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A participatory assessment of nitrified urine fertilizer use in Swayimane, South Africa: Crop production potential, farmer attitudes and smallholder challenges

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Long-term nutrient mining of soil hampers agricultural production across Africa. However, emerging sanitation technologies afford a hygienically safe and ecologically sustainable solution to this development challenge by providing fertilizers derived from human excreta that could facilitate a socio-technical transition toward a more sustainable food system. To evaluate one such technology, nitrified urine fertilizer (NUF), we conducted participatory action research to assess the potential, from both a biophysical and social perspective, of NUF to serve as a soil fertilizer to support smallholder agricultural production in Swayimane, South Africa. To achieve this objective, we formed a stakeholder group comprised of a cooperative of smallholder farmers, a local NGO (Zimele), and researchers from ETH Zurich and the University of Kwazulu-Natal. Over the course of two growing seasons (2016 and 2017) this stakeholder group assessed the potential of NUF to support smallholder vegetable production (i.e., cabbage). First, we adopted a randomized complete block design incorporating five treatments in season 1 (unfertilized control, nitrified urine, nitrified urine+bone meal, urea, and urea+diammonium phosphate (DAP) and six treatments (unfertilized control, urea, urea+DAP, DAP, nitrified urine, and nitrified urine+DAP) in season 2 to assess cabbage yield and leaf nutrient concentration (sodium, phosphorus, potassium, carbon, nitrogen). Although we observed large variability in yields, the urine-based treatments were as effective as any of the chemical fertilizers. Second, beyond the biophysical analysis, we elicited the challenges and opportunities of the smallholder farmers in our stakeholder group, as well as their attitudes toward the use of NUF as a fertilizer. Through this qualitative work, farmers indicated that their attitudes about the use of NUF as a fertilizer improved and that they would be willing to incorporate this product into their production practices if it was available at scale. Thus, we demonstrate the potential of participatory action research to co-produce knowledge and awareness around an innovative technology. In so doing, we provide evidence that this approach can support a change toward nutrient recycling-based agriculture.

KEYWORDS

nitrified urine fertilizer, sustainable agriculture, South Africa, smallholder farming, nutrient recycling

Introduction

Smallholder agricultural production serves as an important livelihood strategy for farmers across Sub-Saharan Africa (SSA) (Baipethi and Jacobs, 2009). However, continued nutrient mining of soils challenges the sustainability of these agroecosystems (Sanchez, 2002). Sub-Saharan African smallholder farmers, constrained by a lack of financial capital, are unable to fertilize their crops at the rates necessary to replenish soil nutrient levels. A common policy reaction to this development challenge is to subsidize the cost of chemical fertilizers. The current iteration of Input Subsidy Programs began in the mid-2000's and currently comprise roughly US$1 billion in investment annually across ten African countries (Jayne and Rashid, 2013). Despite short-term improvements in smallholder productivity, there is growing evidence that the long-term benefits of these programs are questionable (Carter et al., 2014; Jayne et al., 2018). Furthermore, continued investment in these programs is uncertain. For example, citing funding constraints and program inefficiencies, the National Agricultural Input Voucher Scheme (NAIVS) of Tanzania was significantly reduced in 2017 (Cameron et al., 2017). Given the limited success of Input Subsidy Programs and their high opportunity costs, alternative sources of soil nutrients must be found. In this study, we thus address how an alternative soil nutrient system could be implemented in Sub-Saharan Africa. We explore this on the basis of alternative technology—-nutrient recycling from human waste- in a farmer cooperative in South Africa.

Nutrient recycling from human waste is typically neglected as a potential solution to the soil fertility crisis. Despite this, urine as well as human feces have long been used by some societies as a soil amendment, and for good reason (Tajima, 2007). Human urine contains the macronutrients nitrogen (N), phosphorus (P), and potassium (K), as well as various micronutrients, all of which are critical for plant growth; of these N, particularly, is excreted in significant quantities (2.5–4.3 kg N person^{-1} year^{-1}) (Kirchmann and Pettersson, 1995). Numerous studies have confirmed that urine is an effective source of plant available nutrients and could serve to stabilize soil fertility (Mnkeni et al., 2008; Cofie et al., 2010; Semalulu et al., 2011; Idiok et al., 2012). Moreover, developments in alternative sanitation technology can reduce or eliminate health risks associated with the use of human waste as fertilizer. To support the practice, development agencies such as the Stockholm Environment Institute published guidelines on the use of urine as fertilizer (Richert et al., 2010). Despite these efforts, most governments and international development organizations have not adopted the idea of using recycled human waste to support agricultural production in Africa.

Given this problem framing, we set forward to study how nutrient recycling from human waste could gain traction as a solution to the issue of nutrient mining in African agriculture. We pose the following questions: what is the biophysical effectiveness of nutrient recycling from human waste? What are the challenges and opportunities facing smallholder producers in utilizing recycled human waste? What are the farmer attitudes toward this novel fertilizer? On the biophysical side, we focus on urine nitrification technology, which the Swiss Federal Institute of Aquatic Science and Technology (eawag) has optimized over the course of the last decade (Etter et al., 2015; Udert et al., 2015). This technology converts ammonia (NH_3), a volatile compound that can reduce the amount of available nitrogen (N) in the solution, into ammonium nitrate (NH_4NO_3), which is solution stable and contains numerous elements necessary for plant growth in addition to N (Table 1). A second step then reduces the amount of water and thus increases the nutrient concentration in the solution. In addition to reducing the volume, this process of distillation also pasteurizes the solution, ensuring complete inactivation of pathogens. A final step, filtering the urine solution with an activated carbon filter, reduces pharmaceuticals present in the urine. Once complete, the solution is a nutrient stable and hygienically safe product known as nitrified urine fertilizer (NUF). Although initial greenhouse trials have shown the effectiveness of nitrified urine (Bonvin et al., 2015), little is known about its field performance and on-farm effects. To the best of our knowledge, this article presents the first community-based, agroecological assessment of the NUF technology.

While agroecology as a discipline initially focused on the biophysical aspects of food production, experience has shown that for research to effect change in these systems, a broader focus that encompasses the sociocultural aspects of agriculture, and which is action oriented, is important (Altieri, 1989). Since the 1970's, there has been a trend toward integrating

TABLE 1 Chemical properties of the nitrified urine fertilizer (NUF).

Property	Concentration
Ammonium	19.7 g N l^{-1}
Chloride	45.5 g Cl l^{-1}
Electrical conductivity	26,760 mS m^{-1}
Nitrate	18.3 g N l^{-1}
Nitrite	0.2 mg N l^{-1}
pH	3.7
Phosphate	2.6 g P l-1
Potassium	9.7 g K l^{-1}
Sodium	25.4 g Na l^{-1}

Chemical analyses of the NUF was conducted by the certified laboratory Talbot and Talbot, Pietermaritzburg, South Africa.

the perspective of local stakeholders through participation to increase the uptake of international development project results (Hirsch Hadorn et al., 2006; Brutschin and Wiesmann, 2008). For example, participatory action research (PAR) evolved as a response to the recognition that traditional, often extractive approaches to research for development efforts were largely ineffective (Chambers, 1994; Wadsworth, 1998). Through this evolution, we can now distinguish between two distinct "agroecologies."

The first continues to focus on the biophysical processes that impact agroecosystems and is "firmly grounded in the Western tradition and the natural sciences;" a second distinct branch of agroecology seeks "to integrate transdisciplinary, participatory, and action-oriented approaches, as well as to critically engage with political-economic issues that affect agro-food systems" (Mendez et al., 2013, p, 6). This approach makes explicit that although enhancing biophysical knowledge is critical, it is only one component of a complex socio-ecological system. This understanding of agroecology views community stakeholders as actors with the desire and knowledge necessary to participate across the entirety of a development or research endeavor. In so doing, it shifts the perception of community participants as passive recipients of research to active participants with agency and power. PAR encourages researchers and extension officers to act as facilitators in an equal partnership with local stakeholders (Chambers, 1994). It is recognized for its ability to jointly develop, test, and analyze agricultural innovations and has been shown to increase the relevance and adoption of emerging technologies (Chambers et al., 1989; Ashby and Sperling, 1995; Kangmennaang et al., 2017; Kerr et al., 2019).

Key to this evolution was the realization that positivist forms of knowledge production empowered the researcher to the detriment of other stakeholders and the project outcome (Kindon et al., 2010). Instead, PAR aims to conduct research through community participation and action to produce "engaged, human inquiry that orients the researcher toward action-centered practice, focusing on reflection and collaboration with participants to bring about 'meaningful change'..." (Guy et al., 2019, p. 1). It seeks to bring together a diverse set of actors to generate locally appropriate solutions to a concrete societal challenge (Greenwood and Levin, 2007). Over the course of the last several decades, PAR, as a guiding framework, has become common in a variety of research fields such as public health, education, community development, and planning (Chevalier and Buckles, 2019). In the context of exploring the potential of a transition toward agricultural production predicated on human excreta derived fertilizers, this approach is a must. Given the sensitive nature of the topic it is critical to understand what the farmers' perspectives and attitude are regarding this product, particularly given that previous research has found attitudes in SSA toward nutrient recycling of humane excreta to be mixed at best (Mariwah and Drangert, 2011; Okem et al., 2013).

Drawing on this tradition to assess the impact of agricultural research projects, we utilized PAR to generate joint understanding of the biophysical effectiveness of NUF, the challenges and opportunities facing smallholder producers in the case study of South African Swayimane, and farmer attitudes toward this novel fertilizer. As such, we explored avenues available for solutions-oriented research to support the adoption of emerging technologies with a demonstrated capacity to produce local, environmentally sustainable, and hygienically safe plant nutrients.

Materials and methods

Project background and framework

Our research design utilized a PAR approach, conducted collaboratively among researchers from the University of KwaZulu-Natal (UKZN) and ETH Zurich, Zimele (a local NGO focused on increasing community self-reliance and the empowerment of women) and a farmers' cooperative located in Swayimane, Kwazulu-Natal, South Africa (Figure 1). Swayimane was an ideal study site due to the proximity of a treatment facility capable of producing NUF, and because of the presence of the local NGO Zimele and the agricultural cooperatives operating in the community. The latter was important for the social aspect of PAR, as the agricultural cooperatives were a key partner for engaging local stakeholders.

The research began with an initial planning workshop conducted in May 2016 by UKZN, ETH Zurich, and Zimele. The purpose was to bring the various stakeholder groups together to create a shared understanding of the project scope and objectives. Out of this dialogue, consensus between all the stakeholder groups was reached regarding the project design, length (two seasons), objectives, and scope. Each of the 15 participating farmers was informed that the findings

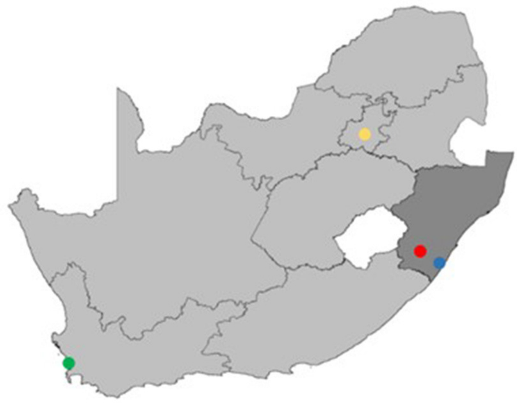

FIGURE 1
Location of Swayimane (red circle), Durban (blue circle), Johannesburg (yellow circle), Cape Town (green circle) in South Africa. The dark gray boundary indicates the province of Kwazulu-Natal.

would be made publicly available, that responses would not be attributed to individual farmers, and that every participant could cease to participate at any time during the study. All participating farmers signed an informed consent form, translated into isiZulu, after discussing the details of the study with representatives from Zimele. To address the biophysical and practical implications of using NUF at a field scale, the study adopted a participatory approach to facilitate understanding of novel intercropping systems (Snapp et al., 2019); this "mother-baby" approach centers on a fully replicated biophysical field trial or "mother site," which allows the full stakeholder group to assess a given innovation. Additionally, farmers tested various fertilizers in their home gardens, the "baby trials." In this case, the mother site was selected by the participating farmers and was located on a property adjacent to the cooperative leader's house.

Biophysical research component

For the first season of the study a randomized complete block design that incorporated three replicates of five different treatments (urea, urea+diammonium phosphate (DAP), nitrified urine, nitrified urine+bone meal, unfertilized control) was jointly developed and established at the "mother site." Due to their prevalence as widely available sources of N and P, urea and DAP were chosen as the chemical fertilizers for the trial. All the treatments were fertilized with 90 kg N ha^{-1} and 20 kg P ha^{-1} applied once immediately prior to planting. During the second season, the treatments were altered due to the difficulty in obtaining bone meal, which because of its cost is not commonly used in the area. Thus, the second season incorporated six treatments: urea, urea+DAP, DAP, NUF, NUF+DAP, unfertilized control. As in the first season, 90 kg N ha^{-1} and 20 kg P ha^{-1} were applied in the second season. To accommodate the agricultural activities that were planned by the cooperative over the course of the study, the experimental plots were moved to an adjacent field with the same biophysical conditions from season 1 to season 2.

The crop chosen by the farmers for both seasons of the experiment was cabbage (*Brassica oleracea*). Immediately prior to planting every plot was tilled by hoe and fertilized. A plot size of 9 m^2, row spacing of 75 cm and in-row spacing of 50 cm were adopted at the recommendation of the farmers. Seedlings were obtained from a local agricultural store and transplanted 5 weeks after sowing. The cabbage was harvested when the farmers indicated they felt the crop was mature, this was around 70 days after transplanting for both seasons. A collaborative management strategy was developed with the farmers, development workers, and researchers to distribute necessary tasks such as weeding, watering, and harvesting. Soil type at the mother site was identified as Dystric Leptosol with baseline properties listed in Table 2.

To assess the biophysical impacts of NUF, soil sampling was conducted at the beginning of the trial to obtain baseline soil characteristics. To obtain a representative sample from the field, three 20 cm deep cores were taken at random using a 1.58 cm diameter soil auger and composited. The pH was measured with a VWR pHenomonal MU6100L meter after shaking for 1 h in a 1:2.5 ratio of soil to deionized water. Quantification of total C and N of soil (sieved 2 mm, ground, oven-dried at 40°C for 7 days) and plant matter (oven-dried, ground) was conducted with a LECO CHN628 Series Elemental Determinator. The elements (Na, P, K) concentration of the dried plant matter was quantified *via* atomic spectroscopy (Agilent 5100 ICP-OES). Preparation for the plant material (200 mg) involved a two-part digestion, first with 15 ml HNO_3 heated to 120°C for 30 min followed by a second heating cycle with the addition of 3 ml H_2O_2 for 90 min at 120°. Yield was measured as wet mass of cabbage (kg ha^{-1}). To collect these data the cabbage heads were cut by hand from every plot by a team of farmers and researchers when the farmers indicated the harvest should occur. The heads were collected and bagged from every plot and weighed on a scale in the field. These results were then discussed collectively on site with the farmers. Statistical analyses of the results from the mother site were made using a linear mixed effects model analysis of variance. The statistical package R studio 24 was used to perform this mixed procedure, considering treatment as fixed factor and block as a random factor. Pairwise comparisons were conducted based on the Tukey test. Significance was accepted at $p \leq 0.05$.

In addition to the mother trial, non-replicated baby trials were conducted during the first season of the study. All the farmers were invited to grow up to three vegetables, lettuce, cabbage, spinach at their home gardens. They were also asked to select up to three of the fertilizer treatments utilized in the mother trial to support the growth of these vegetables. The

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TABLE 2 Baseline soil properties.

Sand (%)	Silt (%)	Clay (%)	pH	Total C (%)	Total N (%)
$n = 4$	$n = 4$	$n = 4$	$n = 18$	$n = 18$	$n = 18$
50.7 ± 3.2	16.8 ± 2.1	26.4 ± 1.4	5.1 ± 0.11	3.27 ± 0.05	0.19 ± 0.003

Samples taken prior to the start of the experiment. Values based on dry weights (means ± standard errors, n = 3).

selection of the fertilizers was noted, and the farmers were then asked to explain their choice of fertilizers. At the end of each season, it was planned that the farmers would report on the yield results of these baby trials.

Social component

Following a PAR approach, we also analyzed the challenges and opportunities faced by smallholder farmers as well as their attitudes toward the use of NUF in Swayimane. To understand smallholder challenges and opportunities, we conducted a series of five focus group sessions (example questions provided in Supplementary Data) throughout the two-season study to identify the major constraints facing smallholder producers in the area. The number of farmers attending each session ranged from nine to sixteen. According to Neuman (2014, p. 471), a focus group should consist of six to twelve people; hence our focus group sizes are on the upper end of what is recommended. Prior to the focus group work, researchers from ETH Zurich and development workers from Zimele discussed qualitative research methods and agreed upon a mode of operating to do everything possible to reduce biases on the part of the research team. Furthermore, it was agreed that the Zimele respresentatives, due to their ability to communicate fluently in IsiZulu, would lead the discussions. Given the focus of Zimele on women's empowerment, women comprise most of the cooperative. Hence, with only one exception all the participating farmers were female. Recordings of the sessions were translated from isiZulu into English and transcribed for analysis (example of focus group questions provided in Supplementary Data).

To assess farmer attitudes, which we define as "the degree of a person's favorable or unfavorable evaluation or appraisal of a behavior in question" (Ajzen, 1991, p. 188), we disseminated individual questionnaires at the end of both seasons of the study. Responses were given *via* a 5-point Likert scale. The purpose of the questionnaire was to provide individual farmers with an opportunity to respond to critical issues free from any potential group pressure. Finally, to build joint understanding about the production of NUF and further assess the farmers' attitudes, we conducted a field visit to a sanitation processing center in Durban, South Africa at the beginning of season 2. Taken together, these efforts provided the researchers and farmers an opportunity to discuss the challenges inherent to smallholder production in the region, to build understanding about the progress of the trial, and to discuss the use of NUF as an emerging technology.

Results and discussion

Biophysical results

Mother trial yield results

Due to the large variability across the replicates, no significant differences in yield were observed at the mother site during season 1 (S1) (Figure 2). We attribute the observed variability, in part, to the adopted community-based management regime. Weeding and watering was conducted by different management teams, which resulted in some plots receiving more care than others. Despite this, conclusions can still be drawn from the yield results. Although not significantly different from the other treatments, the NUF treated cabbage did produce the highest yield (24 tons ha^{-1}) in season 1. Surprisingly, the yield in the unfertilized control responded quite well, with only an insignificant improvement observed with the incorporation of the other fertilized treatments. In season 2, however, larger differences in performance were noticed. The NUF (25 tons ha^{-1}) and DAP (28 tons ha^{-1}) produced significantly higher yields than the urea or the control. These findings are in line with a previous study on the effect of cabbage fertilized with urine, which concluded that urine is capable of producing yield increases on par with industrially produced fertilizers (Pradhan et al., 2007). Furthermore, the control and urea treatments, neither of which provide any P, were outperformed by those treatments that included a source of P. This could indicate that a lack of P was a limiting factor for cabbage growth in the mother trial. However, a lack of corresponding soil data makes it difficult to corroborate this theory and is a limitation of the study. Despite the increased performance associated with the NUF and DAP, yields of cabbage under 30 tons ha^{-1} are considered conservative, which the South African ministry of agriculture defines as a yield that is "a relatively poor crop, and one that is frequently not economical to produce" (KwaZulu-Natal Department of Agriculture and Rural Development, n.d). This reiterates the yield gap challenge faced by smallholder farmers in SSA, even when applying substantial quantities of fertilizer.

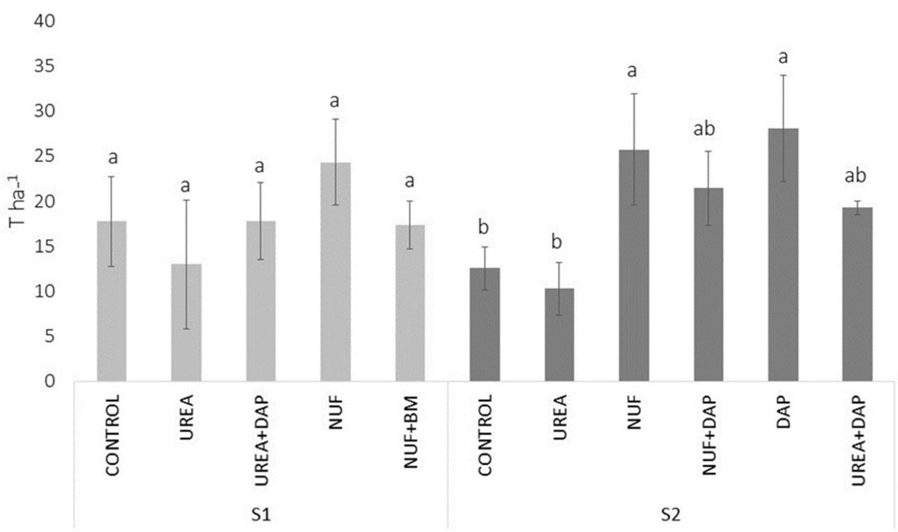

FIGURE 2
Cabbage yield at the mother site field trial. Values are means with bars representing standard errors ($n = 3$). S1 = season 1, S2 = season 2. Bars with different letters (within each season) are significantly different ($p \leq 0.05$).

Mother trial nutrient uptake

Significant differences in nutrient uptake were recorded between all the measured plant elements (Table 3). However, no clear trend was observable in N, P, and K uptake and it is not possible to associate these findings with a treatment effect. Despite this, quite large differences in Na uptake of the cabbage fertilized with NUF+DAP were observed in season 2. Although this difference was not observed in season 1, we hypothesize that this is possibly due to the changing irrigation sources used throughout the study. In season 1, the management teams transported water more frequently from the community water tank to the mother site while in season 2, as the participants became less enthusiastic about the study, there was a tendency to rely more on precipitation. A groundwater report commissioned in 2015 found high concentrations (>350 mg/l) of sodium in borehole water in the region (Geomeasure Group, 2015) which could account for the higher sodium uptake seen across all the treatments in season 1. Conversely, in season 2 lower sodium concentrations were measured in all of the treatments except the NUF+DAP, with uptake of Na in the NUF treated cabbage having the second highest Na uptake. Given the sodium concentration in NUF (25.4 g Na L^{-1}), the higher concentration of sodium in the cabbage fertilized with NUF is not a surprise; other studies in South Africa and other regions of the continent have observed similar increases associated with urine based fertilizer (Mnkeni et al., 2008; Kassa et al., 2018) which, when taken together, highlight a potential long term risk associated with urine fertilizers, an issue that must be considered by practitioners.

Baby trial results

In season 1 of the trial, farmers were provided an opportunity to grow one of three different vegetables (lettuce, cabbage, spinach) in their home gardens with the fertilizer treatments utilized at the mother trial, with 12 committing to this portion of the trial. In addition, the farmers were asked to select three of the fertilizer treatments utilized at the mother site to support their baby trials in order of preference. Nine of the 12 farmers selected urea as their first fertilizer option, with only 2 of the 12 choosing a urine-based fertilizer. As their second option, 7 of the 12 farmers then selected urea+DAP, with the other 5 selecting NUF+BM. At this preliminary stage of the study, it was very clear that the farmers preferred to use chemical fertilizers. When asked to explain their selections, they informed the research team that they selected urea and urea+DAP because of their familiarity with these products. Unfortunately, at the end of season 1 all the farmers indicated that the crops grown in the home garden either did not survive to maturity because of poor germination rates, inadequate irrigation, or they were eaten by livestock. The crops that did grow to maturity were frequently consumed by members of the household unaware that this research was being conducted. Due to these challenges in season 2 the decision was collectively made to focus the groups' effort exclusively on the mother trial.

TABLE 3 Nutrient concentration in cabbage leaves (g kg^{-1} dry weight).

	Season 1		Season 2	
Element	Treatment	Mean ± Std error	Treatment	Mean ± Std error
Na g kg^{-1}	CONTROL	2.0 ± 0.9^{b}	CONTROL	1.3 ± 0.5^{d}
	UREA	4.1 ± 0.2^{a}	UREA	1.7 ± 0.7^{cd}
	UREA+DAP	3.2 ± 0.4^{ab}	UREA+DAP	1.5 ± 0.2^{d}
	NUF	4.0 ± 0.4^{ab}	DAP	3.1 ± 0.3^{bc}
	NUF+BM	4.0 ± 0.1^{a}	NUF	3.7 ± 1.0^{b}
			NUF+DAP	7.2 ± 0.7^{a}
P g kg^{-1}	CONTROL	1.4 ± 0.3^{b}	CONTROL	1.9 ± 0.3^{ab}
	UREA	2.1 ± 0.1^{a}	UREA	1.7 ± 0.3^{b}
	UREA+DAP	1.7 ± 0.3^{ab}	UREA+DAP	2.4 ± 0.3^{ab}
	NUF	1.3 ± 0.2^{b}	DAP	2.7 ± 0.3^{ab}
	NUF+BM	1.9 ± 0.1^{ab}	NUF	2.1 ± 0.3^{ab}
			NUF+DAP	2.9 ± 0.4^{a}
K g kg^{-1}	CONTROL	24.7 ± 3.7^{a}	CONTROL	24.6 ± 2.5^{ab}
	UREA	19.0 ± 1.3^{a}	UREA	20.7 ± 1.7^{ab}
	UREA+DAP	24.9 ± 1.9^{a}	UREA+DAP	19.3 ± 2.3^{ab}
	NUF	17.6 ± 1.4^{a}	DAP	15.1 ± 0.5^{b}
	NUF+BM	18.8 ± 0.7^{a}	NUF	24.0 ± 1.3^{a}
			NUF+DAP	19.0 ± 1.8^{ab}
N g kg^{-1}	CONTROL	27.8 ± 0.1^{ab}	CONTROL	23.0 ± 0.1^{b}
	UREA	31.2 ± 0.02^{a}	UREA	27.8 ± 0.2^{ab}
	UREA+DAP	29.0 ± 0.2^{ab}	UREA+DAP	35.4 ± 0.4^{a}
	NUF	28.0 ± 0.2^{b}	DAP	29.2 ± 0.3^{ab}
	NUF+BM	30.5 ± 0.04^{ab}	NUF	28.5 ± 0.3^{ab}
			NUF+DAP	28.6 ± 0.1^{ab}

Values are means ± standard errors ($n = 3$). Treatment values with different letters (within each season) are significantly different ($p \leq 0.05$).

Smallholder challenges and opportunities in swayimane

Through the focus group work, the farmers identified three major constraints facing their ability to engage in smallholder production. First, water as a limiting factor was repeatedly mentioned throughout the study. Second, access to fertilizers was cited as a critical challenge. Although some of the farmers did occasionally state that they purchased chemical fertilizers, there was general agreement that obtaining sufficient quantities was very difficult due to lack of capital. Finally, the women also made it very clear that market access to sell the produce was a constraining factor.

During the study, it became clear that lack of adequate irrigation was a major challenge facing local smallholder production. At the mother site, although a borehole and storage tank had been installed uphill of the field, the only means of getting that water to the field was with buckets. Analysis of the transcribed discussion sessions indicate the severity of the problem: "We really have a problem of water;" "water is a big problem such that our crops dry up before they are ready;" "we are short of water because the water is only put at the crèche." These statements are supported by a calculation done during season 2 to estimate the recommended water requirements at the mother site. After accounting for effective precipitation, the calculated amount of needed irrigation was 31,978 liters of water; supplying this volume with the available water supplies proved impossible, reinforcing the experiences shared by the farmers. Given that most of the agriculture in Africa is rain fed (Jayne et al., 2018), and that the effectiveness of fertilizer used to improve yield is highly dependent on the availability of sufficient water (You et al., 2011), investments in irrigation infrastructure are necessary to fully benefit from the use of NUF. This lack of critical irrigation infrastructure limits productivity and raises questions about the potential of smallholder agricultural production to support sustainable livelihoods.

Inadequate access to fertilizer was the second major theme throughout the study. According to the Zimele development workers, the women often purchase chemical fertilizers due to inadequate availability of suitable organic fertilizer but can only do so in small and typically insufficient quantities because of a lack of capital. There was also discussion regarding the challenge associated with organic fertilizer: "it is not possible to plant a hectare of land using organic fertilizer because sometimes it is not much that is why we have to buy chemical ones." This experience is in line with a review of mineral fertilizer use in agroecosystems of sub-Saharan Africa; Chianu et al. (2012) found that a variety of factors such as low financial capital, insufficient knowledge, unstable policies, and poor access to credit all exacerbate the situation. A study specific to South Africa found that smallholder farmers apply insufficient mineral fertilizers primarily because of the cost, while the use of organic manures is constrained by insufficient quantity (Odhiambo and Magandini, 2008).

Even with the existing limitations of water and fertilizer, the farmers stated that they do often have surplus production, but that this tends to be wasted. As one farmer stated "the thing that is a problem for me when I have planted my produce is the market. Sometimes I grow my cabbage and the cabbage ends up rotting and my spinach ends up rotting. What I see as a problem to me is the market." Another woman shared a story of how she had been able to reach an agreement with one of the local retailers to sell her produce to the store but realized that the store doubled the price of her cabbage to their consumers: "I once took my spinach and they bought it for R5.00 and resold it for R10.00. I saw that happening in my presence." The farmers made it clear that insufficient market access was a challenge that limits smallholder production as a livelihood strategy. The individual questionnaires support this position, with 80% of the farmers at the end of season 1 indicating that market access is a challenge, and 100% of the farmers indicating the same situation in season 2. As with the issue of fertilizer, literature from across Sub Saharan Africa supports both these positions (Okello et al., 2007; Markelova and Mwangi, 2010).

Despite the challenges, the farmers also discussed perceived opportunities in the land-use situation and organization. For example, land in Swayimane is controlled within the Zulu nation, and this has made it relatively easy for the women to access land for agricultural purposes: "very few people would say they do not have land and mostly if you go to ask for land from the authorities (tribal), you get given." Another interesting discussion focused on the role of the cooperative structure the women developed with the support of Zimele. They described how the creation of the cooperative, done with the support of the local NGO, has allowed them to be more successful and resilient than they would have been as individuals. They discussed that being part of a group enhanced their ability to generate *Umbono* (vision) and *Umthamo* (capacity), sources of social capital that they attribute to facilitating progress and empowerment. From a more practical point of view, the women shared how operating in this structure improved their ability to grow food: "another thing, it [community collaboration] helps because it was difficult to plant alone because you can't look after the crops well alone but if you are many, if you are unavailable, the others are able to carry on with the work." Although this study found that smallholder production benefited from this system, the issue is contested. For example, Dlamini (2016) concluded that the effectiveness of farming cooperatives, a solution often encouraged to ameliorate rural poverty in South Africa is far from certain, with many farmers indicating that the earnings received from participation in cooperative agricultural production is insufficient to support a household.

Attitudes toward NUF

We assessed farmer attitudes at multiple stages throughout the project. Initial attitudes toward the use of NUF were at best mixed (see Table 4). As a group, the farmers indicated that they would be willing to use NUF processed in Durban, but also voiced reservations about the process, indicating that because they could not envision the production process, they maintained skepticism toward the idea. Regarding the use of NUF in the field, one of the dominant themes from the first season was the fact that the women were surprised about the lack of an offensive odor associated with it: in the focus group sessions, one woman stated "it was not what we expected. Even the smell surprised us because it did not smell." 61% of the participants stated that they would be willing to use NUF if it was provided by government free of charge. However, when offered the opportunity to indicate whether they would be willing to purchase NUF if it was available, the overwhelming majority (80%) of the women responded that they would be unwilling to do so.

At the beginning of the second season of the project, the researchers of UKZN and ETH Zurich organized a trip (Figure 3) to the urine processing plant. Located at the Newlands Mashu research station in Durban, SA, this facility is managed jointly by the eThekwini municipality and the Pollution Research Group (PRG) of UKZN. The purpose of the visit was to foster and improve understanding of the treatment process, as well as to view the effects of the NUF on several agronomic studies that were underway at the time of the visit. This site-visit proved to be particularly pivotal for the farmers; willingness to pay for NUF increased dramatically after this. At the end of the first season the farmers were asked if they would be willing to purchase NUF if it was commercially available and 80% stated that they would be unwilling to do so. By the end of the second season, this number had dropped to 18%.

Through the focus group sessions and individual questionnaires, we also explored the attitudes held by the

TABLE 4 Results of the individual questionnaire disseminated at the end of seasons 1 and 2 ($n = 15$).

Question asked	Response		Pertinent statement
	Season 1	Season 2	
I found the fertilizer trial conducted to be informative.	Strongly agree: 47% Agree: 40% Disagree: 0% Strongly Disagree: 0% No response: 13%	Strongly agree: 64% Agree: 36% Disagree: 0% Strongly Disagree: 0% No response: 0%	*"We have gained knowledge through the way he taught us."*
I would be willing to use NUF to fertilize my crops if it was provided to me by government.	Strongly agree: 13% Agree: 48% Disagree: 6% Strongly Disagree: 20% No response: 13%	Strongly agree: 64% Agree: 18% Disagree: 18% Strongly Disagree: 0% No response: 0%	*"It was not what we expected* [NUF]*. Even the smell surprised us because it did not smell." "I had a problem in the beginning when I was told that the fertilizer is from human urine. Later on, it did not bother me."*
If it was for sale, I would be willing to purchase NUF to fertilize my crops.	Strongly agree: 7% Agree: 13% Disagree: 53% Strongly Disagree: 27% No response: 0%	Strongly agree: 46% Agree: 36% Disagree: 18% Strongly Disagree: 0% No response: 0%	*"If it's [NUF] not expensive we would buy it because it has good results." "They [other members of the community] wouldn't buy it because they have not been taught about it."*
Lack of irrigation infrastructure is a limiting factor in my ability to grow food.	Strongly agree: 87% Agree: 0% Disagree: 0% Strongly Disagree: 0% No response: 13%	Strongly agree: 73% Agree: 9% Disagree: 0% Strongly Disagree: 9% No response: 9%	*"We really have a problem of water. Water is a big problem such that our crops dry up before they are ready."*
Inadequate access to markets is a problem for farmers who want to sell their products.	Strongly agree: 80% Agree: 0% Disagree: 0% Strongly Disagree: 7% No response: 13%	Strongly agree: 100% Agree: 0% Disagree: 0% Strongly Disagree: 0% No response: 0%	*"There is a market at the municipality but it's not there all the time and the other problem is we live far away here in Swayimane… sometimes if there is too many vegetables for sell they tell you that there is too much so they take your products for very little money. "*
I would be willing to eat food grown with NUF.	Strongly agree: 80% Agree: 7% Disagree: 0% Strongly Disagree: 7% No response: 6%	Strongly agree: 64% Agree: 27% Disagree: 0% Strongly Disagree: 0% No response: 9%	"*People who have not been taught* [about NUF] *will not be able to say yes." "For us that have learnt about it it's easy for us now. We understand but for the others it will be impossible for them to understand."*

The respondents are members of an agricultural cooperative that works closely with Zimele, a local NGO that focuses on women's empowerment. Cells highlighted in blue indicate a very strong positive shift in attitude of ≥ 20% of the respondents from season 1 to season 2.

farmers toward the use of human waste as a fertilizer. For example, they shared that there was little precedent for recycling human waste in their community and that they had little knowledge of the use of human urine as a fertilizer. This is in line with a study conducted in an adjoining municipality, eThekwini, which also found that there was little knowledge of the potential of urine as a fertilizer (Okem et al., 2013). Additionally, there was a great deal of confusion at the beginning of the project regarding the urine collection process. In Kwazulu-Natal pit latrines are ubiquitous (Mkhize et al., 2017) and their use does not allow for the source separation of urine. This initiated a discussion regarding the process utilized to obtain the urine. With the assistance of the Zimele representatives, it was explained that a community in Durban had been provided with urine diversion toilets (UDDT) and that it was from this community that the urine was collected. Necessarily, they were also somewhat skeptical of the nitrification technology and the development workers and researchers initially had a difficult time building a joint understanding of the treatment process. This led to a suggestion by one of the farmers to conduct a site visit to Newlands Mashu, where the nitrification technology is located. The farmers indicated that this event, the opportunity to view the technology and to speak with local experts regarding its safety, was responsible for a large shift in their attitude toward NUF.

FIGURE 3
Community stakeholders visit the processing facility and speak with Lungi Zuma, local manager and environmental engineer at the Newlands Mashu Research Station. Source: Ben Wilde.

This experience is by no means unique. Working on the same issue, Andersson (2015) observed that an action research platform developed in Uganda created the conditions to assess and then shift existing cultural norms around the use of urine as a fertilizer. Studies in other sectors (Buck et al., 2014; Fam and Lopes, 2015; Winkler et al., 2017) also indicate that providing community members the opportunity to engage directly with an emerging technology through PAR programs can facilitate increased levels of acceptance. However, the farmers also noted that many in the community would be reluctant to use NUF. In their opinion, a lack of understanding and familiarity with the process of urine nitrification would make it difficult to successfully scale up the technology. They shared their opinion that this lack of familiarity would pose a risk to farmers trying to sell their produce if they became associated with the use of waste-based fertilizers and would inhibit adoption. They also questioned whether it would be feasible to install a reactor in Swayimane and rhetorically asked how NUF would be transported from the processing site in Newlands to the peri-urban farmers in Swayimane.

Limitations of the study

With regards to the biophysical component of the study, several limitations must be noted. First, due to logistical constraints facing the research team, only baseline soil data was taken. This lack of information regarding the availability of soil nutrients associated with the different treatments hinders our ability to interpret the yield results. That said, a complementary study focusing exclusively on the biophysical implications and yield potential of NUF to support maize productivity in Kwazulu-Natal was done and will address these limitations. In addition, although the study appears promising regarding the use of NUF, caution must be taken when interpreting the results. First, it must be noted that, due primarily to logistical limitations, the study only incorporated the opinions of a small (15) number of community participants. Thus, it cannot be said that the study is representative of smallholder, rural communities across Kwazulu-Natal. In addition, a general concern about focus group research involves the suppression of voices that are at odds with the group consensus (Cary and Smith, 1994). In the course of the study, it became clear that there was a power structure that influenced how the cooperative operated, a fact which likely influenced the discussion sessions. One method of controlling for this was through the additional individual questionnaires disseminated at the end of each season.

The farmers themselves identified limitations in this study that often hinder the ability of participatory research processes to effect change more broadly: project duration, long term commitment, and scalability. Although they conceded that the project had succeeded in shifting their attitudes toward the use of NUF as a fertilizer, they pointed out that the community at large would still be quite critical of the idea. With no long-term plan in place to continue building knowledge about the issue of nutrient recycling in the community, the researchers had to concede that the effort was largely an academic exercise. This critique, initiated by the community stakeholders, speaks to the challenges of leveraging research, even when structured as a participatory endeavor, to effect social change. Upon reflection, we contend that this issue of no long-term plan is a weakness not only of the study but of participatory research generally. Indeed, transformation processes require a longer time scale to take root than is typically available within an academic research effort (Cahill and Torre, 2010). This presents a fundamental limitation of PAR to affect change in our opinion.

Conclusion

We employed a PAR approach to assess the potential of NUF to improve smallholder capability in Swayimane, South Afica. On the biophysical side, the NUF treatments were as effective as any of the chemical fertilizers, despite large variability in yield within and across treatments. In terms of nutrient uptake, the most noteworthy result was the high concentrations of Na associated with the cabbage grown with the urine-based fertilizer. This finding reiterates the high concentration of Na in the NUF, and the need for practitioners to be cognizant of this when utilizing NUF. On the social side, we found key challenges such as water scarcity, lack of fertilizer and market access to constrain farmers. The adoption of safe, locally sourced excreta derived fertilizers such as NUF could alleviate some of these challenges. However, the farmers cautioned that the use of a waste-based product such as NUF for agricultural production was not a common practice in the region, and that this lack of familiarity could be a hindrance to possible upscaling of the technology.

The farmers' invaluable insights into the potential of NUF have shown that this alternative technology has capacity to produce local, environmentally sustainable, and hygienically safe plant nutrients. Furthermore, we demonstrate the potential of PAR to shift existing attitudes about a potentially sensitive issue such as the adoption of recycled human waste as a source of plant nutrients. They indicated their surprise at the lack of offensive odor and the general dissimilarity between raw urine and NUF. A key learning outcome was the impact of the visit to the urine processing plant. The farmers and development workers identified this opportunity as critical in shifting attitudes regarding NUF. Despite the limitations noted in the discussion above, we contend that this study provides evidence that PAR can support efforts to facilitate change toward a circular food system, one predicated on the utilization of recycled nutrients derived from human waste.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

BW, EL, EP, AO, and JS: conceptualization, design, data analysis, data interpretation, and writing of the manuscript. BW and AO: data collection. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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