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The Impact of Using Co-Compost on Resource Management and Resilience of Smallholder Agriculture in South India

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Abstract: Agriculture is the main source of income in India, with most farmers being smallholders and facing multiple challenges, such as climate change and land degradation. For the sustainable implementation of alternative circular approaches, it is important that agriculture benefits. To assess this, the impact of using co-compost (organic waste and black water consisting of feces and urine) was evaluated through surveys of 120 smallholder farmers in two case studies in South India. All 149 questions related to the overarching research question: what is the impact of using co-compost on closing loops in smallholder agriculture in terms of resource management and resilience. Secondary smallholder resources were found to be well managed and local networks and economies proved to be particularly effective in pandemics, reinforcing the potential for nutrient sources from urban areas. For most farmers, using co-compost improved yields (90%), soil (80%), plant health (93%) and, consequently, profits (67%), as well as water management (53%). Water management was significantly less of a problem for co-compost users (15%) than non-users (42%). In addition, the users of co-compost were able to save resources. Chemical fertilizer use was significantly reduced from 1.42 ± 2.1 to 0.9 ± 1.35 t (acre·year)$^{-1}$, with total savings ranging from 37 to 44%. Overall, 67% were able to reduce chemical fertilizer use and 25% were able to reduce chemical spray use. Additionally, 53% reduced water consumption by 30.3% ± 19.92%. The visible benefits could motivate others to try co-composting. The reservations of non-users were due to personal or societal aspects (25%). In addition, the desire of farmers to convert to organic farming and try alternative farming methods, such as using smart technologies, vermicomposting or co-compost, was high (43%) and was positively influenced by the profitable use of alternative circular concepts. Information dissemination was mainly promoted by advertising (60%) and demonstrations (27%), which influenced openness to alternative circular concepts and products. In conclusion, co-composting and co-recycling approaches have a positive impact on the resource management and resilience of smallholder agriculture and thus, contribute to achieving sustainability goals.

Keywords: co-compost; co-recycling concepts; farmer perspectives; resilience; resource management; smallholder agriculture; South India; sustainable development goals

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1. Introduction

1.1. Problem Status

India faces a number of challenges, such as rapid urbanization, population growth, food security, water scarcity, pollution and climate change, which significantly affect farmers [1]. Agriculture is the main livelihood in India, accounting for 70% of rural households, with the majority (82%) of farmers being smallholders [2]. Smallholders are also of great global importance, growing at least half of the world's food crops [3]. They face many problems; for example, soil degradation is progressing worldwide and the predicted average soil erosion rate in Asia is 3.47 Mg ha^{-1} yr^{-1} [4]. Smallholders often face low productivity, lack access to productive resources and finance, are highly dependent on cultivation and harvesting, and are at the mercy of climate and crises, while potential opportunities for improvement lie in high soil fertility and increasing the overall rural economy [5–7].

Sustainability and resilience are closely related, with the former having a long-term perspective and the latter having more of a current perspective for dealing with unexpected disruptions [1]. Both are important aspects of smallholder agriculture and climate change and must be strengthened. Climate change is causing problems in agriculture as conditions, such as water availability, are changing and smallholders are highly vulnerable and dependent on these inputs, making the sustainable use of resources essential [8,9].

Due to the high energy demand, the production of chemical fertilizers causes the greatest environmental pollution in agriculture [10] and creates dependencies, which is why smallholders must be guaranteed secure and affordable access to fertilizers [11]. The overuse of chemical fertilizers can affect soil health, water resources [12,13] and human health [14,15]. Despite the increasing use of chemical fertilizers, India is experiencing soil quality degradation and agricultural productivity is stagnating [16].

In addition, the waste and wastewater situations pose many challenges, such as solid waste management. In Asia, due to the high population and the currently insufficient supply of improved sanitation facilities, there is great potential for covering P requirements through the use of alternative recycling technologies [17]. Plant nutrients, such as nitrogen and phosphorus, are excreted in human feces and urine, which, together with organic waste from urban areas, form nutrient sinks that are associated with the removal of nutrients from agricultural soils [18]. In addition, production and consumption behavior is changing, which has an impact on waste management [19,20]. The high proportion of organic waste (61% by weight) from urban households, together with black water and green waste, has great potential for agricultural use as a natural fertilizer [17,21,22]. "Natural fertilizer" in this study refers to organic fertilizer and also co-compost, which has not been declared as an organic fertilizer in India. Recycling secondary household resources into natural fertilizers could improve the situation for smallholder agriculture by improving soil fertility and thus, counteracting the widespread soil degradation [23].

1.2. Relevance

Links between rural and urban regions and between the waste and agricultural sectors through co-recycling offer the potential to close carbon and nutrient flows and counteract many of the current challenges that are acute in India, as well as other countries in the Global South [21,23,24]. Looking at India, co-compost has excellent potential to address multiple sustainability issues while benefiting the waste and agriculture sectors [23,25].

This underscores the fact that multiple Sustainable Development Goals (SDGs) could be addressed with appropriate circular economy concepts, such as co-compost [21,23,26–28]. This study focused on contributing to SDG 2 "Zero Hunger", with the target of doubling the productivity and income of smallholders by 2030 (target 2.3) and ensuring and implementing sustainable food production systems and resilient agricultural practices that strengthen the ability to adapt to climate change (target 2.4) [27]. In addition, there are further opportunities for circular economy approaches to have positive impacts on the SDGs, including direct impacts on SDG 12 "Responsible Consumption and Production" and SDG 13 "Climate Action" [23,27]. A closer look could also address other goals, such as SDG 6 "Water and Sanitation" by increasing water use efficiency (target 6.4) and SDG 11 "Sustainable Cities and Communities" by minimizing environmental impacts through waste management (target 11.6) [23,27]. These examples, which represent just some of the positive impacts of circular economy concepts, underscore their far-reaching importance. To achieve these goals, it is crucial to meet the needs of farmers, who are at the core of these circular economy approaches, to enable sustainable development [23].

1.3. Research Gap

More holistic approaches are needed to implement new recycling concepts, such as an integrated systems approach is needed to understand the interactions of the circular economy [29,30], including the farmers' perspectives. Social acceptance is one of the most important aspects when introducing new circular economy concepts [1]. In addition, further research is needed on how resource management is changing through composting practices, and what challenges smallholders face [23].

The literature contains some experimental studies on the co-composting of household organic kitchen waste and black water [31,32], but few cases of practical application [33], with most co-composting concepts involving the recycling of animal manure, agricultural residues, and sewage sludge published more than 10 years ago. Although there is literature on the perception of the use of co-compost [34] or of human excreta in agriculture [35], the literature is notably lacking on the impact of co-composting on smallholder farmers from their perspective, providing a broader perspective on the opportunities and challenges related to resource use and resilience in India, and in general.

1.4. Objective

The aim of this study was to answer the research question of how the use of co-compost from secondary household resources (black water consisting of feces and urine, kitchen waste, and green waste) to close cycles between urban and rural areas affects smallholder agriculture in terms of resource management and resilience. This is divided into the following sub-objectives, all of which are related to smallholder farmers: identify current challenges, the impacts of co-compost use, the status of resource management, and opportunities for improvement.

2. Materials and Methods

A total of 120 on-site interviews were conducted in India between 15 October and 15 December 2021. The study areas were the Nilgiris Mountains around the Ketti co-composting facility (near Ooty) and a peri-urban region of Bangalore around the Devanahalli co-composting facility. A total of 100 farmers were interviewed in Nilgiris and 20 in Devanahalli, half of whom were users of co-compost.

2.1. Co-Compost

The technical details of the production process for the co-compost include the composting of secondary household resources black water and kitchen waste, as well as public green waste, restaurant, and market waste. Black water (fecal sludge) from household septic tanks is desludged by septic tank operators and then taken to the fecal sludge treatment plant. The treatment process includes solid–liquid separation via sedimentation, stabilization, and dewatering. The sludge is further processed through drying under polycarbonate sheets in sludge drying beds. Composting then takes place with treated fecal sludge and organic waste in a weight ratio of 1 to 2 in Devanahalli, and 1 to 4 in Nilgiris, and composted for 42 days (with one turn per week) in Nilgiris and for 60–75 days (with one turn every two weeks) in Devanahalli. The capacity of the plants is 6 m^3/day in Devanahalli and 6.7 m^3/day in Nilgiris. The information in this section comes from on-site interviews with the operators of the plants [25].

The co-compost produced using this method has a content of 0.9:0.5:0.5% NPK (nitrogen–phosphorus–potassium) in Nilgiris and 0.7:0.2:1% NPK in Devanahalli [25]. In comparison, fertilizer No. 5 (an ammonia-based fertilizer), one of the fertilizers commonly used by farmers in Devanahalli, has a content of 6:12:6% [25]. Nevertheless, the recommended rates for co-compost are equal to, or at most, double those for mineral fertilizers, as the application of co-compost brings other beneficial effects [25]. Usually, combinations are used, and chemical fertilizers are replaced only to a certain extent [25]. In terms of cost, co-compost costs 5–7 rupees (~ 0.07–0.09 $) per kilogram, while fertilizer No. 5 in Devanahalli and fertilizer in Nilgiris (using muriate of potash MOP) cost about three times more [25]. For further comparison, farmyard fertilizer costs about 3–5 rupees/kg (~0.04–0.07 $) [25]. All USD values follow the conversion factor from Table 1 and are noted for the 2021 survey period.

Table 1. Background information of the interviewed farmers.

Indicator	N	Unit	User [1]	Non-User [1]
Place				
• Nilgiris	100	%	83	83
• Devanahalli	20	%	17	17
Age	120	Years (average) [2]	47 ± 12	46 ± 13
Gender				
• Female	19	%	15	17
• Male	101	%	85	83
Land size	120	Acres (average) [2]	2.13 ± 2.04	2.18 ± 2.74
Property				
• Own	74	Valid %	63	62
• Rented	36	Valid %	27	33
• Both	9	Valid %	10	5
• No indication	1	Frequency	1	0
Irrigation system				
• Sprinkler/butterfly	85	Valid %	78	75
• Manual	14	Valid %	15	11
• Drip irrigation	12	Valid %	7	14
• No indication	1	Frequency	5	4
Water source				
• Own well/pond	52	Valid %	52	50
• River/stream	29	Valid %	26	31
• Shared/public well/pond	17	Valid %	18	15
• Other	4	Valid %	4	4
• No indication	1	Frequency	10	8
Annual income [3]				
• <910 $	42	Valid %	39	32
• 910–1560$	31	Valid %	29	24
• >1560 $	45	Valid %	32	44
• No indication	2	Frequency	1	1
Distance to the closest market	120	km (average) [2]	41.88 ± 15.98	42.34 ± 14.9
Usage of middlemen				
• Yes	41	Valid %	39	34
• No	54	Valid %	43	54
• Both	17	Valid %	18	13
• No indication	8	Frequency	4	4
Co-compost (average numbers)[2]				
• Years of usage	120	Years (average) [2]	1.94 ± 1.09	0.00
• Price [3]	120	$/kg (average) [2]	0.07 ± 0.007	0.07 ± 0.008
• Distance for pick up	120	km (average) [2]	5.84 ± 5.91	4.94 ± 5.05

N = Number of respondents. [1] The number of respondents of users and non-users is 60 each. [2] Average numbers are given with standard deviation. [3] ₹ = Rupees. Exchange rate of 1 ₹~0.013 US Dollar $ in October/November 2021.

2.2. Background of The Investigation Area

Much of the information is presented as a percentage, which always refers to the sample size divided into 60 users and 60 non-users, or to the total number of survey participants from 120 smallholder farmers. More detailed information about the respondents is given in Table 1. Most of the participants are male (84%), the owned farmland area averaging about 2 acres, and sprinklers are used for irrigation from their own water source. In total, 35% of the respondents are under 40, 49% are between 40 and 60, and 16% are over 60 years old. The income categories are distributed around the average income of farming in southern India [1]. In total, 67% have no additional source of income besides farming, while 93% indicated that farming is their main occupation. The distance to the market is about 40 km, with about half of the farmers using middlemen for transport. Co-compost users have been using the co-compost for an average of 2 years. About half of the respondents (45%) cited problems with the co-compost, while almost all (97%) are interested in continuing to use it.

The participants' main crops are carrots (grown by 83% of farmers), potatoes (58%), beetroot (44%), and garlic (37%). Another 30 different plants, such as beans and flowers, are cultivated, with a greater diversity being seen in Devanahalli. This diversity also occurs in livestock farming. Overall, 17 farmers have 3.47 ± 2.10 cows, 8 farmers have 12.25 ± 10.01 chickens, 6 farmers have 9.00 ± 4.65 sheep, and 5 farmers have 8.80 ± 7.19 goats.

2.3. Methodology

The users of co-compost were randomly selected via the village cluster using the contact data pool of the supporting organizations Consortium for the DEWATS Dissemination (CDD) Society in Bengaluru and the Rural Development Organization (RDO) Trust in Ooty [36,37]. The non-users were selected equally in the village clusters according to the snowball principle [38].

A combination of different survey approaches was used to reduce errors and to verify values. Open and closed questions were integrated, and on-site observations were also included [39,40]. The questionnaire contained 149 questions on background data, and the research questions. Control, filter, and icebreaker questions were integrated, and metric, ordinal, and nominal data were collected [39]. Five test surveys were carried out in advance. A translator was always available for the direct translation of the interviews. Translations were made from Tamil, Kannada, and further local languages, into English. All questionnaires were filled out directly from the author and signed by the respondents [39,41].

To obtain even more precise quantitative data, in addition to the exact amounts, categorizations (limitation of value ranges) and personal impressions of the amounts (as good, acceptable, or problematic) were requested. In the cases of changes caused using co-compost, the participants were also asked to classify these in percentages and percentage classes.

The quantitative evaluation was carried out with IBM SPSS Statistics. Mean values, and maximum and minimum values, as well as standard deviations, were determined for the metric data. Frequencies were counted for the ordinal and nominal data. All data were checked for significant differences for the user, non-user, Nilgiris, and Devanahalli groups. For this purpose, cross tables were tested with Chi-squared, phi, and Cramer-V, etc., and contingency coefficient [39]. Significance levels of $p \leq 0.05$ were used for all means and enumerations. Thus, the null hypothesis that values do not differ significantly between users and non-users is rejected when $p \leq 0.05$ with a 5% probability of error [39]. The Eta coefficient describes the extent to which metric variables can be explained using normalized variables (users and non-users), and shows whether a relationship exists, whereby a value of greater than 0.3 can already be regarded as a rather strong relationship [39].

3. Results

3.1. Challenges

Looking at Figure 1a, it becomes clear that the most frequently perceived problems for smallholder farmers are high input costs and unstable sale prices. This is followed by topics related to climate change and water resources, which also receive a lot of attention. Significant differences can be seen for water resource problems, with $p = 0.002$ (Figure 1b—including all ratings), with 15% of users and 42% of non-users perceiving water resources in agriculture as being unproblematic. For the other problems from Figure 1, no significant differences between users and non-users could be determined. This also includes the problematic aspects that are directly related to the cultivation of the crops (health, yield, and germination rate).

However, in the detailed questions on harvest yields (by means of qualitative assessment by the smallholders), there are clear differences for beetroot with $p = 0.05$, and for all crops combined, with $p = 0.011$. More non-users reported poor to very poor crop yields (N = 30 for beetroot with 20%, and N = 60 for all crops with 14.6%). This compares to users who rarely or never gave this rating (N = 24 for beetroot with 0%, and N = 60 for all crops with 2.3%).

Yields differed between users and non-users, but not to a significant extent, considering information on actual plant yields using quantitative estimates (Table 2).

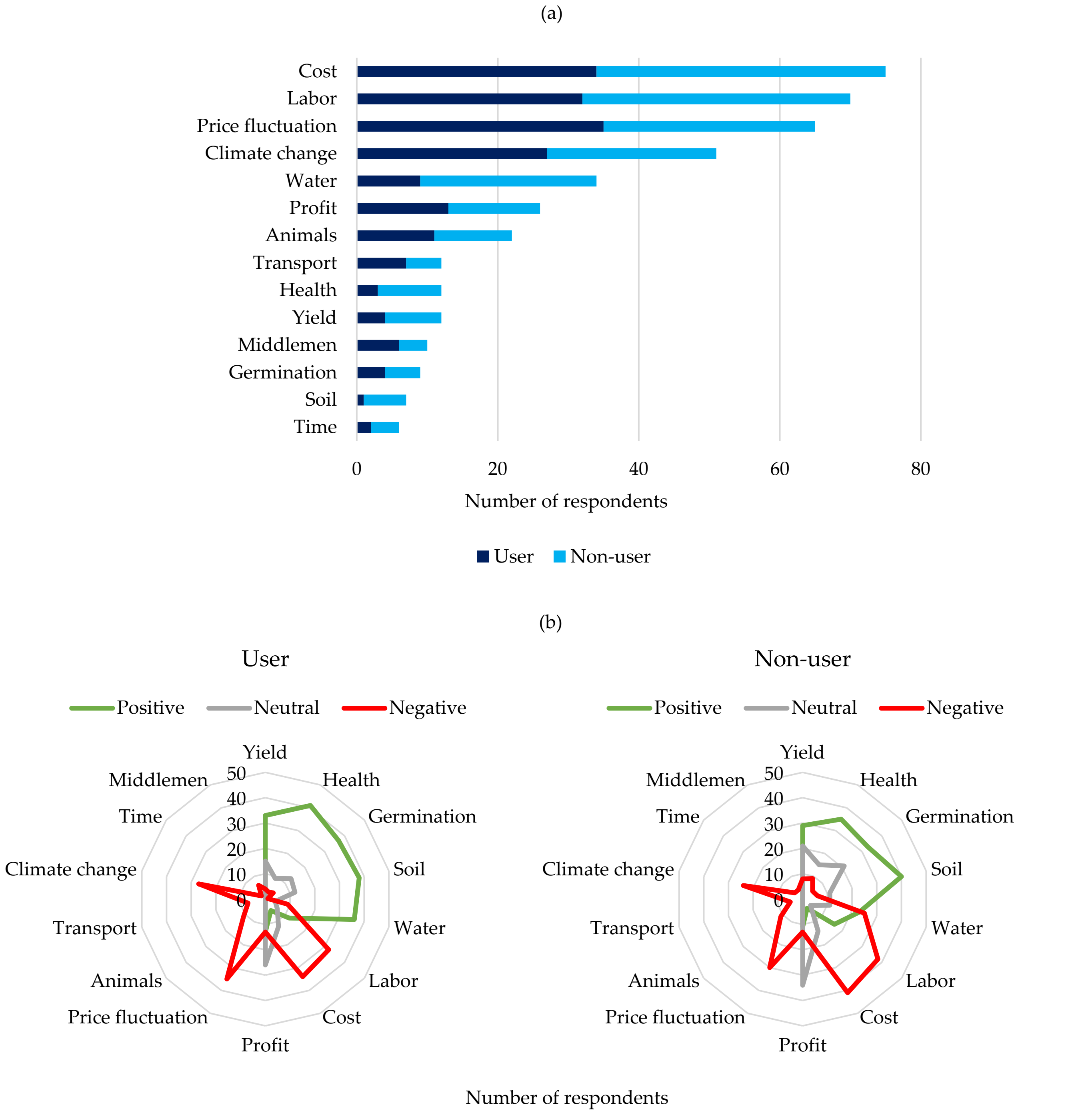

Figure 1. Main challenges of smallholder farmers, including users and non-users of co-compost, with multiple responses possible. (**a**) shows the challenging (negative) factors (**b**) includes the neutral, positive, and challenging (negative) ratings. All given in N = Number of respondents.

Table 2. Yield of the main harvested crops. N = number of respondents.

Indicator	N (User)	N (Non-User)	Unit [1]	User	Non-User	Eta-Coefficient
Carrots	48	52	t/acre	13.52 ± 7.76	11.41 ± 6.27	0.150
Potato	31	39	t/acre	9.15 ± 6.10	7.17 ± 4.10	0.193
Beetroot	27	30	t/acre	11.76 ± 8.14	9.64 ± 7.48	0.137
Garlic	22	22	t/acre	6.15 ± 3.68	6.42 ± 3.88	0.037

[1] Given in average values tons per acre and standard deviation. Referring to the year 2021.

Farmers have changed their farming practices due to climate change, with significant differences, with $p = 0.017$ between users (33%) and non-users (55%). The crops or varieties grown changed (15% user, 22% non-user), chemical use is increasing (7% user, 23% non-user), and water management changes (13% user, 17% non-user). With a significance of $p = 0.04$ between users (63%) and non-users (45%), smallholder farmers have noticed changes in soil fertility since the beginning of their agricultural practice. The majority have reported that soil fertility improved with organic fertilizer (43% of users and 39% of non-users) and co-compost (63% of users), and only a minority considered the use of chemicals to be the main contributor (10% of users and 8% of non-users), with significant differences of $p = 0.001$.

The problematic points are almost all felt to be improved using co-compost (seen in Figure 2), whereby the costs and the availability of labor remain unaffected by the changed resource management. In particular, plant and soil health, and crop yield improved. At the same time, the costs for the substrate used and water consumption fell. These aspects together explain the improved profit. All responses show significant improvements when directly compared to non-user responses for the same issues. Significance is shown for plant health ($p = 0.027$), yield ($p = 0.014$), soil ($p = 0.001$), germination ($p = 0.012$), and water ($p = 0.017$). Few respondents attributed the fact that the water requirement worsened and thus increased to the heat radiation of the co-compost. Although there are significantly fewer water issues for users of co-compost than for non-users (Figure 1), this is not the main criterion that is seen as a benefit of co-compost. The focus is on returns and profits (Figure 2).

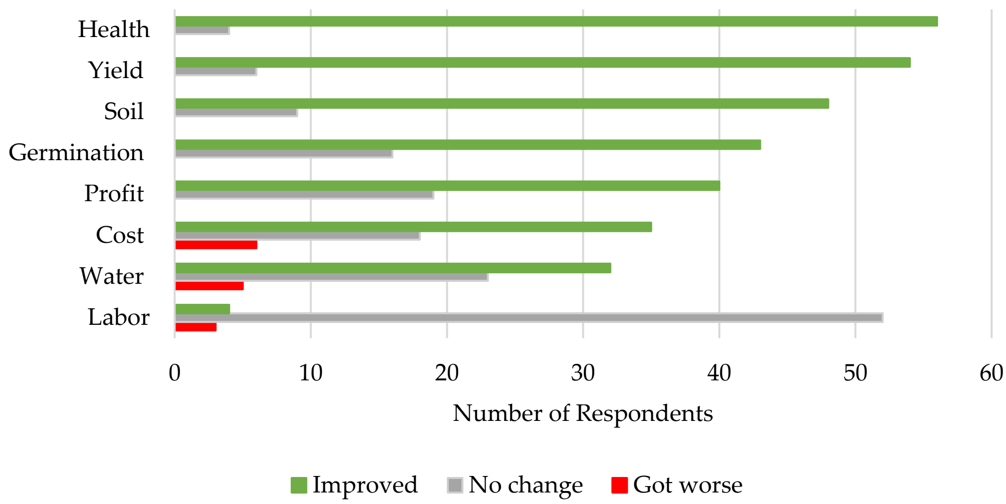

Figure 2. Changes in agriculture after using co-compost. Responses from co-compost users.

The problems for most farmers in 2020–2021 during the COVID-19 pandemic was that prices for their crops were very low (50% user, 37% non-user), and that they could only sell in local markets (17% user, 25% non-user) or not at all (25% user, 27% non-user). Therefore, transport (32% user, 15% non-user), labor (13% user, 12% non-user), and the market and the associated lack of income were very problematic. In particular, market problems were seen due to difficulties with transport (30% user, 44% non-user), labor (12% user, 15% non-user), profit (15% user, 10% non-user), and middlemen (5% user, 13% non-user). Another difficulty was the lack of availability of inputs (fertilizers, corn production products, and seeds) for agricultural practice (7% user, 8% non-user). Access to co-compost was rated as unproblematic more often (25%) than the access to and the pricing of chemical fertilizers (3%). However, most farmers who engaged in farming during this period had their own stocks or were supported by supplies in the community. Farmers managed on the one hand, with savings (37% user, 28% non-user), and on the other hand, with the help and credit of relatives, neighbors, and friends (22% user, 13% non-user). Other solutions were external work (5% user, 20% non-user), loans from banks (15% user, 7% non-user), state support (7% user, 8% non-user) and other internal earning opportunities (7% user, 12% non-user).

3.2. Resource Management

A total of 91% of smallholders composted their plant residues (visible in Figure 3). These were often either mulched or composted in windrows directly in the field. A total of 94% of respondents had their kitchen waste collected, and 43% composted some or all of it. A minority of farmers used the black water directly (6%) or after composting (4%). Since only the use of black water was the subject of the survey, it was not recorded here that most farmers had their black water collected with suction vehicles (called honey suckers). While 28% of smallholder farmers blended charcoal from stoves into compost, 18% used it directly in agriculture or in kitchen gardens. Dumping, slash-and-burn practices, and selling to middlemen played a minor role. No significant differences between users and non-users could be determined in resource management.

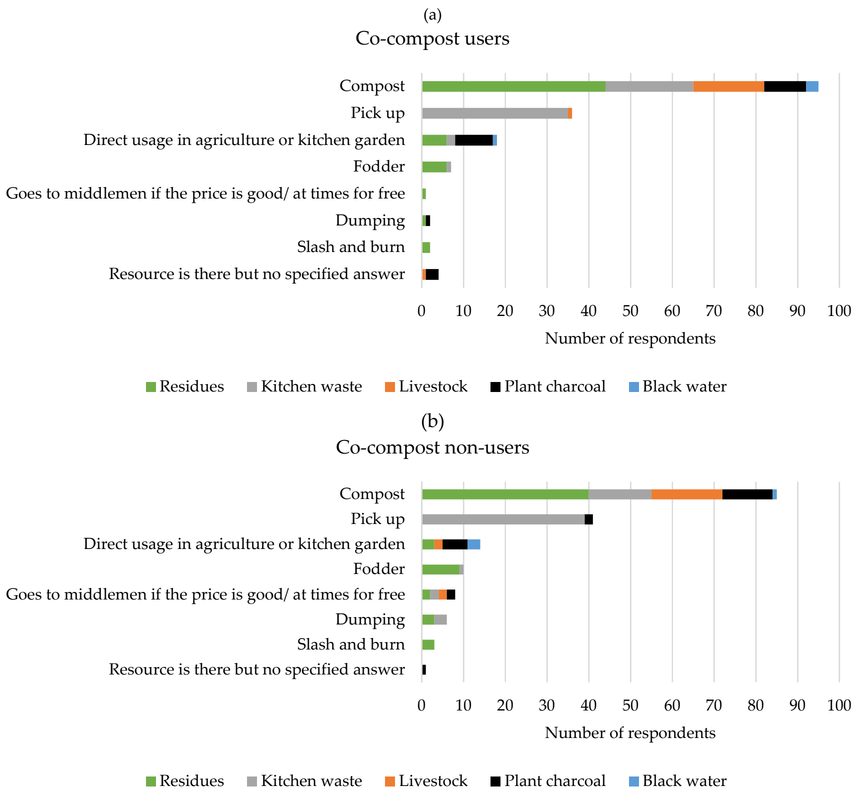

Figure 3. Practices in the internal resource management of (**a**) co-compost users and (**b**) co-compost non-users with N (number of respondents) = 120 (60 users and 60 non-users). Multiple answers were possible. Only data for internal use were collected for black water, which is why the collection via suction vehicles was not recorded here. "Pick up" includes collection from households and municipal collection points.

From Figure 4, it can be seen that farmers using co-compost did not renounce traditional organic and chemical fertilizers. The most popular fertilizer among users was co-compost, at 42%, followed by farmyard manure (23%) and chemical fertilizers (12%). Non-users preferred farmyard manure (50%), followed by 10%, who preferred chicken waste, and 10%, who preferred chemical fertilizer. However, the most commonly used inputs were still chemical fertilizers (used by 90% of users and 97% of non-users) and sprays (used by 97% of users and 87% of non-users). Chemical sprays in these interviews included herbicides, pesticides, and insecticides.

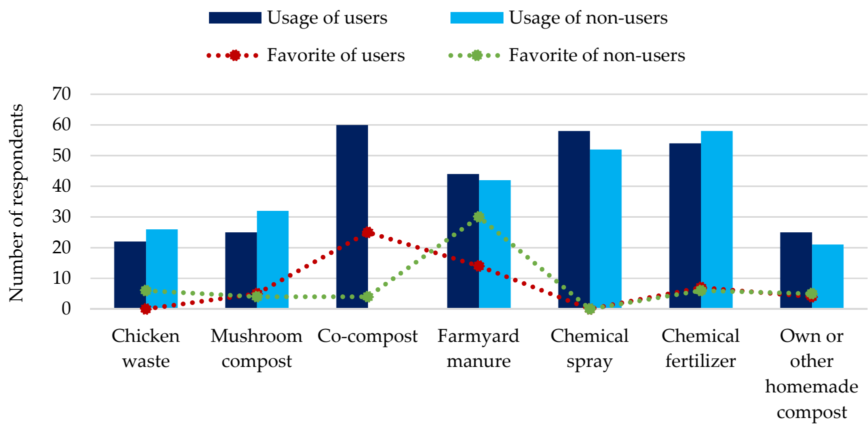

Figure 4. External input of smallholders. Showing the actual usage and the preferred one.

Table 3 shows that co-compost is used in smaller quantities compared to other natural fertilizers, with an average of 3.3 t $(\text{acre}\cdot\text{season})^{-1} \pm 6.7$, which is recommended. Looking at the farmers who used farmyard manure (users: 73% and non-users: 70%, visible in Figure 4) and the quantity in Table 3, it becomes clear that this plays an important role for farmers, alongside the use of chemicals (referring to chemical fertilizers and sprays). This applies for both users and non-users. In Table 3, the Eta coefficient is well below 3, indicating that there are no significant differences between users and non-users. Nevertheless, it can be stated that the use of chemicals and water consumption for users decreased after co-composting.

A quarter of the co-compost users indicated that using co-compost did not change the amount of chemical fertilizer. Here, 23.3% noticed a reduction of under 25%, and 43.3% saw a reduction of over 25 %. This result confirms the results from Table 3, which show a reduction potential of between 37 and 44%. In total, 70% of smallholders did not change the amount of sprays (herbicides, pesticides, and insecticides) when using co-compost. Here, 11.7% recorded a decrease of up to 25%, and 13.3% of over 25%. In total, 1.7% reported an increase of less than 25%. The result that only a few farmers see a potential for saving pesticides by using co-compost is supported by the results in Table 3, which shows a low response rate. If farmers manage to reduce, then the reduction is between 19 and 35%.

A total of 38.3% (Figure 2) of farmers could see no change in water management. A total of 36.7% of users saw a reduction in the amount of water used, by up to 25%, and 13.3% by more than 25%. Overall, 53.3% (Figure 2) of users saw a reduction. The results from Table 3 show an average reduction (with 36.7% of users) of 30.3% ± 19.92, also with a wide range. A minority of 8.3% saw an increase of less than 25%, and thus, a negative impact on water demand (Figure 2).

Table 3. Quantitative data on smallholder resource management. N = number of respondents.

	Unit	User			Non-User			Eta-Coefficient
		N	Mean	SD	N	Mean	SD	
Own compost	t $(\text{acre}\cdot\text{season})^{-1}$	11	2.24	3.86	8	2.28	4.17	0.016
Co-compost	t $(\text{acre}\cdot\text{season})^{-1}$	43	3.3	6.7				
Mushroom waste	t $(\text{acre}\cdot\text{season})^{-1}$	22	9.22	10.36	30	13.08	16.63	0.134
Farmyard manure	t $(\text{acre}\cdot\text{season})^{-1}$	34	13.82	16.8	36	12.51	11.61	0.046
Chicken waste	t $(\text{acre}\cdot\text{season})^{-1}$	18	8.66	11.19	20	12.66	13.37	0.163
Plant charcoal	kg $(\text{month})^{-1}$	17	26.53	24.76	18	18.54	24.28	0.165
Chemical fertilizer								
• Before co-compost usage	t $(\text{acre}\cdot\text{year})^{-1}$	46	1.42	2.1	53	1.57	5.42	0.019
• After co-compost usage	t $(\text{acre}\cdot\text{year})^{-1}$	35	0.9	1.35				
• % reduction [1]	%	33	44.21	15.91				
Chemical spray								
• Before co-compost usage	L $(\text{acre}\cdot\text{year})^{-1}$	26	8.16	12.88	29	8.35	13.62	0.007
• After co-compost usage	t $(\text{acre}\cdot\text{year})^{-1}$	4	6.63	9.03				
• % reduction [1]	%	11	35.45	21.27				
Water usage reduction in dry season [1]	%	22	30.3	19.92				

[1] The percentage reduction in chemical consumption has been queried separately from the amounts reported, as some farmers have preferred to report the change as a percentage.

3.3. Motivation

The motivation to start co-composting comes when the benefits are seen and communicated (Figure 5). In total, 60% of users cited advice and promotion from NGOs and local actors as the main reason, with trust playing an important role. A total of 27% saw benefits from recommendations or demonstrations from neighbors, friends, and family. Additionally, the main reasons for continuing to use co-compost were to improve crop yield (58%), and plant and soil health (30%), as well as monetary reasons, such as price and profit (15%). Most non-users have not yet used co-compost, due to a lack of information (advertising or demonstration, 40%), resources (logistical or monetary, 18%), or personal or societal factors leading to hesitation (25%). Above all, there is a lack of information flow, including about profit opportunities. The willingness to pay is shown as follows: 5.49 rupees (± 0.57) (~0.07 $) on average (Table 1), and would like to pay 4.09 rupees (± 1.45) (~0.05 $), while non-users (N = 51) would like to pay 3.81 rupees (± 1.4) (~0.05 $) per kilogram of co-compost.

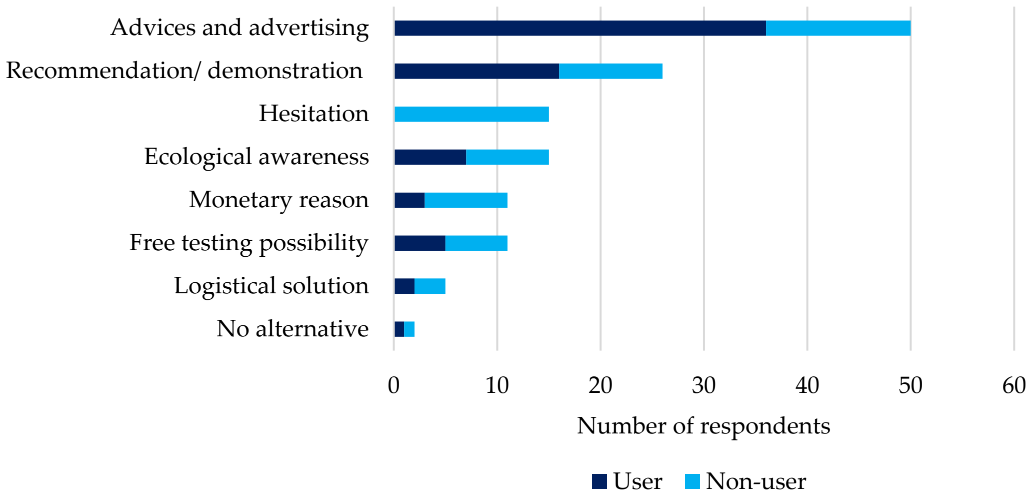

Figure 5. Motivation of co-compost users and non-users to try co-compost (N=120 and N=15 for multiple choices). N = number of respondents.

Co-compost is seen as needing improvement, particularly in terms of availability and information about it (20%), quality (15%), transport (12%), and price (8%). However, most users were satisfied and had no complaints or suggestions for the improvement of the co-compost.

Almost all respondents used either a septic tank or a pit latrine, and only 2% used open defecation and a public toilet. Although nearly half of the respondents indicated that they would like to try a separate toilet (53% of users and 34% of non-users), reservations were expressed (visible in Figure 6). Both users and non-users initially cited a lack of practicality, options, and space (27% each). Reluctance due to personal or societal values was higher among non-compost users (25%) than among users (12%). A lack of resources such as time, money, and labor (12% each), and a lack of knowledge (13% user and 3% non-user) were also mentioned.

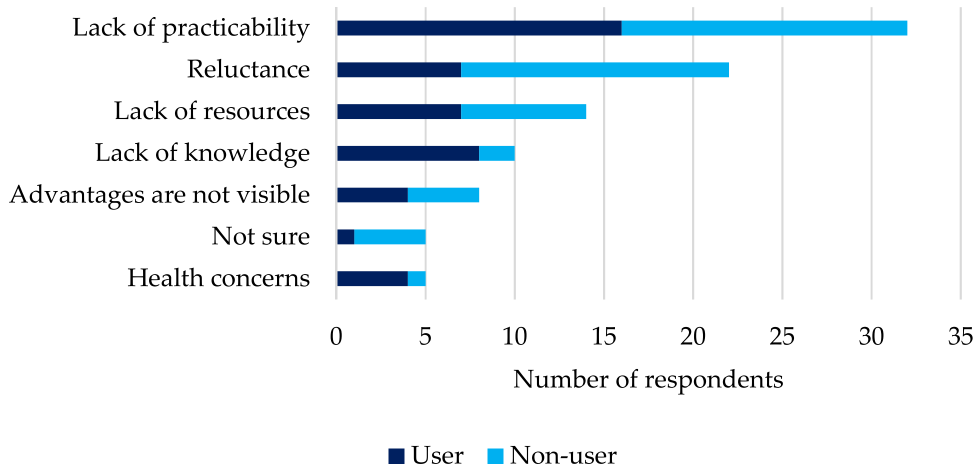

Figure 6. Reservations about alternative sanitary facilities using the example of a dry separating toilet.

Although the main desire of smallholder farmers (35% users, 23% non-users) is to switch to organic farming (Figure 7), most respondents do not believe that full conversion is possible for them (47% of users and 57% of non-users). On the other hand, 40% of users and 30% of non-users believe that this might be possible under certain circumstances. In total, 7% of users and 2% of non-users are already organic, and a minority think that it is entirely possible (3% users, 8% non-users).

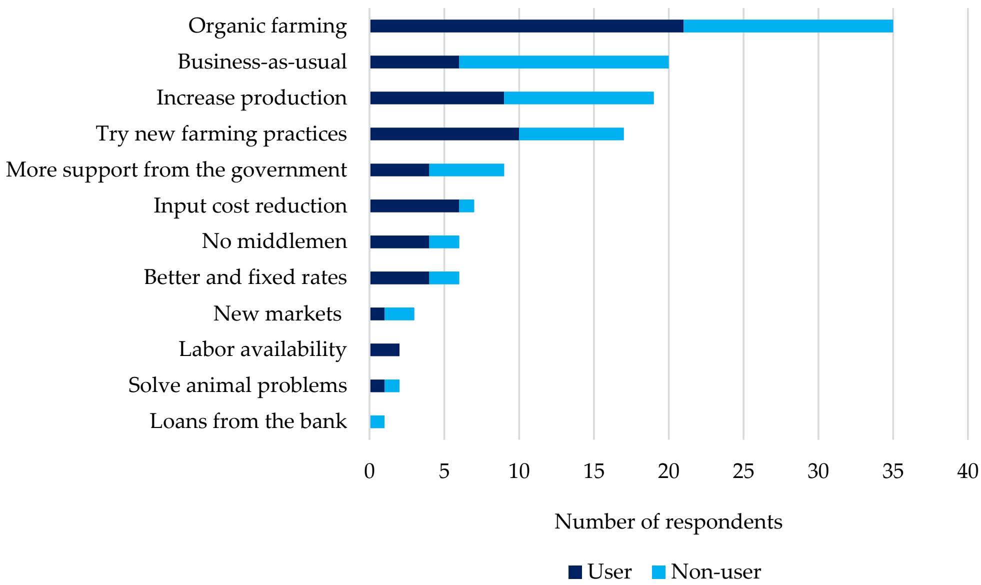

Figure 7. Main motivations (summarized), wishes and goals of the farmers for the future. Multiple choices possible.

The farmer' wishes showed significant differences in the answers ($p = 0.048$) (Figure 7). The second most common wish from farmers was that they would like to continue as usual, which was mostly expressed by non-users (31% versus 10% users). Other commonly cited interests were increased production (15% users, 17% non-users), new farming practices, including smart technologies (17% users, 12% non-users), and improved financial situation through support, credit, better and fixed rates, and lower input costs (24% users, 15% non-users).

4. Discussion

4.1. Alternative Circular Co-Concepts

Farmers manage their resources well. New resources need to be identified or the link between urban and rural areas strengthened, as there are sources in rural areas. The degradation of nutrients from agricultural soils by food creates nutrient sinks in urban areas, since plant nutrients are not absorbed by a healthy human body, but are excreted in the form of feces and urine, for example [18].

Innovative, alternative circular co-concepts are considered to be promising for hygienic uses as fertilizer and wastewater treatment, and therefore, they also have positive effects on the climate, which also applies to the use of urea-separated toilets [42–44]. Here, co-concepts such as co-compost have a higher potential for sustainable soil fertility management, compared to mono-compost [23].

Alternative co-recycling systems (systems that consider different waste streams simultaneously) for black water and organic waste to those in industrial cities, which are often resource-intensive and non-circular, also have the potential to reduce pollution and improve public health [43,44]. This points to the need for action in India and globally, to leapfrog conventional concepts and embrace alternative circular ones.

4.2. Co-Compost for Agriculture

Alternative co-cycle concepts that also recycle black water are suitable for sustainable soil management [23,32,42]. Many aspects can be positively influenced, such as phosphorus availability, the soil's ability to store plant-available nutrients and water, soil organic matter content, and soil pH, all of which result in improved soil fertility and crop yields [23,42]. Yield improvements from using co-compost are significant in India compared to chemical input materials [31,32], which can also be observed in other countries of the global South [23]. Economic profitability can also be given [21,45,46]. These aspects underline the results of this study. However, the effects on the amount of work and time as identified in other studies [23] could not be confirmed here. If the technical conditions are good, the microbial load can be reduced to a minimum, and the co-compost can be free of pathogen contamination [31,32]. On the other hand, if the pretreatment is inadequate, there is a risk of soil contamination [47,48].

This study shows that changes in water management and the increased use of chemicals are two major factors that have changed resource management in smallholder agriculture, mainly caused by climatic changes, the dependence on chemical resources, and their long-term unilateral use. This shows the need for resilient structures. There is a potential for alternative recycling concepts to increase agricultural resilience to environmental influences [1,29]. Promoting agricultural resilience through soil organic matter is critical in the face of climate change, as it contributes to water storage capacity and erosion resistance [23]. Research has shown that low-cost, circular approaches in India improve community resilience, reduce pollution, boost regional economies, and have positive impacts on waste and wastewater management [1]. This underscores our finding that smallholder agriculture has more resilient structures through the use of co-compost, which can have a positive impact during critical times such as pandemics. The impact of lockdowns on farmers in India varies widely due to differences in market infrastructure and regional regulations [49].

4.3. Attitude of Farmers

Farmers can appreciate these mentioned visible benefits of using co-compost [23]. The use of human excrement, on the other hand, is sometimes stigmatized [21]. The societal acceptability of farmers is determined, for example, by awareness, religiosity, income, source of income, and environmental attitudes, with an overall rather positive attitude of farmers towards recycling human waste [35,50]. Obstacles to co-composting are mainly due to fears of health risks, as well as socio-cultural/religious beliefs and odor nuisance, and furthermore, collection, transport, storage, and limited information on availability, with differences between rural and urban regions [34,35]. The lack of identification with the use of co-compost, and the uneasiness towards customers [34] could not be confirmed in the results of this study. The negative perceptions of the Farmer Producer Organization were mainly driven by factors such as an insufficient availability of information [34] that approximates our findings, as well as improved crop yields, soil health, and higher income [34,35] as the main motivations of farmers. It can also be seen that people who have used co-compost before or that know others who have used it do not have negative perceptions [34], pointing to the big factors of experience and demonstration. The many different aspects depending on the context and methodology [35] show that there are recurring factors that need to be discussed anew for each region, as they partially appear in our results when implementing new systems. On the other hand, the results of this study and numerous other studies contain factors that can be considered as central aspects, regardless of the region and the methodology.

In order to establish circular bio-economy concepts, it is necessary to understand the influences of farmer attitudes [50]. In order to take a step towards nutrient recycling in agricultural systems, it is imperative that farmers socially accept human excrement for their fields [35].

4.4. Communication Aspects

Communicating through participatory agricultural demonstrations, health campaigns, and participatory demonstrations could help increase knowledge, awareness, and social acceptance [35]. The keys are knowledge transfer, the mainstreaming of dissemination strategies, and promotion, and thus, the communication aspects of alternative circular bio-economy approaches such as co-composting, which play a role both in India and worldwide [21,23,25,34,50,51]. Moreover, local networks independent of co-compost are fundamental for knowledge transfer, but also for resilience against challenges [52], such as pandemic situations or climate change issues. Seeing and hearing about co-compost increases the acceptance of buying plants that have been fertilized with it [51]. Farmers would often not buy compost (in developing countries) as there is no obvious financial benefit, as chemical fertilizers are sometimes cheaper, while the demand automatically increases when farmers see the positive effects and benefits [23]. This shows that our results from Southern India can also be relevant for other regions.

4.5. Approach of the Methodology

The connection between agriculture and waste management is necessary to create sustainable concepts [23]. Further work is needed to understand different contexts, particularly in the least developed countries, where sanitation can easily be linked to resource recovery, the willingness to pay, and the identification of other benefits [35]. Holistic approaches are needed to understand the barriers to adaptation, and to address the motivations of smallholder farmers [29].

Various key indicators and barriers to adaptation that are deeply embedded in the sitespecific environments of farming communities show the need for the implementation of new circular economy concepts, and qualitative and quantitative data should be integrated to understand the local conditions [29].

This is an excerpt and cannot stand on its own. These results help to broaden the picture of smallholder farmer attitudes, which should be part of new circular concepts to be implemented, although further additions are needed. Therefore, the need for more combined holistic approaches is highlighted.

5. Conclusions

The current situation of smallholder farmers shows that they face many challenges, and that co-compost can significantly improve this situation, and thus, the resilience. Climate change and a dependence on chemical products affects smallholder farmers' resource management in terms of water and increased chemical use.

The use of these resources can be considerably reduced by using co-compost. Therefore, water is seen as significantly less of a problem by co-compost users. In addition, in the context of agricultural problems that arise during pandemics, local networks and local economies are particularly important for smallholder farmers.

Furthermore, the results of this study underline that knowledge transfer on visible benefits is necessary for disseminating and improving circular concepts, and partially for reducing personal and social reservations. The evaluation confirms that this has an impact on experience and openness, which also has an impact on the spread of other alternative approaches, possibly in other regions. This is reflected in the increasing willingness to try new agricultural practices.

This study also shows that there is good secondary resource management through recycling via smallholder farmers or other institutions and, thus, little potential for untapped resources from agriculture.

This again underscores the need for alternative circular approaches and the use of urban nutrient sinks that both create more resilient structures for smallholder farmers and make the waste and wastewater situation sustainable, thus also benefiting the environment and society. Consequently, the study shows that smallholder farmers have significant benefits using co-compost produced nearby, which represents a great opportunity for the implementation of sustainable circular approaches. Consequently, co-composting systems, and thus, co-recycling approaches, can help to achieve sustainability for the benefit of smallholder farmers in relation to SDG 2 "Zero Hunger", SDG 12 "Responsible Consumption and Production", SDG 13 "Climate Action", SDG 6 "Water and Sanitation", and SDG 11 "Sustainable Cities and Communities".

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