The idea is to gradually intensify screening trials for rhizobia that are adapted to such ecological stresses. The Nairobi MIRCEN project also explored the potential of *mycorrhiza*, a fungal strain, on plant roots that assists the plant to extract P and water from the soil. The Nairobi MIRCEN also developed a marketable bio-fertilizer called *Biofix* (Odame, 1997). Two non-governmental organizations (NGOs) [Kenya Institute of Organic Farming (KIOF) and the Organic Matter Management Network (OMMN)] played a significant role in distributing Biofix to farmers. Over time, KIOF's active involvement in Biofix promotion over-stretched its financial and human resources and waned.

In the 1990s, the FAO supported a project to select better strains of *Rhizobia* in Tanzania (Mugabe, 1994). Through this, Sokoine University of Agriculture (SUA), Morogoro, developed a bio-fertilizer (*Nitrosua*) for use in soybean production. In collaboration with the Ministry of Agriculture and some NGOs, SUA also established extension activities to disseminate *Nitrosua* to local farmers. These activities also waned over time (Bala, 2008). Inoculants were produced in Uganda by at least two plants (Madhavani Ltd. and the BNF of Makerere University, established in 1990 with the help of USAID). These two plants functioned up to 1997 and, for the contract order by the FAO produced 14.2 tons of soybean inoculants between 1995 and 1997. In Rwanda, inoculant production started at the Institut des Sciences Agronomiques du Rwanda (ISAR) in 1984 and had by 1990 reached an annual production level of 2.4 tons (Cassien and Woomer, 1998). Activities were, however, disrupted by the civil war of the 1990s. Following the end of the war and the renovation of the laboratory, BNF activities resumed. However, pre-civil war levels are yet to be reached (Giller, 2001).

Commercially manufactured South African inoculants first appeared in the market in 1952 but were of doubtful quality until an independent quality control system was introduced in the early 1970s (Strijdom, 1998). Since 1976, all inoculants must be manufactured with sterilized peat and must contain at least 5×10^8 rhizobial cells g^{-1} of peat (Strijdom, 1998). The quality control measures ensured that South African inoculants compared well with the best quality inoculants produced outside Africa (Strijdom and van Rensburg, 1981). A range of inoculants are produced for a number of crops including soybean, groundnut and cowpea (Deneyschen et al., 1998). In Malawi, commercially available inoculants for crops such as soybean and cowpea, produced by Chitedze Agricultural Research Station, Lilongwe, were available and sold in 50-g packets (Khonje, 1989), starting from the 1970s. Sales rose dramatically from 450 packets in 1976 to about 1800 in 1987/88. The presence of a large and well-established commercial soybean sector in Zimbabwe suggests widespread use of inoculants in the country (Mpepereki et al., 2000). The Soil Productivity Research Laboratory (SPRL) spearheaded a project in the 1990s for enhancing BNF technology in Zimbabwe, supported by the IAEA (IAEA, 1998 cited by Bala, 2008). The project developed the capacity to mass produce inoculants (120 000 packets per year) which were distributed to small farmers through the Government's extension system. The University of Zimbabwe also undertook *mycorrhizal* inoculation research in some regions (Mugabe, 1994).

3. INOCULATION AND GRAIN LEGUME NODULATION

Due to the importance of legumes in N_2-fixation, soil fertility improvement, and human and livestock nutrition in SSA, the agricultural extension services in SSA have traditionally promoted and encouraged their inclusion in the farming systems (e.g., through promotion of cereal-legume intercropping). The cereal-legume intercrop has been shown to increase the total value of cereal and legume production, land equivalent ratio and returns to labor and other inputs (Maingi et al., 2001; Dapaah et al., 2003). This suggests the suitability of the cereal-legume intercropping system for smallholder farmers with limited land and resources to buy inorganic fertilizer and other external inputs. Hence promotion of the cereal-legume intercropping system by the extension services in SSA will also increase the adoption of *Rhizobium* inoculation technology.

Studies have shown that *Rhizobium* inoculation is needed in all agricultural lands deficient in N and where N supply is a key limiting factor in crop production (Odame, 1997). Examples of such lands abound in SSA (e.g., marginal lands, arid and semiarid lands, some highland areas that have lost their fertility) (Mugabe, 1994). Inoculating legumes with species-specific *Rhizobium* increases the success of their establishment, root nodulation, biomass and biomass N yields (Java et al., 1995; Zhu et al., 1998). Inoculation helps to increase the number of effective rhizobia (Boahen, 2008). It may also be necessary if a legume, newly introduced into an area, is to form effective symbiosis. Kaizzi (2002) and Giller et al. (1994) reported that Velvet bean (*Mucuna pruriens)* accumulated 68–220 kg N ha^{-1} in eastern Uganda, 50% of which was derived from the atmosphere through BNF. Indigenous *Bradyrhizobium* spp. also does not meet the demand for N by soybean all the time. Poor yields may occur whenever effective bradyrhizobia are inadequate or even when available in adequate numbers (Ken Giller, pers. commun.). The overuse of classical N fertilizers substantially contributes to environmental degradation through groundwater pollution by nitrates (Paynel et al., 2008). This leaching of N into waters is an economic flaw since only a part of the fertilizer is used by the plants. *Rhizobium* inoculants have been used to address the problems of soil fertility and inadequate fertilizer application in grain legume production and have been found to be a cheaper and usually more effective agronomic practice for ensuring adequate N nutrition of legumes, compared with the application of N fertilizer (Tran, 2004; Paynel et al., 2008). Studies have also shown that under the natural BNF inhibiting conditions, inoculation is much cheaper than mineral N fertilizer (Odame, 1997). A 100-g packet of Biofix (a form of *Rhizobium* inoculant), sufficient to inoculate 15 kg of common bean seed, enough to plant 1 acre, costs KShs 75 (or US$1.20). In contrast, 100 kg of inorganic CAN (Calcium Ammonium Nitrate) fertilizer, required for 1 acre, is sold for KShs 2040 (or US$34). Apart from being cheaper (28 times) than commercially produced N fertilizers, a 100-g packet of Biofix is also lighter to transport.

Worldwide, the use of *Bradyrhizobium* in soybean has been a major success in bio-fertilizers and constitutes an example of traditional biotechnology application. However, it is important to note that unlike soybean, cowpea hardly responds to inoculation in most parts of SSA because of the presence of suitable native rhizobia in the soil.

3.1. Inoculation response of commercial vs. promiscuous soybean varieties

Commercial soybean varieties are specific and require repeated inoculation due to non-persistence of the rhizobia. Corby (1965) was the first to describe the nodulation of soybean by rhizobia indigenous to African soils. He observed that a variety, 'Hernon 147', nodulated effectively with indigenous rhizobia and did not respond to inoculation in five out of six sites in Zambia and Zimbabwe. Field studies at the IITA (International Institute of Tropical Agriculture) in Nigeria showed that seed inoculation with commercial rhizobial inoculants significantly improved neither nodulation nor yield of three Asian soybean varieties, 'Malayan', 'Orba' and 'TGm 686', while the American varieties 'TGm 294-4-2371', 'Bossier' and 'Jupiter' formed very few nodules without inoculation and showed yield increases of 40 to 97% (Nangju, 1980). The Asian varieties rarely responded to inoculation even when inoculation more than doubled the yields of the American varieties (Pulver et al., 1982). Weaver and Fredrick (1974) suggested that inoculant rhizobial numbers of up to 1000 cells g^{-1} soil need to be applied to soybean seed to obtain greater nodule occupancy by inoculant rhizobia than the indigenous strains.

In some cases, however, the introduced legume such as soybean could form effective symbiosis with sufficient numbers of local rhizobia, thus obviating the need for inoculation. Chowdhury (1977) reported that soybean had been grown successfully without inoculation in certain parts of Nigeria, Tanzania and DR-Congo and attributed this to the selection for and increase in efficient *Rhizobium* strains due to cultivation over the years. All the varieties tested by Chowdhury (1977) formed nodules but only those bred locally from 'Hernon' varieties or 'Malayan' (Asian variety) formed many nodules. However, Sanginga et al. (2000) noted that promiscuous soybean is incapable of nodulating effectively with indigenous rhizobia in all locations in the moist savanna zone of Nigeria. Similarly, Bala (2008) observed that it is also not clear whether promiscuous soybean cultivars are effectively nodulated by indigenous rhizobial populations in all soils and under all conditions. A study by Eaglesham (1989) showed that the promiscuous soybean varieties showed inconsistent response to inoculation. This author, therefore, concluded that it may be safer to rely on effective inoculant strains rather than breed for the ability to nodulate with indigenous rhizobial strains of unknown potential. Early studies in South Africa showed local soybean cultivars to specifically form symbiosis with *B. japonicum* (Van Rensburg and Strijdom, 1969). However, it is important to note that even promiscuously nodulating soybeans (that often do not require inoculation), developed and cultivated in some parts of Africa, sometimes respond to inoculation. A study carried out by Osunde et al. (2003) at five sites in the moist savanna region of Nigeria showed that promiscuous soybean varieties (Tropical Glycine cross TGx 1456-2E and TGx 1660-19F) responded to inoculation (see Tab. I). However, 'Magoye', an exceptionally promiscuous line released in Zambia in 1981, nodulates readily in all soils of southern Africa where it has been tested and rarely responds to inoculation in Zambia and Zimbabwe (Mpepereki et al., 2000).

Promiscuity was used as a major selection criterion in the IITA for more than 10 years without in-depth microbiological studies (Sanginga et al., 2001). Recent studies on symbiotic effectiveness of indigenous rhizobia nodulating promiscuous soybean varieties in 92 Zimbabwean soils led to the identification of three isolates with superior N_2-fixing potential in the 'Magoye' variety than the commercial strain MAR 1491 (Musiyiwa et al., 2005a), although the M3 isolate was later identified as superior to the commercial strains MAR 1491 and 1495 (Zengeni and Giller, 2007). Thus, local soybean cultivars in South Africa may have had some evolutionary promiscuity, which might have been overlooked by the exclusive use of the specifically nodulating commercial varieties. Using four promiscuous soybean varieties (TGx 1485-1D, TGx 1456-2E, TGx 1448-2E and TGx 1660-19F), Okogun and Sanginga (2003) observed no significant difference between the yield of inoculated and uninoculated crops at three sites in the savanna of Nigeria even though the number of native rhizobia in soils at the three sites differed by orders of magnitude. On the basis of these results, the IITA initiated a soybean breeding program in 1978 to develop 'promiscuous' soybean varieties that nodulate with indigenous soil bradyrhizobia, thus eliminating the need for inoculation (Kueneman et al., 1984). The aim was to confer the ability to nodulate with indigenous rhizobia on the American soybean varieties, which had greater yield potential and better tolerance to diseases than the Asian varieties. This effort led to the development of over 60 TGx soybean lines. Studies aimed at establishing the degree of promiscuity of soybeans with indigenous rhizobia need to be further investigated to confirm these results (Musiyiwa et al., 2005b). According to Mpepereki et al. (2000), the symbiotic interaction between soybean genotypes and rhizobial isolates varies widely (e.g., in terms of ability to nodulate, and effectiveness in N_2-fixation). All plant genotypes tested by Mpepereki et al. (2000), including varieties considered to be highly specific, nodulated with indigenous isolates in some soils.

Table I. Nitrogen fixation and N accumulation by two promiscuous soybean cultivars [with(out) inoculation] across five sites in the southern Guinea savanna of Nigeria.

Treatment	Stover N (kg ha^{-1})	Grain N (kg ha^{-1})	Total N[a] (kg ha^{-1})	N_2 fixed (%)	N_2 fixed (kg ha^{-1})
N source:					
Inoculated	36	131	166	50	83
Uninoculated	32	121	153	46	70
60 kg N ha^{-1}	26	98	124	26	32
LSD (5%)[b]	4	21	25	10	11
Cultivar:					
TGx 1456-2E	30	135	165	43	70
TGx 1660-19F	33	98	131	39	50
LSD (5%)[b]	NS[b]	27	31	NS	15

[a] Total N of above-ground dry matter; [b] Least Significant Difference; NS = not significant.
Source: adapted from Osunde et al., 2003.

3.2. Response to inoculation: variability and determinants

Among others, inoculation response (e.g., soybean response to *Bradyrhizobium* inoculation) is regulated and influenced by the number and quality of indigenous rhizobia as well as abiotic and biotic factors (Abaidoo and Woomer, 2008). Figure 1 shows that the likelihood of response to inoculation by soybean is strongly influenced by the number of effective rhizobia in the soil. Soybean growing in a soil with a small number of effective rhizobia (20–50 cells g^{-1} soil) will

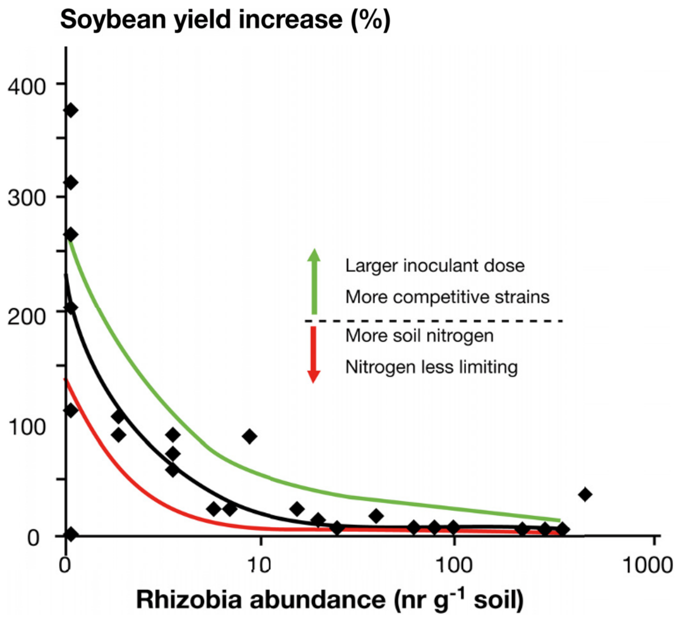

Figure 1. Soybean response to inoculation as regulated by the number of indigenous rhizobia (after Thies et al., 1991).

likely respond to inoculation (Singleton and Tavares, 1986; Thies et al., 1991).

Weaver and Fredrick (1974) suggested that for inoculation to be beneficial, nodule occupancy by inoculant strains must be more than 50%, requiring an inoculum rate of at least 1000 times the soil population. In practice, however, the presence of a large indigenous population of compatible rhizobia does not necessarily preclude response to inoculation, provided the inoculant rhizobial strains are competitive and highly effective (Giller, 2001; Osunde et al., 2003). According to Danso (1990), by increasing the numbers of inoculant strains, it is possible to increase the number of nodules they occupy.

A number of biotic and abiotic factors affect N_2-fixation (see Tab. II). Symbiotic N_2-fixation is highly sensitive to water stress, a major limiting factor to legume productivity in semi-arid tropics (Serraj et al., 1999). Nitrogen fixation in soybean also declines under soil moisture deficit (Devries et al., 1989; Kirda et al., 1989). Similarly, Sinclair et al. (1987) observed that N_2-fixation in soybean was sensitive to drought, a situation that underscores the shortcomings of N_2-fixation in the drylands, where 38% of the rural poor in SSA live (Ryan and Spencer, 2001). High temperature, soil acidity and salinity also inhibit growth of *Rhizobium*. Nutrient deficiencies, especially P, and the lack of efficient strains of rhizobia are also among the major factors limiting symbiotic N_2-fixation (Zaman-Allah et al., 2007).

These and other factors have led to efforts to inoculate legumes. Therefore, trials for establishing the need for inoculation should include tests for the limitation of BNF by other nutrients (Bohlool et al., 1992). For example, El-Hamdaoui et al. (2003) observed that application of boron and calcium increased N_2-fixation in salt-stressed soils.

3.3. Nitrogen fixation by promiscuous soybean varieties

A major advantage of promiscuous soybean varieties is their indeterminate growth, resulting in the production of large biomass (Mpepereki et al., 2000). Results from measurements based on the ^{15}N isotope dilution method showed that the amount of N_2 fixed by five promiscuous soybean varieties planted for 2 years in the southern Guinea savanna of Nigeria averaged 91 kg N ha^{-1}, representing 46% of the total plant N. In general, however, different lines of promiscuous soybean varieties growing on the same soil vary considerably in their ability to fix nitrogen (see Tab. III, further summarized in Tab. IV).

Differences in their efficiency for N_2-fixation among the genotypes, reproducible across sites, have also been a basis for selection in current soybean breeding work of the IITA, aimed at enhancing N_2-fixation in the absence of inoculation (Sanginga et al., 2000).

4. SUCCESS IN THE USE OF INOCULANTS TO INCREASE YIELDS: TRIALS

Early inoculation studies indicate yield advantage in soybean grain yield in tropical Africa (e.g., Sivestre, 1970; Nangju, 1980; Bromfield and Ayanaba, 1980). Sivestre (1970) noted yields of 1440 kg ha^{-1} in inoculated soybean compared with 240 kg ha^{-1} for the uninoculated. Bonnie (1957, cited by Bala, 2008) had reported yield increases of 80–300% with inoculation in DR-Congo. In Nigeria, a series of field experiments conducted in 1978 to screen strains of *B. japonicum* that were efficient in N_2-fixation showed that grain yields of the American soybean cultivars Bossier and TGm 294-4 were increased by as much as 100%, while cultivars of Asian origin showed no significant response (Ranga-Rao et al., 1981). Inoculation also led to grain yield increases of 40–79% in American soybean cultivars when grown in the southern Guinea savanna of Nigeria (Nangju, 1980; Pulver et al., 1982; Ranga-Rao et al., 1984). Bromfield and Ayanaba (1980) reported that inoculation of soybean in acid sands of south-eastern Nigeria resulted in grain yield increases of 300–500% when lime was added and 270–970% in the absence of lime.

In an on-farm experiment in two districts (Moshi and Rombo) in northern Tanzania, using rhizobial inoculants (*Rhizobium tropici* strain CIAT 899 for common bean, and *Bradyrhizobium japonicum* strain USDA 110 for soybean), Ndakidemi et al. (2006) observed that at harvest, soybean and common bean growth was significantly ($P \leqslant 0.05$) greater with (brady)rhizobial inoculation compared with N and P supply or uninoculated control. Relative to uninoculated unfertilized plots, grain yields of common bean increased from inoculation alone (60–78%) and from inoculation + 26 kg P/ha (82–95%); with soybean, there was 127–139% increase in grain yield from inoculation alone, and 207–231% from inoculation + 26 kg P/ha. Thus, the combined application of bacterial inoculants and P fertilizer to soybean and common bean increased biomass production and grain yield compared with the singular use of N and P or (brady)rhizobial strains (Ndakidemi et al.,

Table II. Factors limiting biological nitrogen fixation in soybean and recommendations.

Factor	Effect	Reference	Recommendations
High soil temperature	Reduces the survival of rhizobia in soil and inhibits nodulation and N_2-fixation	Munevar and Wollum, 1982; Michiels et al., 1994	Surface mulching; placement of inoculum in deeper soil layers; select heat-tolerant strains
Soil moisture	Reduces rhizobial numbers, limits migration of rhizobia, reduces nodulation and N_2-fixation	Hunt et al., 1981	Optimization of soil moisture; select moisture-stress-tolerant strains
Soil acidity	Reduces the survival of rhizobia in soil, inhibits nodulation and N_2-fixation and leads to P fixation. Increases aluminum toxicity and calcium deficiency	Graham et al., 1994; Zahran, 1999; Giller, 2001	Use of acid-tolerant legume cultivars and rhizobia; liming of soil to pH at which Al and Mn are no longer toxic
P deficiency	Inhibits nodulation, N_2-fixation and rhizobial growth	Gates and Muller, 1979; Cassman et al., 1981	Addition of P fertilizers, amelioration of soil acidity, inoculation with effective mycorrhiza, and selection of P-efficient cultivars
Salt stress	Reduces nodule formation, respiration and nitrogenous activity	Tu, 1981; Delgado et al., 1994	Select salt-tolerant strains
High soil N level	Inhibits root infection, nodule development & nitrogenous activity	Abdel-Wahab et al., 1996; Imsande, 1986; Arreseigor et al., 1997	Breed cultivars which are less sensitive to mineral N
Herbicides, fungicides and insecticides	Inhibits rhizobial growth; reduces nodulation and N_2-fixation; deforms root hairs and inhibits plant growth	Mallik and Tesfai, 1993; Isol and Yoshida, 1990	Test the particular rhizobial inoculum and its behavior in respect of the product used before application; separate placement of rhizobia and fungicides
Competition from native organisms	Suppression of inoculation by native rhizobia	Dowlig and Broughton, 1986	Targeted research

2006). Economic analysis shows that the increase in grain yield with inoculation translated into higher marginal rate of return (MRR) and profitability for soybean and common bean small farms. With common bean, relative to the control, there was 66% increase in profit with inoculation in the Moshi district and 92% in the Rombo district; with provision of supplemental P (26 kg P/ha), these profit margins rose to 84% (Moshi) and 102% (Rombo). With soybean, however, the increase in profit with inoculation was much larger, about 140% (Rombo) and 153% (Moshi). With P supplementation, these rose to 224% (Rombo) and 250% (Moshi). In Zimbabwe, studies have shown that, depending on soil fertility and rainfall, inoculant use can be more cost-effective than mineral fertilizer application (Brenner, 1996). However, Kipkoech et al. (2007, p. 18) compared the efficacy of *Rhizobium* (in groundnut cropping systems) with other soil fertility-enhancing technologies (Di-ammonium phosphate, DAP, NPK and Farm yard manure, FYM) and the control in western Kenya. Results show that groundnut yield under *Rhizobium* inoculation (1362.9 kg/ha) ranked third after yield under DAP (1800 kg/ha) and NPK (1646 kg/ha). It was, however, better than the yield under FYM (1218.5 kg/ha) and the control (1208.7 kg/ha). The benefit cost ratio (BCR) follows the same trend, with *Rhizobium* inoculation coming third (with a BCR of 2.5:1) after DAP (with a BCR of 3.0:1) and NPK (with a BCR of 2.8:1). With a BCR of 2.2:1, FYM even trailed behind the control (BCR of 2.4:1) (Kipkoech et al., 2007, p. 19). These results show the importance of promoting inoculant use in African agriculture, especially among resource-poor farmers who cannot afford expensive mineral fertilizers (Ndakidemi et al., 2006). Besides, economic analysis of another four trials showed that farmers gained 19% more benefits from inoculation compared with urea application (Tran, 2004). In virtually all situations, there was economic benefit of inoculation, both for the legume itself and for subsequent crops. Soybean N_2-fixation has an economic value in terms of the N that it supplies to the plant from the air which otherwise would need to come from soil and/or fertilizer sources. There is also an economic value in the residual benefits for soil N fertility and increased productivity of subsequent crops (Tran, 2004). In most soils, the savings were equivalent to 40–60 kg N/ha. In a report by Duong et al. (1984), 240 kg N/ha would have been required to produce an equivalent grain yield to the inoculated treatment.

The key lesson learned with the successes of *Rhizobium* inoculation based on on-station experiments or experiments simulating farmers' conditions is that it does not really guarantee widespread uptake by the smallholder farmers, no matter how attractive the results are.

Table III. Nitrogen fixation (kg/ha) by selected breeding lines grown for two seasons in three sites with poor N in the Guinea savanna of Nigeria.

Breeding line	Site			Means
	Gidanwaya	Mokwa	Zaria	
High fixers:				
1485-ID	63	71	55	64
1830-20E	67	74	42	61
1526-5E	60	64	57	60
1798-7F	54	75	43	58
1799-8F	44	72	53	57
Intermediate fixers:				
1838-10E	47	50	39	46
1831-28E	39	54	38	44
1837-6E	40	52	36	43
1833-20E	36	60	33	43
Samsoy-2	34	54	38	42
Low fixers:				
1838-5E	45	34	21	33
1805-33F	37	27	36	33
1740-3F	32	37	27	32
1837-2E	29	35	32	32
1814-2E	23	32	37	31
Means	41	55	39	45
LSD[a]	26	25	19	13

[a] LSD = least significant difference.
Source: Sanginga et al., 2000.

5. SUCCESS IN THE USE OF INOCULANTS TO INCREASE YIELDS: FARMERS' FIELDS

Based on the obvious benefits of inoculation of legumes with suitable *Rhizobium* strains, a lot of trial research has been directed at BNF in SSA, with significant advances made. This section reviews the farm-level adoption of inoculants and the growing of promiscuous soybean varieties in Africa. Smallholder farmers in many parts of the moist savanna of Nigeria have widely adopted promiscuous soybean varieties, especially the high-yielding TGx 1448-2E (Manyong et al., 1998; Sanginga et al., 2001). In southern Africa, the exceptionally promiscuous nature of 'Magoye' led to its widespread promotion and adoption (Mpepereki et al., 2000). However, inoculating soybean with effective rhizobia is a key strategic research intervention that has contributed to significant improvement in the productivity of soybean in SSA. The development of local production of inoculants in Rwanda led to rapid expansion of the area under soybean production (Saint Macary et al., 1986). In Zimbabwe, a soybean promotion program including the use of inoculants saw to its widespread adoption by smallholder farmers, with farmer education on inoculation being a major driving force for the success of the program (Marufu et al., 1995). Presently, over 55 000 smallholder farmers in Zimbabwe inoculate and grow soybean as a result of this promotion (Mpepereki, pers. commun.). Initially designed to promote the cultivation of 'Magoye', farmers' improved access to seeds and inoculants encouraged them to adopt both 'Magoye' and specifically nodulating cultivars. Farmers were keen to plant the latter for their high yields and income generation, and 'Magoye' for its non-requirement for inoculants as well as its large biomass used as fodder and for soil fertility maintenance and improvement. Overall, the trial discoveries have led to very few opportunities for enhancing grain legume (e.g., soybean) production among smallholder farmers in Africa due to limited farm-level availability and adoption of inoculants (Bala, 2008). There is, therefore, relatively little evidence (across SSA) to show any substantial inoculation practice among smallholder farmers.

Key lessons learned on the drivers of success at farmers' field level indicate that these include: (i) widespread demonstration of the inoculants with particular attention to the needs of small farmers; (ii) within-country collaboration and involvement of media agencies; (iii) well-coordinated collaborative research-for-development efforts; (iv) involvement of top government officers and decision-makers; (v) joint efforts of a number of national, international and private-sector organizations over many years; (vi) involvement of the private sector in production and dissemination of the inoculants, and (vii) farmer education on inoculation. These strategies have worked well in pilot areas and should be scaled up and out to reach more smallholder farmers that produce the bulk of the food (especially grain legumes) eaten in SSA. This scaling could be attained through an appropriate innovation platform involving all stakeholders. Appropriate incentives are also needed to support the private sector and industries for an effective role and delivery in the scaling up of the inoculant technology.

6. LIMITATIONS TO THE USE OF INOCULANTS TO INCREASE YIELDS

There have been several failures in the effort to use inoculants to increase the yields of grain legumes in different parts of the world, especially SSA. Adoption and use of bio-fertilizers is very limited among small farmers in many African countries such as Kenya (Odame, 1997). This author also noted that many of the modern biotechnology products (Bt. Maize, transgenic sweet potato, genetically-engineered livestock vaccines, etc.) have yet to be used by farmers. Private technology markets are undeveloped in many SSA countries (Brenner, 1996). Therefore, specific measures, such as tax incentives and exemptions, will be needed to stimulate the development of BNF technology markets and the creation of local firms (Brenner, 1996). Kueneman et al. (1984) described inoculation of soybean with specific strains of *Bradyrhizobium japonicum* as an investment that most farmers cannot afford. With very few exceptions, countries in SSA do not have industries to produce viable inoculants at prices that smallholder farmers can afford (Kueneman et al., 1984). In West Africa, other than experiments that are limited to research farms, there is hardly any country where rhizobial inoculation is commonly undertaken by farmers. The Dakar (Senegal) MIRCEN, which has a mandate for inoculant production, does not appear to be actively involved in either inoculation trials or the production of inoculants. The most visible BNF endeavors appear to come from East and Southern Africa. In Zimbabwe,

Table IV. Nitrogen fixation by class of soybean breeding lines in three sites with poor N in the Guinea savanna of Nigeria.

Class of breeding line	Lower end N fixed (kg/ha)	Upper end N fixed (kg/ha)	Mean N fixed (kg/ha) across sites	Lower end breeding & site	Upper end breeding & site
Low N-fixers	21	45	32.3	1838-5E (Zaria)	1838-5E (Gidanwaya)
Intermediate N-fixers	33	60	43.3	1833-20E (Zaria)	1833-20E (Gidanwaya)
High N-fixers	44	75	59.6	1799-8F (Gidanwaya)	1798-7F (Mokwa)

Source: derived from Sanginga et al., 2000.

the cultivation of specifically nodulating soybean with inoculants was promoted among smallholder farmers in the 1980s. However, when the project ended, soybean cultivation failed to make any appreciable increase, largely because of farmers' difficulty in accessing seed and inoculants (Mpepereki et al., 2000). In Kenya, in line with the obvious potential of *Biofix* to replace the often unavailable and expensive mineral fertilizers, together with the Agricultural Society of Kenya (ASK), the Nairobi (Kenya) MIRCEN sells inoculants to farmers. Between 1992 and 1993, average sales were estimated at 1350 kg per year (Mugabe, 1994). However, cutbacks in government expenditure as a part of the structural adjustment policies resulted in a 40% reduction in financial support to extension programs, affecting their agricultural programs (Mugabe, 1994). This demonstrates the unsustainable dependence on government as a major consumer of the inoculants and the need to commercialize inoculant marketing and consumption. There is also the lack of specific policy incentives to stimulate the involvement of the private sector at all stages of the innovation process to induce adoption (Brenner, 1996).

Experiences from Zambia show that the technical feasibility of *Rhizobium* inoculants for common beans remains doubtful (Sakala, 1990; Mvula et al., 1996). Elsewhere, it has been noted that, except for soybean, responses to inoculation are sporadic (Silver, 1976), mainly due to the presence of an adequate and aggressive native rhizobial population (Woomer et al., 1997), ineffective strains (Parker, 1977) or competition from indigenous rhizobial flora (Silver, 1976; Miller and May, 1991; Woomer et al., 1997). In Malawi, inoculant use has not been widely adopted by smallholder farmers, largely because they are mostly not well informed of the technology. Another problem is the fact that inoculants require refrigeration, an investment that is obviously beyond an average smallholder farmer (Khonje, 1989).

6.1. Lessons from the reasons for failure in the use of inoculants to increase yields

Some key lessons have been learned on the causes of failures in the use of inoculants to increase the yield of grain legumes. These include: (i) a disconnect between farmers' problems and biotechnological emphasis, (ii) the path from research to development and to dissemination of a biotechnology product is fraught with uncertainty (Brenner, 1996), (iii) policy and institutional arrangements are critical for widespread dissemination and adoption of *Rhizobium* inoculants, (iv) increase in the involvement of other local actors (e.g., private entrepreneurs, NGOs, etc.) may be more sustainable interventions for BNF distribution than total reliance on government agencies (Odame, 1997), (v) the problems of Biofix were caused by a variety of technical factors that include: complexity of tropical soils, selectivity of *Rhizobium* strains in infecting specific legume species, residual effects of inoculation, and the need for phosphate fertilizers to stimulate nodulation and nitrogen fixation. The other lessons are: (vi) farmers' concerns on the efficacy of *Rhizobium* inoculants (e.g., Biofix) in increasing crop yields as well as their operational feasibility, (vii) inadequate participatory and interactive approach among key stakeholders (including farmers) in the development of *Rhizobium* inoculation technology, (viii) production and marketing of inoculants (e.g., Biofix) was centralized, affecting effective distribution, (ix) weak linkages with private-sector manufacturers, local stockists, NGOs and farmers, and (x) inadequate capacity building and technical assistance for African Universities in *Rhizobium* inoculation technology development.

7. CONSTRAINTS AND CHALLENGES TO PRODUCTION AND FARMERS' USE OF INOCULANTS IN SSA

This section reviews the social, economic, cultural and policy constraints and challenges to the production and farmers' use of *Rhizobium* inoculants in SSA. These, including their effects and possible recommendations, are summarized in Table V. Due to limited capacity many national agricultural research systems in SSA lack the skills to set priorities in the application of biotechnology. This situation hampers the development of BNF technologies. Current research and development programs in Africa are often isolated, with little coordination, coupled with inadequate funding. Most of the time, these organizations are not need-driven and lack the ability to develop specific products. Besides, there is weak protection of intellectual property rights in many parts of Africa, hampering innovations, inventions, investments, and development of new technologies including biotechnologies.

Table V. Socioeconomic and policy constraints to the use of *Rhizobium* inoculation technology in sub-Saharan Africa and possible intervention measures.

Socioeconomic and policy constraint	Effect	Reference	Recommendations
Limited farmer awareness of and access to inoculants	Low adoption and use of inoculants in farming systems	Odame, 1997; Woomer et al., 1997; Kipkoech et al., 2007	Private sector involvement
Poor quality control of inoculants	Low viability of *Rhizobium* inoculants and uncertain performance	Johnson et al., 1994; Odame, 1997	Cold storage, use of modern technologies, and more research
Lack of trained personnel	Limited awareness by farmers of the existence of BNF (including inoculants)	Kannaiyan, 1993; Odame, 1997; Woomer et al., 1997	Raise farmer awareness about legume root nodules; familiarize farmers with *Rhizobium* inoculants
Fear over possible human and livestock health risks of inoculants by farmers	Limited adoption and use of *Rhizobium* inoculants to increase legume productivity	Odame, 1997	Involvement of farmers in the process of development of inoculants; participatory approach
Absence of policy or weak policy support and insufficient biotechnological framework	Forestalls widespread adoption; weak development of the production and marketing of inoculants	Mugabe, 1994; Odame, 1997; Silver and Nkwiine, 2007	Include the issue of bio-fertilizers in governments' effort towards addressing the problems of low and declining soil fertility
Limited scientific expertise, applied BNF brain drain, and poor research funding	Limited production of inoculants and low quality inoculants	Brenner, 1996; Ndakidemi et al., 2006	Linkages between Universities in SSA with those in the North with expertise in *Rhizobium* science; government policy support

7.1. Socioeconomic constraints and challenges

A successful transfer of *Rhizobium* inoculation technology from the laboratory to farmers' field depends on some crucial interactions among many players (research, policy, etc.). Farmers' access to inoculants remains the most controversial phase in the evolution of *Rhizobium* inoculation technology (Woomer et al., 1997) and explains why despite its acclaimed attributes the use of inoculants among smallholder farmers has been limited, making it a technology with a low rate of adoption.

Most farmers in SSA are not aware of inoculants or that legumes fix N in their nodules, yet traditional and modern farming systems almost invariably include grain legumes. Contrary to the thinking of Kueneman et al. (1984), the cost of inoculants is probably not usually a constraint to farmers who normally set aside some funds for seeds that are clearly more costly than *Rhizobium* inoculants. However, for farmers that use non-commercial seeds, there may be little incentive to purchase inoculants. Poshiwa et al. (2006) found that inoculant awareness in Zimbabwe was extremely low (2%). In central Kenya, among farmers who cultivated grain legumes, less than 15% used inoculants (Woomer et al., 1999). Although Poshiwa et al. (2006) and Woomer et al. (1999) collected data on social characteristics (e.g., age, gender, education) of the heads of the households surveyed, none of them linked these characteristics with the adoption of BNF, critical information required to explain better the low use being widely observed. The BNF adoption parameters examined by Woomer et al. (1999) includes: legume cultivation, nodule awareness, inoculation benefit awareness and inoculant use. There is the need to expand the knowledge base on BNF utilization among farmers in SSA beyond binary measures (e.g., awareness or use) to include more qualitative aspects of farmers' knowledge, willingness to pay and the long-term relevance of inoculants in farm objectives. Generally, it is necessary to understand the structure and function of knowledge held by farmers, especially the adopters of inoculants, so as to bridge the gaps between farmers' and scientific knowledge.

Brain drain, lack of trained personnel and inadequate resources have also been noted to be a major concern (Odame, 1997), just like the lack of capacity by scientists to understand the full potential for BNF application in local agroecosystems. The capacity building efforts on BNF have also been challenged by the mass exodus of plant biologists from applied BNF to other fields (Bohlool et al., 1992). It is clear that lack of complete understanding of legume BNF interactions under diverse farming systems contributes to the low understanding among experts in particular settings. Besides, a vast majority of smallholder farmers in SSA are not aware of the existence of BNF (including inoculants) due to lack of resources to create awareness in BNF and improve its distribution (Odame, 1997). This explains why researchers at the Nairobi MIRCEN project attributed the limited use of Biofix to "technological ignorance of smallholders", poor communication, and limited understanding of *Rhizobium* and plant biology (Kannaiyan, 1993; Woomer et al., 1997). They emphasized the need to raise farmer awareness about legume root nodules (in which *Rhizobium* bacteria live) as part of the familiarization with *Rhizobium* inoculants (Woomer et al., 1997).

There are problems related to inoculant packaging size, influencing uptake potential by farmers. The minimum quantity of inoculants that a farmer has to buy is a key issue. A 100-g packet of inoculants (e.g., Biofix) is needed for 15–16 kg of common bean seed (for instance), sufficient for planting one acre of land. However, few smallholders can plant such a relatively large area with common bean. On average, farmers require only 25 g of Biofix – sufficient for 2–3 kg of common bean seed, to be planted on 0.25 acres of land, which is the approximate farm size usually allocated to legumes in SSA. Thus, if the packet size is not reduced, each packet needs to be opened and shared among several farmers, raising the issue of high administrative and other costs. Lastly, there were fears over possible health risks to young children and domestic animals. Participants at a focus group discussion described Biofix as 'poison', the leftover of which they were unsure of what to do with (Odame, 1997).

7.2. Quality constraints and challenges

The uncertain performance of *Rhizobium* inoculants may explain the limited farmer adoption despite their potential to reduce the mineral fertilizer requirement, and reduce cost of production, and the fact they are lighter to transport and are more environmentally friendly than mineral N fertilizers (Odame, 1997; Kipkoech et al., 2007). Poor quality control in inoculant production processes as well as transportation and storage problems negatively affect the viability of inoculants (Odame, 1997). Based on a report for the World Bank, difficulty in obtaining and keeping inoculants was one of the factors that constrained soybean production in Zimbabwe (Johnson et al., 1994). Cold storage which might improve its viability is beyond the reach of smallholder farmers. Another constraint has to do with the limited production of inoculants due partly to limited scientific expertise, inadequately funded agricultural research and extension, and poor infrastructure (Ndakidemi et al., 2006). Limited investment of public funds in R&D and the diffusion of new technology through the national extension systems add to this problem (Brenner, 1996).

7.3. Policy constraints and challenges

Rhizobium inoculation has the potential to offer more environmentally friendly agricultural production than the mineral fertilizer-intensive model (Brenner, 1996). However, this will only be realized if certain conditions that involve difficult policy choices and trade-offs are met (Brenner, 1996). From a policy point of view, the constraints and challenges range from a complete absence of to very weak policy support for BNF technologies. Research into the basic mechanisms of BNF processes is an important goal for improving N_2-fixation. Much knowledge on BNF has been gathered with several successes documented, especially in developed countries. However, bio-technology research in SSA has generally been science-driven, ad hoc (and non-holistic), and not integrated into the wider agricultural and overall development objectives (Brenner, 1996). It is concentrated in universities which have little tradition of interaction with farmers and the private sector. The focus of scientists has been on the supply side of biotechnology (Brenner, 1996). Even in that area, there are still issues widely unattended to, including bio-safety and intellectual property rights.

Lack of policy and political support at the national level has been blamed for forestalling widespread adoption of *Rhizobium* inoculation and other suitable forms of biotechnology (e.g., germplasm) in SSA (Odame, 1997; Silver and Nkwiine, 2007). Efforts of many governments to address soil fertility problems in SSA have mostly been directed to mineral fertilizer subsidies (Jayne and Boughton, 2006). The limited commitment to non-fertilizer soil fertility management options has contributed to the weak development of the production and marketing of inoculants in SSA. For instance, *Nitrosua*, developed by SUA, could not be effectively disseminated to local farmers in Tanzania due to poor government budgets for agricultural extension (Mugabe, 1994).

In many SSA countries, bio-fertilizers are not fully addressed in national fertilizer recommendations (Odame, 1997). Only a few SSA countries (e.g., Zimbabwe) have set up national biotechnology institutions and implemented bio-safety procedures (Brenner, 1996). Besides, the question of IPRs (Intellectual Property Rights) related to biotechnology is still unresolved in most countries (Brenner, 1996).

The current research agenda on BNF has evolved due mostly to individual efforts with limited government policy support (Mugabe, 1994). African governments must reconsider their policy on agricultural biotechnology research so as to provide a strong institutional basis for BNF (Mugabe, 1994). In the same vein, although genetically modified plants could result in increased productivity, serious concerns (e.g., health and environmental safety, etc.) have been raised over their R&D policy process in SSA (Odame, 1997). To efficiently develop, produce and disseminate new technologies, an elaborate value chain [to enhance scaling up and involving key stakeholders (researchers, farmers, extension agents, agro-input dealers, etc.)] adequately backed up with relevant policies is required. There is limited linkage among inoculant stakeholders presently. Although such linkages are poor in most other agricultural technologies in SSA, the inoculants' value chain is probably among the most poorly developed value chains, limiting its trade and dissemination.

7.4. Other constraints and challenges

These do not strictly fall into either socioeconomic, quality or policy categories. The most important has to do with decision-making about the level of biotechnology required in different SSA countries. These challenges fall into: (i) development of the knowledge base for appropriate decision-making on use of biotechnology approaches, (ii) lack of sufficient studies that have clearly analyzed biotechnology-related data to assist policy-makers on *Rhizobium*-related policies, (iii) lack of priority setting for biotechnology aimed at solving problems of national importance, (iv) capacity development, and (v) the establishment of linkage and cooperative mechanisms for biotechnology development, transfer, and sustainable applications. The emphasis given to *Rhizobium* in bio-fertilizer research shows its high specificity to only legumes (common bean 47%; lucerne 23%; soybean 14%; desmodium (a leguminous pasture species) 9%; and other minor legumes 7%; in that order) unlike mycorrhiza, that works in 80% of all plants (Odame, 1997). A wider use of *Rhizobium* inoculants in marginal areas depends on the ability to develop strains which are tolerant to high temperatures, soil acidity, drought and salinity (Odame, 1997).

8. OPPORTUNITIES FOR PRODUCTION AND USE OF INOCULANTS IN AFRICA

Given that widespread decline in soil fertility and agricultural productivity has largely been blamed for widespread poverty in Africa and that biotechnology has great potential to lead to increases in agricultural production, as has been demonstrated in some of the instances in this review article, we see a great opportunity for increases in the production and use of *Rhizobium* inoculants in the farming systems of SSA. The recent (2008) increases in the price of mineral fertilizers (even over and above the oil prices), driven by growing demand for mineral fertilizers resulting from commercial responses to increasing food prices (IFDC, 2008; Nehring et al., 2008) have also reinforced the need to develop alternative soil fertility management strategies. The price of nitrogen-based fertilizers rose from US$277 per ton in January 2007 to over US$450 per ton in August 2008 (IFDC, 2008). The dramatic increase and soaring prices of food reveal the large potential for developing and disseminating BNF and inoculation technologies to poor farmers who cannot afford the high fertilizer prices. The increasing concern about environmental pollution also presents an opportunity for increasing efforts to develop and promote BNF and inoculation. It is estimated that only 30–40% of fertilizer applied worldwide is used by plants. The remainder is lost, especially through leaching and volatilization, etc. (Hardarson et al., 2003).

However, these opportunities can be exploited if SSA countries develop long-term policies on BNF and biotechnology in general. Such policies should: (i) promote national biotechnology need assessment and implementation, (ii) target biotechnology research and execution to needs, (iii) provide incentives and environment for commercialization of biotechnology research and enterprises, (iv) promote partnerships among local public R&D and foreign industries in biotechnology, (v) improve scientific capacities and technological infrastructure for optimal biotechnology execution, and (vi) integrate biotechnology risk management into existing environmental, health and agricultural regimes. Otherwise, the potential benefits of biotechnology (e.g., *Rhizobium* inoculation) may not be tapped for the improvement of human welfare in SSA. Besides, policy related to biotechnology (e.g., BNF, *Rhizobium* inoculation) should address the need to: (i) strengthen institutions (e.g., agricultural extension, NGOs) that serve the interests of smallholder farmers as they adopt biotechnology, (ii) enhance their capacity, and (iii) improve their participation in adapting and testing BNF and *Rhizobium* inoculation technologies. Instead of ad hoc approaches, SSA countries must opt for an integrated approach for biotechnology, which also requires policy intervention (Brenner, 1996). The integrated approach will ensure that biotechnology research is at the service of problems confronting smallholder agriculture.

9. HIGHLIGHTS AND KEY MESSAGES

Given the unsettled state of knowledge on the response of different varieties of soybean to inoculation and the fragmentary evidence of its economic benefits at the farm level, there is the need to initiate further studies on inoculation response of promiscuous soybean varieties as well as the commercial or specifically nodulating soybean varieties. Holistic studies addressing the challenges facing the use of inoculants by farmers have been rare in SSA. For instance, unlike experimental data, only a few studies have examined the socioeconomic and policy constraints affecting household adoption and utilization of inoculants by farmers. Trials for establishing the need for inoculation should include tests for the limitation of BNF by other nutrients (e,g., boron, calcium, etc.).

Secondly, there is also a pressing need for more in-depth analysis of short- and long-term economic and social costs and benefits of *Rhizobium* inoculation and the need to expand the knowledge base on BNF utilization among farmers in SSA beyond binary measures (e.g., awareness or use) to include more qualitative aspects of farmers' knowledge, willingness to pay and the long-term relevance of inoculants in farm objectives.

Thirdly, policies and institutions promoting the development of soybean inoculants and widespread farmer adoption for increased production of both promiscuous and commercial soybean varieties are needed. This must be accompanied by targeted research to effectively address the specific needs of specific soybean growing areas in SSA. This is because, despite its potential to address low N and its "assumed" cost effectiveness and importance in ensuring sustainable and low cost production by smallholder farmers in SSA, the demand for inoculants remains low for reasons that include poor quality, and inadequate and inefficient marketing channels and outlets, as well as inadequate extension services covering inoculant use. In virtually all situations, there was economic benefit of inoculation, both for the legume itself and for subsequent crops. The lesson learned with the successes of *Rhizobium* inoculation based on on-station experiments or experiments simulating farmers' conditions is that it does not really guarantee widespread uptake by the smallholder farmers, no matter how attractive the results are. Like *Rhizobium* inoculants, many of the modern biotechnology products (Bt. Maize, transgenic sweet potato, genetically-engineered livestock vaccines, etc.) have yet to be used by SSA farmers, especially given that private technology markets are still highly undeveloped in many SSA countries. Specific measures, such as tax incentives and exemptions, will be needed to stimulate the development of BNF technology markets and the creation of local firms. There is the need for specific policy incentives to stimulate the involvement of the private sector at all stages of the innovation process to induce adoption. The trial discoveries have led to very few opportunities for enhancing grain legumes (e.g., soybean) production among smallholder farmers in Africa due to limited farm-level availability and adoption of inoculants (Bala, 2008). There is, therefore, relatively little evidence (across SSA) to show any substantial inoculation practice among smallholder farmers. There is the need for SSA countries to develop long-term policies on BNF and biotechnology in general.

Fourthly, the review article indicates that *Rhizobium* inoculation is needed in all agricultural lands deficient in N and where N supply is a key limiting factor in crop production, especially since it is not clear whether promiscuous soybean cultivars are effectively nodulated by indigenous rhizobial populations in all soils and under all conditions (e.g., soil fertility and rainfall status). Although smallholder farmers in selected countries in SSA (e.g., Nigeria, Zimbabwe, Zambia, etc.) have widely adopted promiscuous soybean varieties (e.g., TGx 1448-2E, Magoye, etc.), inoculating soybean with effective rhizobia is still a key strategic research intervention that has the potential to significantly contribute to noticeable improvements in the productivity of soybean in SSA. However, some exceptionally promiscuous soybean varieties (e.g., Magoye) nodulate readily in most soils and rarely respond to inoculation. Results also confirmed the importance of promoting inoculant use in African agriculture, especially among resource-poor farmers who cannot afford expensive mineral fertilizers (e.g., DAP, NPK, etc.).

Fifthly, experiences from some SSA countries (e.g., Zambia) show that the technical feasibility of *Rhizobium* inoculants for some grain legumes (e.g., common beans) remains doubtful. It has also been noted that, except for soybean, responses to inoculation are sporadic, mainly due to the presence of adequate and aggressive native rhizobial population, ineffective strains or competition from indigenous rhizobial flora. Finally, there is the need to involve other local actors (e.g., NGOs, agro-input dealers, etc.) to ensure more sustainable interventions for BNF distribution than total reliance on government agencies. There is also widespread lack of skills to set priorities in the application of biotechnology in SSA, hampering the development of BNF technologies and often leading only to isolated cases with little coordination and inadequate funding. The increasing concern about environmental pollution also presents an opportunity for increasing efforts to develop and promote BNF and inoculation.

10. CONCLUSION

Several conclusions could be drawn from the outcomes of this review article. Firstly, while in principle, privatization of public sector institutions and activities is being encouraged, biotechnology R&D in SSA is presently focused on improving agriculture with over 85–90% of the biotechnology R&D in the region still within the public sector. Little or no incentives have been provided to encourage private sector interest in the development and application of biotechnology products. Except for South Africa, development, production and dissemination of biotechnology are limited to public institutions. Secondly, most issues around *Rhizobium* inoculation in parts of SSA still revolve around research with little or no effort to disseminate the results and products. Virtually no attention has been given to the demand side and to the ways in which biotechnology could best contribute to solving farmers' production problems. Most research activities and information generated started and ended with scientists who are yet to finalize even on issues of quality control. There were unsustainable interventions in the *Rhizobium* inoculant distribution, due to too much reliance on government agencies and little or no serious involvement of local actors (e.g., private entrepreneurs, non-governmental organizations, farmers' co-operatives, local stockists, trade associations, etc.). A coordinated program is needed to develop a capacity to produce and supply sufficient quantities of high quality inoculants to farmers and to educate extension workers and farmers about the benefits of inoculation. Thirdly, although bio-fertilizers could potentially benefit smallholder farming systems in SSA, policy support necessary to create a suitable environment for the active participation of non-government agency players is critical to ensure widespread production, distribution and application of bio-fertilizers. Unfortunately, such policies are nearly absent in most SSA countries. Fourthly, bio-fertilizer research in SSA has been science-driven, *ad hoc*, uncoordinated and unintegrated. Attention has essentially been focused on the supply side (e.g., training of scientists in molecular biology, biochemistry, microbiology, etc.). Little effort has been made to set clear priorities and to integrate research efforts with the broader objectives set for agricultural research. There is little interaction among the multiple actors and institutions (e.g., biotechnologists and plant breeders; the public and private sectors; scientists and farmers; and among the scientific community and policy-makers) most closely involved with biotechnology R&D and diffusion. Indeed, public research institutions at times tend to compete (rather than collaborate) for scarce resources. More importantly, there is little interaction and/or collaboration between the public and private sectors. Fifthly, efforts to develop rhizobial inoculants also need to be accompanied by research that facilitates their efficient use that is relevant to resource-poor farmers. Breeding programs can also help to develop crop varieties that nodulate under abiotic stresses. Finally, there is a strong need to train policy-makers and scientists to increase their awareness of the need to reshape biotechnology towards the needs of smallholders, and for farmer participation in prioritizing areas to be addressed by biotechnology research and policy.

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