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Case Report

Partial Acidulation of Rock Phosphate for Increased Productivity in Organic and Smallholder Farming

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Abstract: There is a need to investigate and identify locally available organic substrates with acidifying potential, which can be used as an additive in rock phosphate (RP)-organic material composting mixtures. This paper reviews attempts to increase P availability in the context of smallholder, low-input and organic farming, and presents a case study from Central India that used a participatory approach to address P deficiency issues in cotton-based organic systems. Study was conducted from 2010 to 2014 through 61 on-farm trials and investigated the agronomic effectiveness of buttermilk-acidulated RP compost. The application of buttermilk-acidulated RP manure resulted in higher yields of cotton in all field trials and higher yields of soybean in all but one field trials. While on majority of the farms (18 out of 28), wheat yields increased with the application of buttermilk-acidulated RP compost, a quarter of the field trials (7 out of 28) exhibited yields lower than farmers' practices. The study showed that it was possible to develop a locally adoptable solution to an agronomic constraint using locally available resources including the indigenous knowhow. Buttermilk proved to be an effective acidulating agent that can be added to RP-amended compost.

Keywords: phosphorus; organic agriculture; smallholder farming; partial acidulation of rock phosphate; participatory technology development; buttermilk

1. Introduction

Crop production in organic systems strives to achieve closed nutrient cycles by enhancing ecological processes and recycling of nutrients. However, since many organic farms have little or no livestock, it is often improbable to achieve nutrient balance without relying on external sources [1,2]. After nitrogen, phosphorus (P) is the most limiting nutrient for crop production in both organic and conventional production systems [3–5]. The global P cycle is far from being closed, as P exports from the field through harvests have not been adequately replenished by providing sufficient external P sources. This is especially the case in organically managed production systems because of the limited number of permitted P fertilizers. Without external inputs, extensive and intensive organic crop production systems often show signs of P deficiency [6–8].

In conventional agriculture, part of the gap has been closed by applying mineral P fertilizers such as single or triple super phosphate that are produced by treating rock phosphate (RP) with strong inorganic acids such as sulfuric acid. These P fertilizers have higher solubility and therefore get dissolved in the soil-water and are readily available for plant uptake [9]. However, the finite nature of

RP and high energy inputs in the production of these mineral fertilizers render them unaffordable for most resource-poor farmers across the world. Additionally, cost of production, transportation and application of fertilizers into remote regions also compounds the high prices of production [10,11], which reduces the cost benefit ratio of farming, a crucial pillar for sustainability of smallholding farmers. Hence, there is a need to develop locally adapted, and thus adoptable and affordable technologies that can increase P availability for smallholder and organic farmers.

The challenge of P availability is even more pronounced in organic agriculture since organic regulations ban most of the commercially produced P fertilizers. Although, P containing organic materials such as bone meal and rock phosphates (RP) are admissible for organic crop production (Council Regulation (EC) No. 834/2007), they have limited efficiency. RP is a common but ineffective P source, especially for soils with high pH and low organic matter [12,13]. Due to contextual and resource-based differences, strategies to address P deficiency in organic production systems also vary between large-scale organic farming and smallholder low-input organic farming. For organically certified large-scale farms, sourcing P off-farm as manure and compost, or commercial organic P fertilizers could be costly or inefficient, especially when in the forms of RP or bone meals [2,14]. Thus, strategies targeting large-scale organic farms seek solutions in minimizing external inputs and focus on soil biological processes, increasing biological cycling of P, as well as, alternative cropping system designs using various plants with high P use [3,15]. Additionally, in systems where widespread RP application is reasonable, strategies involving plant and microbiological mechanisms that promote RP solubilization have been suggested [16]. These management interventions in large-scale organic and conventional farming can broadly be classified into following:

- Farming system design (i.e., crop-livestock integration);
- Putting plant functional diversity to work (i.e., integration of P mobilizing species into crop rotations and intercropping);
- Biological inoculants (i.e., phosphate solubilizing bacteria (PSB), other fungi, bacteria, and actinobacteria);
- Combined use of RP with green manure crops, which are capable of extracting P from RP, and supply it to a subsequent crop through organic P mineralization;
- Breeding P-efficient plants focusing on root growth and architecture, through manipulation of root exudates and soil exploration;
- Breeding plants that favor plant-microbial associations such as arbuscular mycorrhizal fungi and microbial inoculants.

These interventions and their combinations for P management in organic agriculture, particularly in the context of broad-acre field crop farming in Australia, Canada and Europe, where soil P resources have been depleted by P exports in crop biomass over extended periods, have extensively been discussed in literature [2,4,7,14,16,17]. To a much lesser extent, it has also been discussed in the context of low-input smallholding and organic farms, where most of the efforts are geared towards identifying cost-effective methods of improving P availability of RP using organic resources [18–20]. Building upon this background, the main objective of this paper is to discuss strategies for improving P availability in smallholder and organic farming with a development oriented perspective. While some of the interventions mentioned above could be applicable in the context of smallholder low-input farming (i.e., crop rotation, plant functional diversity and PSB), there is a strong need for context specific local solutions. The external input approaches with P enrichment through partial acidification with locally available organic substrates could offer an opportunity, but are still under-studied. This paper reviews past and current attempts to increase P availability in the context of smallholder, low-input and organic farming, and presents a case study from Central India that used a participatory approach to address P deficiency issues in cotton-based organic production systems.

2. P Availability and Acidulation of RP

2.1. P Availability in Soils

In soils, P can be found in different substrates, often bound to solid organic or inorganic compounds with low solubility. Most of the P (up to 80%) in soils is in inorganic form and bound strongly to positively charged minerals [21]. Some of this inorganic P is dissolved into the soil solution, and is subject to adsorption and desorption to/from the rapidly exchangeable adsorbed P pools of the soil, depending on the soil and environmental conditions. Another pool, organic P, is mainly found in the soil organic matter and is not readily available to plants. Phosphatase-like enzymes secreted by plant and soil microorganism can hydrolyze and make organic P more available to plants [2]. A smaller proportion of soil P is in the microbial biomass and can play a major role in P availability when the turnover time is short [22]. For instance, the rate of microbial P cycling is generally greater in organically managed soils compared to conventional soils because of greater manure additions in organic systems [15,23]. Since, plants can only take up orthophosphate ions ($H_2PO_4^-$ and HPO_4^{-2}), it is necessary to mobilize P from the solid matter into the soil solution near the roots of plants (rhizosphere). This happens by desorption of adsorbed P, as well as by breakup of Ca-Phosphates and mineralization of organic P. The mobilized P will diffuse to the rhizosphere following the concentration gradient [21]. Besides immobilization (conversion into organic P), P ions may either adhere to Aluminum (Al) and Iron (Fe) compounds in the soil at soil pH levels lower than 6 (sorption), or form phosphate rocks with Calcium minerals at soil pH levels higher than 7 (precipitation). These processes render part of the soil P unavailable for plant uptake.

2.2. Partial Acidulation of RP

Since availability of native soil P is limited by several biological, chemical and physical factors, crop production in most cases need to rely on external inputs of P. In case of conventional farming, crop need is generally met through synthetic P fertilizers. Among the few external inputs available for organic and low input farming, rock phosphate is probably the most reliable and accessible one in most of the developing countries. RP reserves exist in many regions of the world but they greatly vary in terms of plant available P. The basic premise for increasing P availability to plants from RP is the acidulation of RP through various methods that release humic acids and chelating agents forming complexes, hence dissolving P from the RP [18]. Partial acidulation of RP (PARP) is a cost effective method to improve the P supplying ability of indigenous RPs that have inherently low solubility [24]. In PARP, RP is acidulated with lesser quantity sulfuric acid and phosphoric acids than the quantities of acid needed to produce superphosphate or triple superphosphate [25]. Although, the effectiveness of this method depends upon several factors, there is a general consensus that PARPs prepared from highly reactive indigenous RPs and acidulated to the level where 40% or more P is present as water soluble P, could be as effective as superphosphate fertilizers [24,26,27]. Despite, PARP being one of the most commonly promoted methods for conventional smallholders, its application is limited and not widespread because these acids may not be locally accessible to the smallholder farmers in developing countries and moreover, in organic farming, the use of these synthetic acids is not allowed.

Additionally, agronomic effectiveness of RP depends on many factors besides the chemical and physical characteristics of native RPs, such as climatic and soil properties, soil pH, cation exchange capacity, P sorption capacity, as well as crop species and management practices [26,28]. For instance, Kato et al. [28] observed that solubility of RP decreased in soils with low cation exchange capacity (CEC) and this resulted in a reduction of its agronomic effectiveness. Relying on locally available acid sources to increase RP's P availability offers suitable solution particularly relevant for development context. In this regard, technologies involving the co-composting of RP with various acidifying organic by-product materials that include livestock manures, stubbles and crop residues have been receiving more attention.

3. Increasing P Availability of RP for Organic Systems

The smallholder, low-input organic farmers rely on on-farm produced organic materials for soil fertility [29]. These organic resources have been used in different forms to improve P nutrition. Depending on the locality and the availability of organic resources, P availability of organic materials could be enhanced by addition of RP. Various reviews and experiments from across the globe have reported on several on-farm and off-farm sourced organic materials used in co-composting with RP [24,30,31]. Since the type of organic matter used directly affects the P availability, the effectiveness of various RP enriched compost materials has been investigated [32]. The organic materials used in conjunction with RP range from cereal straws/residues [33,34] to shrub/tree or other plant leaves [35], from by-products of industrial crops [36] to chicken, cow or sheep manures [37–40], as well as vermicompost [35,41] or a combination of one or more of these resources [30]. Organic materials or manures are generally co-composted with RP to facilitate acidulation of RP, but in some cases are just mixed with RP and applied directly without composting, yet with lower effectiveness [38,42].

Biological processes employing plants and P solubilizing microorganisms solubilize RP by means of H^+ excretion and organic acid production [18]. Microbially induced production of organic acids and acidity during composting of these various substrates is the key process that solubilizes RP [16]. The most common bacterial solubilization mechanism is the production of organic acids that results in acidification of the microbial cell and its surroundings [43]. For instance, PSB can increase the solubility of P in calcareous soils by decreasing the soil pH and excreting carboxylic anions that have a high affinity to calcium; although the buffering capacity of the medium can reduce the effectiveness of the PSB [44].

Type of organic matter, pH, electrical conductivity, C:N and C:P ratio, moisture and temperature are the main determinants of P availability in composts [31]. Treatment of locally available organic materials through composting, processing or acidulating with various acidic compounds could address the P shortage in organic systems. However, there has been no standardized procedure or consistent outcome from most of the applied organic materials [2]. The large variety of organic materials available in different agroecosystems makes it difficult to suggest a standardized procedure for treatment of organic materials in order to release P. Additionally, the focus of most of the past and present research has been on utilizing generic organic materials with no or little attention to acidifying potential of these substrates. Researchers generally relied on the various organic acids produced during the composting process rather than the addition of external, affordable pH-decreasing compounds. Hence, limited information has been accumulated on alternative, locally producible RP-acidifying materials for organic and low-input systems [45]. There is a strong need to investigate and identify locally available organic substrates with acidifying potential, which can be used as an additive in RP-organic material composting mixtures.

4. Development of Indigenous Low-cost RP Acidulation Method—the Case of SysCom India

4.1. Study Area—Farming Systems and Soil Types

This study was conducted in the Nimar valley of Madhya Pradesh state in central India. The study region has a semi-arid climate receiving an average of 800 mm precipitation in a single peak monsoon between the months of June and October. The meteorological year can be divided into three seasons: the monsoon season called *"Rabi"*, mid-June to end October, the winter season called *"Kharif"*, November to March and the summer season between April and May, which alternates between dry periods of several weeks and heavy rains that exceed the water absorbing capacities of the soils. Cotton is a major cash crop in the region, which is cultivated in rotation with other crops such as cereals, vegetables, and legumes [46,47]. Organic cotton and wheat yields are generally variable and lower than attainable yields [46,48,49]. For instance, cotton yields in the region range from 800–1000 kg ha^{-1} in light soil areas with no irrigation, up to 4000 kg ha^{-1} in heavy soil areas with irrigation facilities.

Farm size can vary from 0.2 to 10 ha. Cattle plays an important role in local farming systems, and manure is used extensively for soil fertility amendment.

The most prevalent soils in the project region are vertisols, which are rich in calcium and magnesium carbonates, iron and aluminum, but have low phosphate, nitrogen and organic matter contents. A reference soil test for the Narmada belt was taken in the village Gopalpur, District Khargone, by the National Bureau of Soil Survey and Land Use Planning [50]. With 52%, clay content in the A horizon was very high, while sand and silt accounted for 20% and 28%, respectively. Water holding and retentive capacity was high due to the high clay content. Soil pH in the A horizon was 8.1, in the B horizon 8.3 and as a consequence the soil acidity can be classified as moderately alkaline. Also, exchangeable Ca with 30 cmol/kg was high. With an organic carbon content in the A horizon of 0.58%, and a cation exchange capacity of 46%, soil fertility status is medium to good compared to other subtropical soils. Another soil test for undulating land was taken from the village Jalda, District Khargone (30 km away from Narmada belt), by the same institution. Soil texture was similar: 51% clay, 20% sand and 28% silt. Although clay content was high, water holding and retentive capacity was just medium, because of the medium thickness of the solum. Soil pH in the A and B horizons was at 7.5 and 7.6, respectively, and thus classified as slightly alkaline. Exchangeable Ca with 24 cmol/kg was medium. It has to be noted that these are just two examples of typical soils in the area. In every farmer's field, the conditions and farming systems vary considerably in terms of size, crop rotations, irrigation opportunities and resource availability [29].

4.2. Using a Participatory Approach to Find Solutions to the P Limitation

The challenge of P deficiency in intensively cultivated organic production systems under high pH, alkaline vertisol soils was identified at the beginning of a Long-term Farming Systems Comparisons (SysCom) project [46]. Recognizing the need for identification of locally available RP-acidifying organic resources, a participatory technology development (PTD) process was initiated in the region. Participatory research approaches—along with other benefits—are a powerful tool to identify specific problems and find collective and corrective solutions to issues faced by local farmers [51]. Particularly in cases where farmer and stakeholder knowledge and experience is not well documented, PTD approaches become crucial tools in identifying the local experiences and knowledge. Hence, from 2010 to 2014 several PTD activities on different agronomic management techniques including partial acidulation of RP were carried out, as described by Andres et al. [52]. PTD activities were coordinated by the Innovation Platform jointly set up in 2006 by the Research Institute of Organic Agriculture (FiBL) and bioRe association. bioRe association is a farmer's association adjoining bioRe® India Ltd., which is an organic cotton enterprise working with some 4000 small scale farmers in the Khargone district of Madhya Pradesh.

Our approach of participatory technology development followed an 'innovation development cycle' (Figure 1) where farmers—along with other stakeholders—participated at every step, right from setting the research priorities to identification of potential solution and testing on field. Right at the beginning of the long-term project, a 'farmer advisory committee' was formed, that comprises of nine organic and nine conventional farmers from the local area. This committee meets twice a year to exchange feedback on project progress, sharing new developments/challenges with research staff as well as establishing consensus on next steps. Besides that, the project capitalizes on the extensive network of organic farmers producing organic cotton for bioRe. The research staff has identified a group of so called 'lighthouse farmers', who are willing to participate in the technology development process and also volunteer to test new innovations on their fields. Using a 'mother-baby trial concept', the proposed innovations are first tested in mother trials i.e., on research station and then the selected solutions in a more refined form are tested in baby trials i.e., on farmers' fields. Performance of both the on-farm and on-station trials is co-evaluated by researchers and farmers. This marriage of scientific perspective with farmers' knowhow offers unique strength to the process of locally adapted technology development.

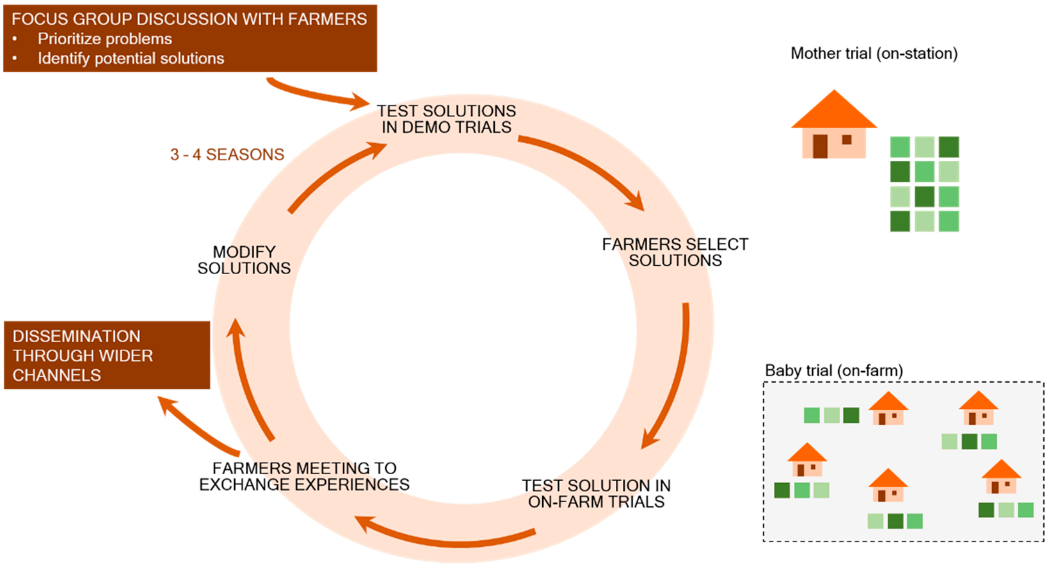

Figure 1. Participatory Innovation Development Cycle with Mother and Baby trial approach.

The study commenced with a meeting of farmer advisory committee followed by two focused group discussions involving farmers, extension workers, traders and researchers. In 2010, village level meetings were carried out in four villages (Amlathan, Choli, Nimrani and Badi) with an objective of synergistic utilization of scientific and local knowledge to identify locally available (mainly) plant based sources, which can potentially be used for solubilizing RP. In these meetings farmers were asked questions about their experiences on P availability and available resources. They were introduced to the concept of rock-phosphate acidulation to enhance availability of phosphorus to the plants and were encouraged to identify potential acidic substances or plant materials that were readily available in the area and were affordable.

A total of 38 plant materials likely to have acidity in their leaves, flowers or fruits were mentioned by the farmers. Out of these, 22 materials-based on seasonal and local availability—were tested for their acidification potential. To determine the pH of the plant based solutions, plant materials were ground and diluted with tap water (pH 7.4) and pH of the mixture was determined after 30 min using pH meter. Only 11 acidifying local materials (10 plant extracts and butter milk) were found to have pH lower than 4 (Table 1). Participatory evaluation of locally available organic acidic material in terms of availability, affordability and farmers' willingness to collect and cultivate were also evaluated through discussions. Outcome of these discussions are summarized in Table 2. PTD workshops were also useful in discussing the results of initial on-station and on-farm trials with RP, where buttermilk, an acidic solution of tamarind fruits, as well as phosphorus solubilizing bacteria (PSB) were used as P solubilizing material in composted manure. After these evaluations and preliminary field studies, it became apparent that buttermilk was the most available, affordable and easy to use acidifying material [53]. Although, some other materials (e.g., chickpea, tamarind, lemon) had equal or stronger acidulation effect, they were either very expansive or too complicated to process compared to buttermilk, which is freely available in almost every farming household in Nimar valley. Follow up farmer meetings were held on the trial plots every cropping season, where farmers witnessed the performance of different treatments and contributed to the refinement of P acidulation approaches.

Table 1. Potential locally available organic acidic material, source, and preparation method for RP acidification and their pH (Adapted from Locher 2011 [53]).

Material	Part	Condition	pH
Chickpea (small grain variety)	Leaves (some peas)	Fresh	2.90
Chickpea (large grain variety)	Leaves (some peas)	Fresh	3.72
Amla (Phyllantus emblica)	Leaves	Fresh	3.37
Amla (Phyllantus emblica)	Fruit	Mature	3.01
Tamarind (Tamarindus indica)	Fruit	Mature	2.59
Tamarind (Tamarindus indica)	Leaves	Fresh	3.23
Amari (Hibiscus sabdariffa)	Leaves	Dry	3.22
Wild Plum, Sour variety	Fruit	Dry	3.64
Mango green	Fruit	Fresh	3.32
Lemon	Fruit	Fresh	2.87
Buttermilk (Non-plant material)			3.57

Table 2. Participatory evaluation of locally available organic acidic material in terms of availability, affordability and farmer's willingness to collect and cultivate (Adapted from Locher 2011 [53]).

Material	Availability	Cost (INR kg^{-1})	Farmers Willingness to Collect	Possibility to Grow
Chickpea leaves	High	0	Good, leaves can be washed and used as cow fodder	Very good, but only in particular season (Dec.–Feb.)
Amla Fruits	Medium	30	Good, but for market use	Good, leguminous tree, fruithas market value
Amla leaves	Medium	0	Medium	Good, leguminous tree, gives foliage from 1. Year
Tamarind fruits (unshelved)	Medium	25	Low eaten directly By children	Low, needs 10 years until it fruits
Tamarind leaves	Medium	0	Could be collected with sickle on bamboo stick	Ok, but short growing varieties, possibly grown in hedgerows
Amari	Medium	0	For home consumption	Serves as trap crop for cotton pests
Plum, sour variety	Medium	15 0	Some are collecting, but for selling	Low
Buttermilk	High	0	High	Very common product in households with cattle

4.3. Buttermilk—A Cost Effective Locally Available Solution

Many of the tested plant materials were effective in solubilizing RP, but, buttermilk turned out to be the material of choice under local conditions. Buttermilk is the watery part that remains after skimming of butter from yogurt. Following the local practice, fresh cow milk with 5% water was boiled and cooled down to 25 °C. For fermentation, 10% yogurt with *lactobacillus* bacteria was added. After 1–2 days, yogurt was stirred, and the creamy part (butter) was separated for cooking purposes. The remaining liquid part was mixed with RP in a ratio of 1:10 RP to buttermilk. This mixture was stirred every second day and left for 12 days of incubation. Three days before manure application, the buttermilk+RP mixture was mixed with FYM (1:40 ratio).

In parallel, different options available for improved farmyard manure (FYM) management were also investigated. The "shaded shallow-pit system" (Figure 2) was chosen—jointly by researchers and the local farmers—as preferred method for conserving the quality of FYM [54]. Even though the reactivity of Indian RP is generally low because of its lower carbonate substitution [55], incubation with buttermilk proved effective. Unlike the past studies where RP was applied directly to the FYM, our method comprised of incubation of RP-buttermilk (1:10 ratio) mixture and then mixing of this acidulated RP with FYM that was kept in a tarpaulin foil under the shade to prevent any nutrient losses. After the preliminary studies on research station, on-farm field trials were conducted with local lead farmers. To assure some degree of consistency, every lead farmer in an area produced enough P-enriched FYM to supply five neighboring farmers in their surroundings.

Figure 2. Deep pit system lined with thick foil for improved farm yard manure management.

5. SysCom Participatory On-farm Assessment of Agronomic Effectiveness of Buttermilk RP Compost

From 2010 to 2014, a total of 61 on-farm trials investigated the agronomic effectiveness of buttermilk-acidulated RP compost. All trials were managed organically by the farmers. Researchers provided the assistance to farmers in field selection, treatments' management and data collection. Researchers' role in the selection was to ensure that the field was representative of the farmer's fields and did not have significant flooding or uniformity problems. Each field trial compared the crop grown under farmer's standard practices to that with the application of buttermilk-acidulated RP manure. A carefully selected, uniform field plot was divided into two halves—one receiving farmer's standard practices and the other one receiving buttermilk-acidulated RP manure. Farmers' practices vary considerably in the region depending upon season, crop and availability of organic inputs (e.g., FYM) and labor. In general, farmers apply 5–7 tons of FYM ha^{-1} annum^{-1}. Weeds are managed manually or with a bullock drawn harrow. Pests are managed with botanical extracts. Field size ranged from 100 to 500 m^2. Crop yields were estimated by harvesting the whole field and weighing the grains (wheat or soybean) or lint for cotton. Farmer practices varied from village to village and farm to farm, but generally involved the application of FYM and some biological pest control measures, especially for cotton. Soybean received no manure application.

Comparisons were done on both "heavy" (Vertisol) and "light" (Inceptisol) soils, representative for irrigated and rain-fed cotton growing conditions in Central India [56]. Cotton yields ranged from 200 to 1500 kg ha^{-1}, soybean yields from 400 to 1600 kg ha^{-1}, and wheat yields from 500 to 3800 kg ha^{-1}. Wide variation in interannual and interfarmer yields implies the personalized approach of the farmers to crop management, and the susceptibility of the production systems to weather events. For instance, there were major differences among the sowing date of the crops, where the difference between the earliest and the latest sowing dates was up to 50 days. Despite these variations among farms, care was taken to assure that the conditions on treated and untreated plots on each farm were uniform.

Crop responses to the application of buttermilk-acidulated RP manure varied across crop type, year and farmers' fields. In general, yields of all crops increased with the application of buttermilk-acidulated RP manure (Figure 3). The application of buttermilk-acidulated RP manure resulted in higher yields of cotton in all field trials and higher yields of soybean in all but one field trials. Wheat yields, on the other hand exhibited varying results, with yields increase seen on 18 out of 28 farms. This variability could be explained by the differences across the farms in terms of inherent soil fertility, previous crops and management practices of each farmer. We presume that the effect of this newly developed manuring practice was stronger in cases where farmer's nutrient management practice was not optimal. Since this study banked on conduct of extensive trials on farmers' fields, soil P values upon the addition of buttermilk acidulated RP were not measured, which makes it impossible to quantify the actual increase in P availability in soils. However, in another study conducted in the long-term field trial at same location, we found that with higher biological activity, soils under long-term organic management are capable of maintaining high P availability [23].

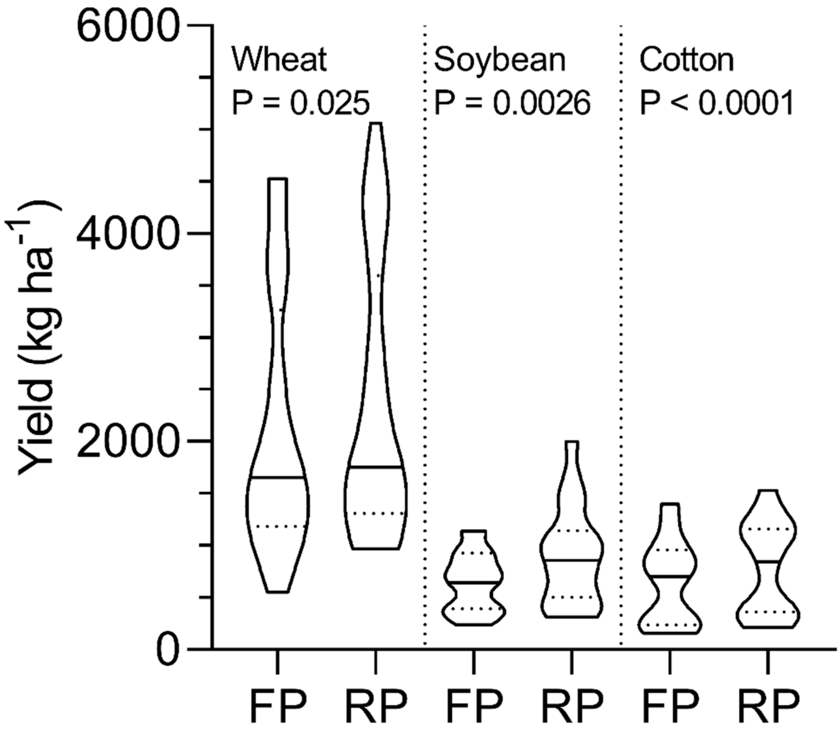

Figure 3. Violin plot of wheat, soybean and cotton yield when buttermilk-acidulated RP compost is applied (RP) versus farmers practice (FP) from 2010 to 2014. P values represent the level of significance difference from paired t test. $n = 61$.

6. Lessons Learned and Implications

The PTD process applied in the SysCom project showed that it was possible to develop a locally adoptable solution to an agronomic constraint using locally available resources including the indigenous knowhow. Unlike the majority of the previous work on acidulation of RP, where RP was simply mixed with a manure/compost, the present project used an additional acidifying substrate to improve RP availability. Buttermilk proved to be an effective acidulating agent that can be added to RP-amended compost. Availability of ample amounts of buttermilk, practically free of cost to most of the farming households in Nimar valley was an important reason for it being selected as preferred material for acidulation of RP. Replicated scientific studies are needed to determine and verify the effectiveness of

RP acidulated by buttermilk and other acidulating agents under different environmental conditions. A number of plants, leaves, fruits and agricultural byproducts could be used as acidifying agents across the globe to increase P availability from RP. Plant-based substrates listed in, Table 1 can potentially be used in RP acidulation in different parts of India and other tropical regions. Evidently, the effectiveness of such acidifying substrates should be investigated alongside their adoption potential by farmers i.e., considering their local availability, affordability and ease of application (Table 2). As a result of its widespread availability, affordability and ease of use, adoption of buttermilk-acidulated RP manure technology gradually spread across the cotton farmers in the area. Further dissemination of this technology is being done through the extension team of bioRe. Such a participatory research and development model could potentially be adopted in other parts of the world to address P deficiency as well as other farming challenges.

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