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Rwandan Farmers' Perceptions of the Acoustic Environment and the Potential for Acoustic Monitoring

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Abstract: Monitoring the farm acoustic environment can provide important information about processes affecting crop production. This paper assesses farmers' knowledge and attitudes toward acoustic technology for farm monitoring in Rwanda. Stratified random sampling was used to select 430 farmers from 3 sectors. Demographic, farm, and technical knowledge data were collected from farmers with a survey. Cross-tabulation results show farmers with secondary and university education are more interested in acoustic technology than those with a primary education and farmers engaged in commercial farming are more interested in technology for monitoring acoustic sources than subsistence farmers. However, nearly all farmers are willing to deploy a listening technology to monitor the acoustic environment. Farmers have a clear priority to listen to animals on the farm, whether they are pests (specifically, birds) or livestock. A chi-square test of independence indicates a significant relationship between farmers' consideration of technology for farm monitoring and their attitudes toward sound monitoring. Farmers want a technological solution, but demand that the solution be low-cost and provide a simple alert. The results inform system requirements for an Internet of Things acoustic network that can deliver this information to the farmer.

Keywords: sound; Internet of Things; farm; passive acoustic monitoring; Rwanda

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1. Introduction

Passive acoustic monitoring (PAM) has fairly wide applications in various natural and human environments, but, in most cases, the target of the acoustic signal analysis is a single species or a specific sound [1–4]. Analysis of the acoustic environment has also been studied, often from the viewpoint of assessing complexity [5–7]. In this paper, we used the term "acoustic environment", which includes all sounds present, unlike the term "soundscape", which consists of sounds perceived by humans. The complexity of the acoustic environment stems from the interaction of sources of sounds produced by animal species, plant species, human species, machinery, and the physical environment, which require a careful assessment to understand how they influence the ecosystem, biodiversity, and agricultural landscape. According to Robinson et al. [8], soundscape can reflect the biological communities within the soil, thereby indicating soil health. This association between the soundscape and soil health suggests the vital role of the acoustic environment in agriculture production. Similarly, Sethi et al. [9] opined that the relationship between soundscape and biodiversity can potentially predict species' presence in the agricultural landscape. Further, human activities, including machine operation, farming, and urbanization, may affect biological acoustic presence [10]. Understanding the dynamics of the acoustic environment in the agricultural ecosystem may provide potential critical information for production and management.

Rwanda's economy is largely driven by the agriculture sector, providing about 30% growth to Gross Domestic Product (GDP) [11–14]. The sector contributes to revenue through crop yields, market access, export, and the implementation of government policies [15,16]. It is worth noting that nearly 83% of the agriculture production is by smallholder farmers, per https://rdb.rw/investment-opportunities/agriculture/ (accessed on 21 October 2024). The agriculture sector alone employs nearly 65% of the growing population [14]. The employment opportunities are boosted by the integration of farmer cooperatives to access funding for farm production [17,18]. Recently, government policies have been instituted to integrate technology into the agriculture sector to boost production for food security [19]. This explains the important role of the agriculture sector in the economy of Rwanda, and efforts are being made to invest in the sector for sustainability, in line with UN Sustainable Development Goal 2 (SDG 2) [20].

The potential contribution of the acoustic environment to agricultural production is little researched, but is a potentially valuable application of monitoring the acoustic environment [1,21]. This paper presents a survey of Rwandan farmers' knowledge and attitudes toward the acoustic environment of their farms. This assessment was undertaken to guide the development of passive acoustic sensing systems using Internet of Things (IoT) principles to capture information that farmers can use to help manage their farms.

The acoustic environment is the blend of every sound present. Sources like rain and wind are called geophony, animals and plant sources are called biophony, and sounds from man-made objects and activities such as machines are called anthrophony [2,4,22–26]. Acoustic monitoring studies have largely focused on bird population density, habitat changes, and the general behavior of endangered species for conservation using microphones [2,4,22,27]. The field of bioacoustics uses PAM to study individual species and their behavior in the rainforest, for example, [22,23,27]. In one of the few studies on sound in agriculture, Doohan et al. [1] recommended that acoustic monitoring should focus on birds and bats because they are easy to monitor for farm management. They further stated that PAM monitoring can potentially provide consistent, repeated, and reliable results, as opposed to traditional biodiversity monitoring, which is geared toward tracking sustainability. Plants also have the chance to benefit from sound waves that can protect them against unfavorable conditions [28]. These studies have suggested that acoustic monitoring has the potential to provide substantial information for agriculture production but failed to consider the other sources of sounds in the agricultural landscape. The holistic monitoring of the acoustic environment has the potential to provide substantial benefits for more effective management in any context, including agriculture. However, most prior applications of acoustic monitoring in farm environments have been for specific targets such as livestock assessment [29–32] or the acoustic detection of insect pests [33,34]. Despite the interest in acoustic monitoring being on the rise, there is limited research on farmers' knowledge and perception of the acoustic environment and on the significant role that the acoustic environment plays in agricultural production. Understanding farmers' willingness to adopt acoustic monitoring technologies is vital for their design and implementation. Assessing farmers' knowledge and perception of the acoustic environment will ensure the provision of tailor-made technologies to meet their preferences.

This study's objectives are to explore farmers' knowledge and perceptions of the acoustic environment on the farm by identifying acoustic sources that they experience, their importance to farm practices, and their impact on farm production. Further, the study seeks to investigate farmers' willingness to adopt acoustic monitoring technologies to enhance farm management.

The development of sensor network systems for the passive acoustic monitoring of farms potentially creates a large volume of data that need to be converted to information for effective farm management. To help design sensor network systems and data analysis workflows, we need to, first ,understand whether the farmers would even consider using the technology; second, their priorities for data gathering; and, third, how they want to receive the information derived from the data. In this paper, we describe the results of a survey designed to examine factors related to the feasibility of applying passive acoustic technology on Rwandan farms and to understand which sounds farmers believe are important to determine which information should be extracted from the data.

The remainder of this paper is organized as follows. Section 2 describes the methods and tools used for data collection as well as the software for analysis. In Section 3, we present results with tables and graphical illustrations. Section 4 is where we discuss the outcomes, and, in Section 5, we conclude our findings and make projections for future research.

2. Materials and Methods

The survey was conducted in the Bugesera District of the Eastern Province in Rwanda. Bugesera District was chosen because of the high number of residents engaged in agriculture and the wide variety of crops grown in the district (MINAGRI-TECAN) [14]. Moreover, the Bugesera District is rapidly developing due to government investment devoted to making Bugesera District one of the agricultural hubs of Rwanda, turning what once looked like a desert into an income-generation zone. The district has a farmer population of 45,125, cultivating maize, beans, vegetables, rice, groundnuts, and tomatoes, among other crops, at the time of the farming season (statistics from Bugesera District Office). In consultation with the Directorate of Agriculture, three out of fifteen sectors were selected for the survey: Mareba (2.13° S, 30.03° E), Nyamata (2.09° S, 30.04° E), and Mayange (2.13° S, 30.11° E). The Directorate stated that the farming population varies per season.

The sampling size was determined based on the methodology proposed in [35–37], i.e., Equation (1):

$$n = \frac{p(100-p)z^2}{E^2}, \quad (1)$$

therefore, the minimum representative sample is 385, but greater sample sizes will improve any inferences from the data [38]. The sample size for this survey was 430. Most farmers in Rwanda belong to a cooperative. Therefore, stratified random sampling was used to obtain adequate information that was representative of the population parameters [38,39]. Stratified random sampling ensures that each group is sufficiently represented and serves the purpose of the study. We obtained a list of 17 cooperative leaders from the district office. We visited each cooperative and explained the rationale for the research. All the cooperative leaders expressed interest in participating in the study. We obtained a list of cooperative members and sampled 25 members from each cooperative through simple random selection, for a total of 425 farmers. Further, five extension officers (agronomists) who expressed interest in the research responded to the questionnaire because they also farm and they train other farmers on new farm practices. The questionnaires were administered to the sampled respondents. Responses were recorded electronically in Google Forms. For those who could not read and write English, two enumerators were engaged to administer the questionnaires in the collection of the data. For the quality control of the entered responses, the authors sometimes accompanied the enumerators to the farms to assess whether the recorded responses matched the translated verbal response. The responses from all three sectors of the district were analyzed together.

Before the administration of the full survey, a prototype questionnaire was designed and tested in April 2022 by visiting about 25 farmers. This questionnaire had 18 items, comprising 14 open-ended and 4 close-ended questions. The pilot test was conducted by visiting farmers and administering the questionnaire face-to-face to ensure that the items captured the intended information effectively for our study [38,40]. Respondents mentioned birds, monkeys, frogs, running water, rain, wind, machines, insects, and people as sources of sounds experienced on the farm. Farmers also indicated that these sound sources have different impacts on farm production. Rain and running water were indicated as supporting crop growth, while birds, insects, frogs, rodents, and farm animals were described as pests to the crops. Some indicated that strong wind can also destroy the crops, depending on the stage of growth. Farmers indicated perceived sounds on the farm, which guided the reconstruction of the questionnaire into a final form with different options for the multiple-response items.

After making adjustments to suit the study's objective, the final questionnaire consisted of 26 questions (Supplementary S1). The questionnaire items were constructed by the authors for this study, as there was no survey research on this subject in Sub-Saharan Africa per our knowledge and search of the literature. The design of the questionnaire allowed us to elicit first-hand information from the respondents to guide the formulation of acoustic solutions. The questionnaire was made up of 13 close-ended items, 7 open-ended items, and 6 multiple-response items. There were 4 question categories: the first is general information about the farmer and the farm, the second contains questions about farmers' perceptions of acoustic signals present on their lands, the third has questions on what farmers monitor and the methods employed, and the fourth has questions about the farmers' use of technology. The general information questions provided responses about gender, age, educational level, crops cultivated on the farm, and farm size, as well as monitoring methods employed on the farm. Questions about the acoustic signals focused on farmers' perceptions of sounds experienced at the farm, the sources of the acoustic signals, and whether the acoustic sources have some effect on farm production. The farmers were asked about the importance that they attach to sound and at what time or season the acoustic sources were present. The questions on farm monitoring were asked to identify what farm processes have the greatest importance to the farmers and the methods that they used to understand or act on those processes. The technology questions focused on farmers' use of technology in monitoring their farms and specifically whether they would consider acoustic technology if it was available.

The questionnaire was administered in the three sectors in the period 4 May to 25 June 2022, corresponding to the beginning of the harvest period for the first of the two annual growing seasons. The dataset, including the responses and variable codes, are available at https://figshare.com/articles/dataset/Farm_Acoustic_monitoring_Survey_dataset/24310495?file=46382674.

Prior to analysis, data cleaning was performed by removing cases where there was no response or inconsistent or incomplete response. These cases occurred mostly for the open-ended questions. Therefore, some open-ended questions did not have all 430 responses. Answers to open-ended questions were categorized into similar responses for analysis. A nominal scale was employed to facilitate the collection of relevant data from the farmers. The nominal scale is useful for understanding categorical data and making inferences [41]. The analysis of data was carried out using the R software package version 4.2.1 [42,43].

Packages such as tidyverse, dplyr, gt, and lessR in R were employed to perform all analysis because they provide a comprehensive collection of tools for statistical analysis (see Supplementary S2) [44]. Frequency tables and cross-tabulation tools were used to provide a descriptive summary of the data and help infer trends and characteristics of these categorical data. Descriptive statistics are tools used to provide an efficient summary of survey data by describing the relationship between the variables [41,45–47]. Cross-tabulation is a useful tool for discovering and establishing relationships between variables in the entire dataset, including subgroups that might go without notice [48]. Bar charts or graphs were used to visualize the data to assess the trends and discover the information that farmers deem important. The chi-square test (χ^2) and Fisher's exact test were applied to assess the statistical validity of some specific responses. These statistical tools are robust in determining the association and relationship between categorical variables [49,50]. These tests are vital in understanding the relationships within the data for potential solutions for developing acoustic technology for monitoring the acoustic environment of the agricultural landscape.

3. Results

3.1. General Information About the Farmers and the Farms

The general information about the farms and the demographic information of the participants are provided in Table 1. About 98% of the farmers are more than 20 years of age. The female population involved in farming was about 43% (184) vs. 57% (246) male counterparts. Out of 430 respondents, 287 (67%) had only received their primary education, 95 (22%) had received up to secondary education, and 47 (11%) had received a university education.

Table 1. Distribution of the demographic and farm information.

	Variables	Frequency	Percentage (%)
Educational Level [1]	Primary	287	66.9
	Secondary	95	22.1
	University	47	11.0
Age	>20	422	98.1
	≤20	8	1.9
Gender	Male	246	57.2
	Female	184	42.8
Type of Farming System	Both (Commercial and Subsistence)	298	69.3
	Subsistence	92	21.4
	Commercial	40	9.3
Farm Size in Hectares	<1	367	85.3
	1 to 5	62	14.4
	>5	1	0.2

Source: Survey data collected by the authors, 2022. [1] Number of respondents is 430; however, 429 responded to educational level item.

About 69% (298) of participant farmers practice both commercial and subsistence farming, while 21% (92) and 9% (40) practice only subsistence or commercial farming, respectively. Therefore, most farmers derive some level of income from their farm products. The size of farm plots is largely less than 1 hectare, as declared by about 85% (367) of the respondents; 14% (62) indicated plot size between 1 and 5 hectares, and there was a single farm greater than 5 hectares.

Next, we examined responses to the questions about the crops cultivated by the local farmers (Figure 1). The most common food crops that the farmers reported were maize, tomatoes, rice, cassava, and bananas. The district agronomist stated that farmers make decisions about which crops to cultivate each season, relying on the timing of the seasonal rains and the availability of subsidies for inputs, which are provided by government partners and aid donors. The government partners include the Ministry of Agriculture and Animal Resources (MINAGRI), Rwanda Agriculture and Animal Resources Board (RAB), and the Ministry of Finance and Economic Planning (MINECOFIN). Maize is the most common crop, cultivated by about 26% of the farmers. The large majority of farmers grow one crop per season, likely due to the prevalence of small farm sizes.

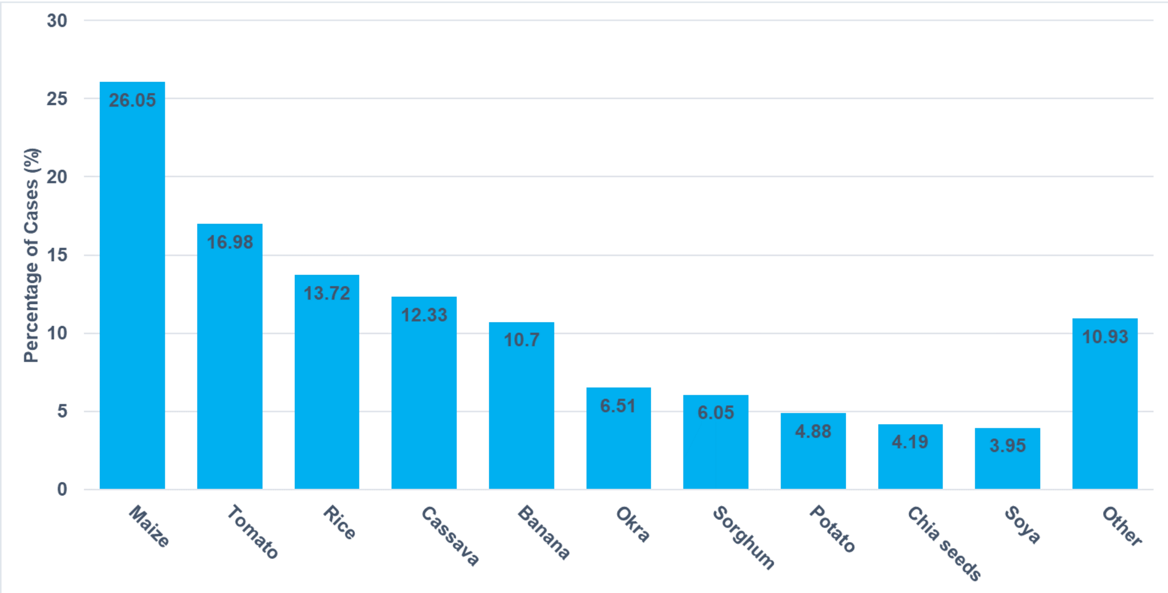

Figure 1. Crops that farmers cultivate in the catchment area. **Source**: Survey data collected by the authors, 2022.

3.2. Farmers' Perceptions of Acoustic Signals Present on Their Lands and Their Importance

The series of questions about sound helped us to assess the farms' acoustic environment. The questions were both to assess the presence of acoustic sources and to discern the importance that farmers attach to a particular sound. Of the 430 respondents, 95.6% (411) experienced a variety of sound activities on the farm, while 2.3% (10) stated they have not experienced any such acoustic signals. Further, 2.1% (9) were not sure whether sound activities exist on the farm or not. The distribution of various sources of sounds on the farm have been categorized into the three components of the acoustic environment: biophony, geophony, and anthrophony (Figure 2). The figure illustrates the percentage of cases regarding each source of acoustic activity, which sum to more than 100% because farmers could describe more than one sound source. Taken as a whole, farmers' responses indicated 65% of the sources to be biophony, 18% to be geophonic sources, and 17% to be anthrophony.

The most common sources of sound were birds, farm animals, and people (Figure 2). Birds were the most frequent source, with 76.51% of farmers indicating that bird activity on farms is common and important. Farm animals and people were the second-most frequent source of sound on the farm, with 38.6% for both cases. The remaining cases of insects, rodents, plants, frogs, monkeys, and bats were also identified as sources of acoustics on the farm, but to a decreasing extent, in 25.35%, 17.44%, 5.12%, 5.81%, 0.93%, and 0.47% of cases, respectively. The geophonic acoustic sources cited by farmers were wind, rain, and flowing water, in 21.16%, 18.14%, and 8.6% of cases, respectively. The main anthrophony source was people talking (38.6%), while machines were mentioned by only 7.91% of farmers.

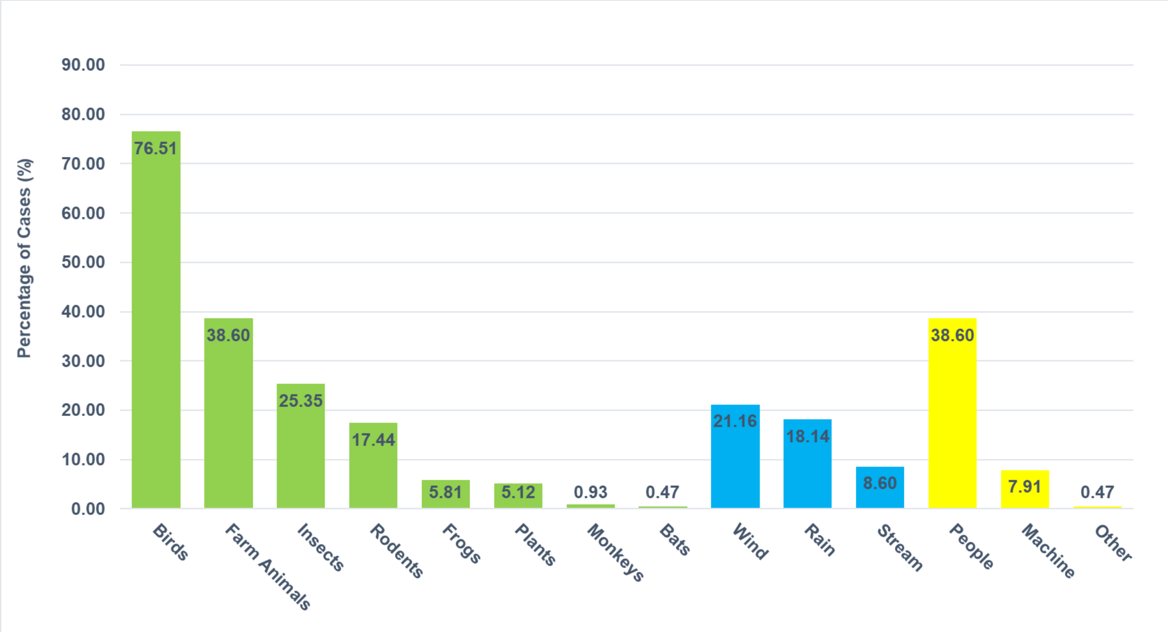

Figure 2. Distribution of acoustic sources that farmers experience on the farm. The values of responses are in percentage of cases and categorized as biophony (green), geophony (blue), and anthrophony (yellow). **Source**: Survey data collected by the authors, 2022.

The responses represented in Figure 3 were derived from questions aimed at investigating the acoustic sources that farmers would monitor on their farms, given access to a listening technology. Participants were asked to select all the acoustic sources that they would monitor from a list of 14 options (see Supplementary S1), which resulted in 586 responses in total. The options were derived from the responses that farmers provided during the prototype stage.

Of the 430 respondents in each of the cases, 234 (54%) suggested bird sounds as the most frequent to monitor. Farm animals constitute the second-most common acoustic source with 112 (26%) cases. Rodents and insects were also mentioned to be monitored, with 50 (12%) and 43 (10%) cases, respectively. The least common biophonic acoustic sources that farmers would wish to monitor were monkeys and bats, which a single farmer identified in each case. Rain was the most frequently mentioned geophony source of sound that farmers expressed interest in monitoring; however, this source was only in 6% of cases. Some farmers would monitor wind (5.6%) and flowing water through drainage canals (1.2%), given the technology. In terms of anthrophony, people would be the most common source of sound to monitor, with 12.6% of cases, while machine sources of sound comprised 1.6% of cases.

Open-ended questions were asked to investigate the impact of the acoustic sources on the farm (Figure 4). While a sizable number of respondents expressed concern about the negative effects of acoustic sources on the crops, a few indicated that there are positive effects on farm production. Of the 430 respondents, 173 (40%) reported that acoustic sources have no impact on their farm operations and production, 146 (34%) reported yield loss, and 87 (20%) reported pest attacks. Out of the other 24, 2% indicated that acoustic sources contribute to crop growth such as rain, 1% indicated harvest time for some plants, and 3% were uncertain about the impact of acoustic sources on the farm. In summary, we found that about 54% of the respondents linked yield loss and pest attacks; however, 40% (173) of the respondents stated that acoustic sources have had no impact on farm production. Only a handful have indicated that acoustic sources have positive effects.

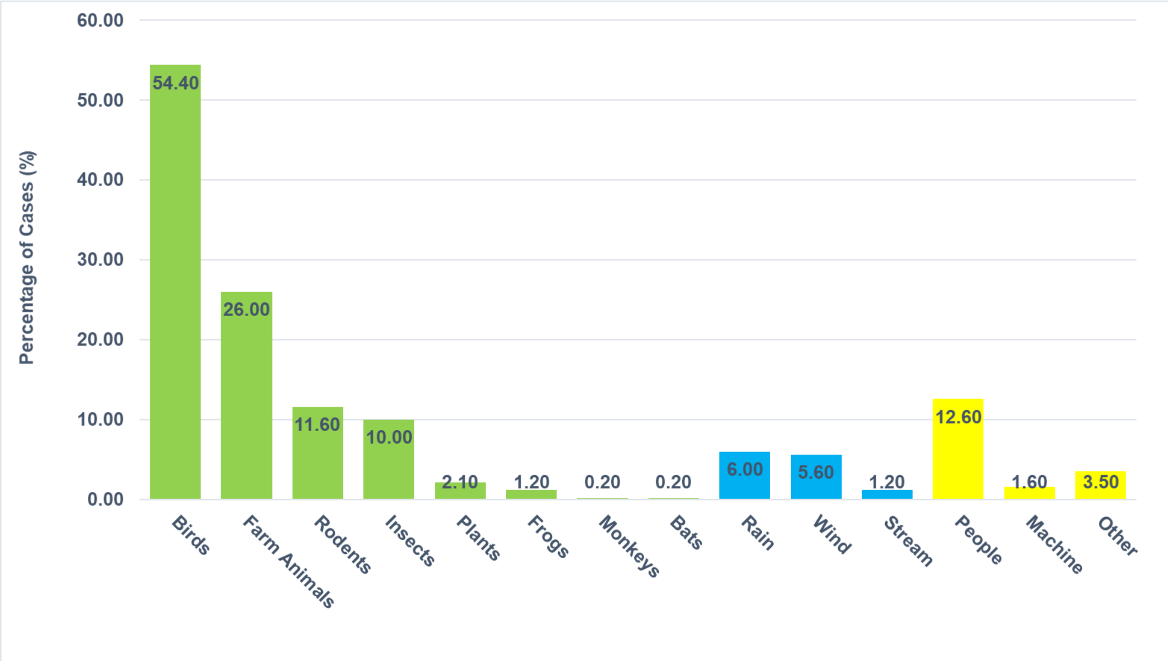

Figure 3. Distribution of specific acoustic sources that farmers would monitor if they had a listening technology. The colors represent biophony (green), geophony (blue), and anthrophony (yellow). **Source:** Survey data collected by the authors, 2022.

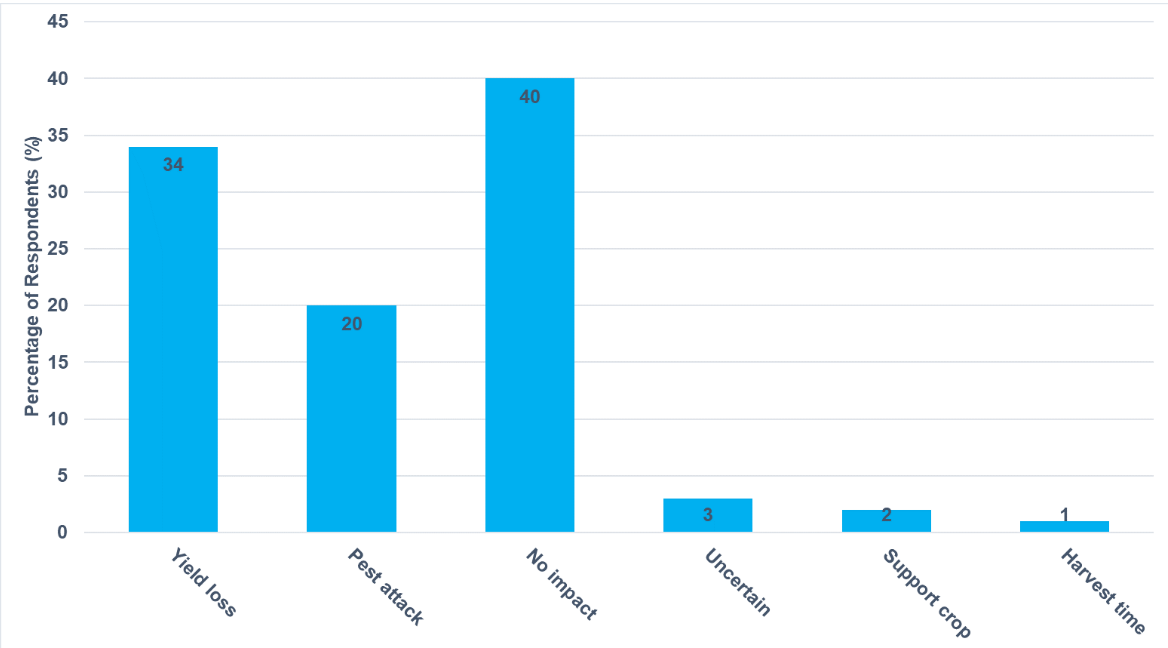

Figure 4. Farmers' responses to an open-ended question about the importance of acoustic sources on the farm. This figure shows the categories of responses provided by the farmers. Notably, the 40% (173) that indicated that acoustic sources have no impact on the crops on the farm might not have understood the item. **Source:** Survey data collected by the authors, 2022.

When farmers were asked about the active periods during which acoustic events are most noticeable, approximately 32.20% (236) indicated morning, whereas 27.56% (202) specified afternoon. Only 11.05% (81) alluded to evening, and about 29.20% (214) responded that acoustic events occur at all times of day.

3.3. Farm Monitoring Methods

Two further questions were asked to investigate what the farmers monitor and the methods that they employ in monitoring activities of interest (Supplementary S1). The 389 farmer respondents revealed that 45% monitor whether farm practices are yielding the expected results, 48% were interested in whether there were pest and disease attacks, and 6% spent time checking for weeds among the crops for control measures (Figure 5). The remaining 1% check for activities of other individuals who might steal the mature crops. The results also revealed that 52% (225) of the farmers monitor their farms while 48% (205) do not monitor. Those farmers who reported monitoring the farm use methods such as visiting or calling neighbor farmers that they assumed to be on the farm, sending their children to check on the farm, or relying on farm hands to obtain information about the farm.

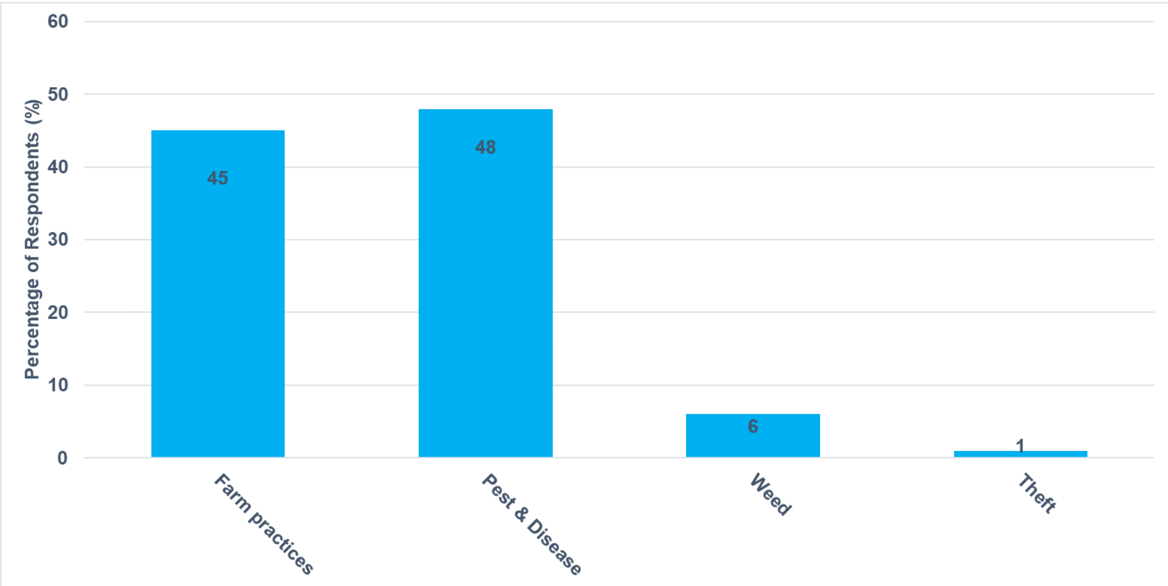

Figure 5. Activities farmers claimed to have been monitoring when they responded to the open-ended question, "What do you monitor on your farm"? Farmers are mainly interested in finding out if there is a pest and disease attack or whether the farm practices put in place are working as expected. A few are interested in whether weeds have grown to compete with the crops so they could take control measures. **Source:** Survey data collected by the authors, 2022.

3.4. Farmers' Opinions on the Use of Technology in Farm Monitoring

The responses to survey questions about whether farmers see a role for technology in monitoring the farm and why helped us to understand their needs (Supplementary S1). Fisher's exact test was conducted to explore the relationship between farmers' consideration of technology for farm monitoring (question 10 with a "yes" or "no" answer) and the reasons for their choices (question 11, positive response categories and negative response categories). The results revealed a significant association between considering technology for farm monitoring and the reasons given ($p < 0.001$). Among the farmers who considered using technology for farm monitoring (n = 197), the primary reasons were "quality control" (n = 56), "timely information" (n = 102), and "increasing yield" (n = 39). In contrast, those who did not consider using technology (n = 213) largely cited "no technology" (n = 138), "capital intensive" (n = 51), and "No technical skills" (n = 24) as reasons (Table 2). The significant associations highlight the differing factors influencing farmers' decisions regarding technology adoption. For those who do not consider technology, the perceived high costs (capital intensive) and lack of technology usage are key barriers. Farmers who consider technology expressed an awareness of the potential benefits of technology in their responses.

Table 2. Contingency table with Fisher's exact test of association between consideration for technology use and reasons.

	Reasons for Considering Technology Use						
Consider Technology Monitoring	**No Technical Skill**	**Capital Intensive**	**No Technology**	**Increase Yield**	**Quality Control**	**Timely Information**	**Total**
No	24	51	138	0	0	0	213
Yes	0	0	0	39	56	102	197
Total	24	51	138	39	56	102	410
Test	p						
Fisher's exact test	<0.001						

Source: Survey data collected by the authors, 2022.

A chi-square test of independence (Table 3) was conducted to assess the relationship between farmers' consideration of technology for farm monitoring (question 10) and their attitudes toward sound monitoring (question 16). The results indicated a significant association between these variables ($\chi^2(2, N = 410) = 7.422, p = 0.024$). Among farmers who consider using technology for farm monitoring (n = 197), a significant majority are interested in sound monitoring (Yes, n = 189), with very few expressing uncertainty (Maybe, n = 3) or opposition (No, n = 5). Interestingly, among those who did not consider using technology for monitoring (n = 213), a similar proportion do use sound monitoring (n = 189), with some expressing opposition (No, n = 16) or uncertainty (Maybe, n = 8). In summary, a large majority (92%) of farmers do use sound for monitoring the farm and approximately half of those are likely to accept the technological solution.

Table 3. Contingency table with chi-square test showing relationship between farmers' consideration for technology and sound monitoring.

	Sound Monitoring			
Consider Technology Monitoring	**Yes**	**No**	**Maybe**	**Total**
Yes	189	5	3	197
No	189	16	8	213
Total	378	21	11	410
Test	Value	df	p	
χ^2	7.422	2	0.024	

Source: Survey data collected by the authors, 2022.

3.5. Tables of Cross-Tabulation Results

We assessed the level of education with respect to gender to enable us make a judgement of decisions that farmers make for production. Of the 287 farmer who had only primary education, 58.5% were male while 41.5% were female. In the secondary category, 45.3% were males and females were 54.7%, whereas 74.5% males and 25.5% females were in the university education category. A single female farmer had no education at all (Table 4).

Table 4. Cross-tabulation distribution of farmers' gender and education level. The whole number is the number of respondents and the numbers in parentheses are the proportion of respondents.

	Educational Level				
Gender	**Primary**	**Secondary**	**University**	**N/A**	**Total**
Female	119 (0.415)	52 (0.547)	12 (0.255)	1 (1.000)	184 (0.428)
Male	168 (0.585)	43 (0.453)	35 (0.745)	0 (0.000)	246 (0.572)
Total	278 (1.000)	95 (1.000)	47 (1.000)	1 (1.000)	430 (1.000)

Source: Survey data collected by the authors, 2022.

Examining open-ended questions on what critical activities or events farmers monitor and the method employed, Table 5 shows a cross-tabulation of the respondents' claims about whether they monitor the farm in their absence against the method employed. Out of 225 (52.3%) farmers who said they actively monitor their farms, 59 (26.2%) use either a phone call to a neighbor or a site visit, 57 (25.3%) rely on farm hands, and 18 (8%) send children to report back. The remaining 91 (40.4%) failed to respond to the question on what method they used; 205 (47.7%) farmers stated they did not actively monitor their farms.

Table 5. Cross-tabulation distribution of farmers' gender and education level. The whole number is the number of respondents and the numbers in parentheses are the proportion of respondents.

	How Do You Monitor?				
Do You Monitor Your Farm?	**Call/Visit**	**Send Children**	**Farm Hands**	**No Method**	**Total**
Yes	59 (26.2%)	18 (8.0%)	57 (25.3%)	91 (40.4%)	225 (100%)
No	-	-	-	205 (100%)	205 (100%)
Total	59(13.7%)	18 (402%)	57 (13.3%)	296 (68.8%)	430 (100%)

Source: Survey data collected by the authors, 2022.

In addition, a cross-tabulation statistic (Table 6) revealed farmers with a higher level of education are more likely to positively respond when presented with the opportunity to apply acoustic technology for monitoring their farms than farmers with primary education. The result showed 70.5% of farmers with secondary education and 53.2% with a university education demonstrated interest in using acoustic technology to monitor their farms. In contrast, only 36.6% of the farmers with solely primary education considered technology for monitoring farm activities when presented with the option. A small number of the farmers (4.4%) have not indicated whether they would consider using acoustic technology for monitoring farms. Also, there are more women than men who considered the use of technology to monitor their farms, as 50% of the female respondents indicated yes compared to 42.7% of the male respondents.

Further cross-tabulation results revealed the type of farming (commercial, subsistence, or both) has some influence on the interest of farmers to use technology. Farmers who are engaged in commercial farming (62.5%) were more interested in using technology for monitoring their farms than subsistence farmers (17.4%) (Table 7). About 70.7% of subsistence farmers have not considered using technology for monitoring their farms.

Table 6. Distribution of farmers' responses about using technology to monitor farms based on their educational achievement. The whole number is the number of respondents and the numbers in parentheses are the proportion of respondents.

	Educational Level			
Consider Technology	Primary	Secondary	University	Total
No	168 (0.585)	25 (0.263)	20 (0.426)	213 (0.497)
Yes	105 (0.366)	67 (0.705)	25 (0.532)	197 (0.459)
N/A	14 (0.049)	3 (0.032)	2 (0.043)	19 (0.044)
Total	287 (1.000)	95 (1.000)	47 (1.000)	429 (1.000)

Source: Survey data collected by the authors, 2022.

Table 7. A cross-tabulation distribution of farmers' consideration for using technology to monitor the farm. The whole number is the number of respondents and the numbers in parentheses are the proportion of respondents.

	Type of Farm			
Consider Technology	Both (Commercial and Subsistence)	Commercial	Subsistence	Total
No	134 (0.450)	14 (0.350)	65 (0.707)	213 (0.495)
Yes	156 (0.523)	25 (0.625)	16 (0.174)	197 (0.458)
N/A	8 (0.027)	1 (0.025)	11 (0.120)	20 (0.047)
Total	298 (1.000)	40 (1.000)	92 (1.000)	430 (1.000)

Source: Survey data collected by the authors, 2022.

It is also evidently clear that more farmers with secondary education attainment are engaged in both commercial and subsistence farming (77.9%) than only commercial (11.6) or subsistence (10.5%) (Table 8). The same observation is made for those farmers who have attained a university education.

Table 8. Farmers' educational level against the type of farming. The whole number is the number of respondents and the numbers in parentheses are the proportion of respondents.

	Type of Farm			
Educational Level	Both (Commercial and Subsistence)	Commercial	Subsistence	Total
Primary	208 (0.725)	15 (0.052)	64 (0.223)	287 (1.00)
Secondary	74 (0.779)	11 (0.116)	10 (0.105)	95 (1.00)
University	16 (0.340)	14 (0.298)	17 (0.362)	47 (1.00)
Total	298 (0.695)	40 (0.093)	91 (0.212)	429 (1.00)

Source: Survey data collected by the authors, 2022.

We assessed the crops cultivated by the farmers against the acoustic sources that they are interested in monitoring. The cross-tabulation revealed that birds are the acoustic source of greatest interest to many farmers, especially rice farmers (85.9%). Bird monitoring was also important for large fractions of farmers growing chia seeds (56.5%), tomato (52.4%), maize (38.2%), sorghum (37.8%), and soya beans (28.1%) (Table 9). After soliciting these initial questions about sound, 92.3% of the farmers identified sound as a means of monitoring the farm environment.

Table 9. Distribution of the crops and the acoustic sources that farmers would monitor with acoustic monitoring technology. The whole number is the number of respondents and the numbers in parentheses are the proportion of respondents for that crop.

	Acoustics Sources Farmers Want to Monitor													
Crop	**Farm Animal**	**People**	**Bird**	**Frog**	**Rain**	**Insect**	**Monkey**	**Wind**	**Machine**	**Plant**	**Rodent**	**Running Water**	**Other Sources**	**Total**
Maize	47 (0.236)	18 (0.090)	76 (0.382)	0	18 (0.090)	12 (0.060)	1 (0.005)	8 (0.040)	6 (0.030)	3 (0.015)	4 (0.020)	1 (0.005)	5 (0.025)	199
Potato	5 (0.147)	3 (0.088)	4 (0.118)	0	1 (0.029)	4 (0.118)	0	4 (0.118)	2 (0.059)	1 (0.029)	9 (0.265)	0	1 (0.029)	34
Rice	2 (0.031)	1 (0.016)	55 (0.859)	0	1 (0.016)	0	0	0	1 (0.016)	0	0	4 (0.063)	0	64
Sorghum	6 (0.133)	5 (0.111)	17 (0.378)	0	2 (0.044)	2 (0.044)	1 (0.022)	2 (0.044)	3 (0.067)	1 (0.022)	5 (0.111)	0	1 (0.022)	45
Cassava	18 (0.205)	13 (0.148)	13 (0.148)	0	5 (0.057)	3 (0.034)	1 (0.011)	5 (0.057)	5 (0.057)	2 (0.023)	20 (0.227)	0	3 (0.034)	88
Banana	21 (0.276)	13 (0.171)	15 (0.197)	0	2 (0.026)	4 (0.053)	1 (0.013)	9 (0.118)	3 (0.039)	2 (0.026)	3 (0.039)	0	3 (0.039)	76
Tomato	4 (0.038)	4 (0.038)	55 (0.524)	4 (0.038)	4 (0.038)	17 (0.162)	0	3 (0.029)	5 (0.048)	2 (0.019)	4 (0.038)	0	3 (0.029)	105
Chia seeds	2 (0.087)	2 (0.087)	13 (0.565)	0	1 (0.043)	0	0	4 (0.174)	0	1 (0.043)	0	0	0	23
Okra	8 (0.182)	6 (0.136)	3 (0.068)	1 (0.023)	3 (0.068)	15 (0.341)	0	0	1 (0.023)	2 (0.045)	2 (0.045)	0	3 (0.068)	44
Soya beans	9 (0.281)	2 (0.063)	9 (0.281)	0	1 (0.031)	3 (0.094)	0	1 (0.031)	1 (0.031)	4 (0.125)	1 (0.031)	0	1 (0.031)	32
Other	12 (0.250)	8 (0.167)	5 (0.104)	0	0	3 (0.063)	0	3 (0.063)	0	0	12 (0.250)	0	5 (0.104)	48
Total	134	75	265	5	38	63	4	39	27	18	60	5	25	758

Source: Survey data collected by the authors, 2022.

The final questions in the survey asked technology-related questions about the design and implementation of an acoustic monitoring system. Concerning the expectations of the farmers regarding what the system might do for their farm, the farmers overwhelmingly responded that the acoustic monitoring system should send them an alert. About 98% (423) indicated a preference to receive system alerts and information via mobile phone in the form of a Short Messaging Service (SMS). All farmers possessed a mobile phone, of which 61% (260) were non-smartphones (feature phones) and the remaining 39% (170) were smartphones.

4. Discussion

To summarize our findings, the survey found that smallholder farmers are engaged in both subsistence and commercial farming, even though the farm sizes are small. The study found that the acoustic environment provides vital information for understanding the dynamics of the farm landscape to inform decision-making. Different acoustic sources in the farm environment require specific attention to improve farm production. Farmers are generally willing to employ acoustic technology for efficient farm monitoring since farmers believe that monitoring pests with acoustic technology can help improve farm production by providing timely information to improve control measures and increase yield. However, farmers have concerns about "no known technology", "no technical skills", and the cost of monitoring technology as the limiting factors for their inability to use technology for monitoring the farm. Education also influences farmers' decision to employ technology for monitoring the farm environment. The cost of investing in technology was found to be one of the limitations to smallholder farmers' adoption of technology in agriculture. Next, we discuss some specific details of our analysis.

The demographic data of the sampled respondents show that most farmers (67%) in the three sectors have only primary education, with 22% having secondary education and 11% having attained university education. According to the National Institute of Statistics of Rwanda [51], at the national level, 69% of households are engaged in some agriculture activities, consistent with our finding for Bugesera District, where 66% of households are in agriculture production. The results show that older men with only a primary education are most engaged in farming as their main source of income and livelihood, perhaps as a consequence of not having any other skills. A lot more female respondents had secondary education than their male counterparts (Table 4), but they could not continue to the university level, which is mostly linked to financial limitations. Furthermore, individuals with higher levels of educational attainment (secondary and university combined) are engaged in some aspect of commercial farming, while farmers with only a primary education are engaged mostly in subsistence farming (Table 8). Formal education, therefore, plays a substantial role in the choice of decision for farm production. Our survey found that 47 (11%) of the respondents with a university education are engaged in some farming activities, suggesting that they are supplementing other sources of livelihood, perhaps because they are yet to find a non-agricultural job. It was also found that most farmlands are less than one hectare (ha) in size, which makes it difficult for farmers to engage in significant commercial farming (Table 1). According to MINAGRI-TECAN [14], lands are allocated for agricultural use but the growth of the rural population drastically reduced farmland, and this resulted in small farm sizes for each farmer. At least one in four farmers are also engaged in livestock farming, as indicated by 26% of respondents who expressed their interest in monitoring farm animals (Figure 3). There are more male (57%) than female (43%) farmers, while the 2022 population and housing census in Rwanda showed that 52% of the population is female [51]. This percentage of female farmers is typical of Africa [52], as women strive to contribute to the food basket in the sub-region. The farmers of the three sectors cultivate a variety of cereals, legumes, tubers, fruits, and vegetables. However, the choice of crop to cultivate depends largely on seasonal rains and subsidies on inputs. Even though farmers cultivate a variety of crops (Figure 1), maize is the most popular in the area of study. This is consistent with other findings that maize is the most common grain farmed by people in Sub-Saharan Africa and that it is vitally important for food security [53–56].

The farm environment exhibits a variety of acoustic sources, both natural and man-made. These sounds include bird songs or calls, mammal calls, machine operations, weather patterns like wind, rain, and thunderstorms, and even the sound of water running through drainage canals. Farmers recognize that they can perceive these acoustic sources on their farms (Figure 2). Further, 54% of the farmers (Figure 4) identified that yield loss and pest attacks are linked to the acoustic environment of the farm. Thus, the farmers were able to relate some acoustic sources to yield loss. The results demonstrate the importance of biophonic sources to the farmers and the dominance of birds as their primary interest (Figure 3). This further suggests that farmers are interested in monitoring birds in the farm environment. Follow-up discussions and observations found that farmers employ some traditional methods to scare birds away. A specific finding of the survey suggests that, if an acoustic monitoring system is available, these farmers will monitor the acoustic environment for pests on the farm (Table 9) [57–59]. The results also suggest that acoustic sources are more noticeable during the morning hours than in the afternoon and evening. A large fraction (29.2%) of farmers indicated that acoustic events are always present on the farm. The implication is that, for monitoring to be effective, it must be continuous. Farmers discussed employing traditional methods such as scarecrows, children, and farm hands to scare birds away. The results confirm that farmers do not use any technology to monitor the acoustic environment of their farms.

Although birds are the clear priority, a number of farmers are also interested in monitoring other sources such as farm animals, rodents, insects, and people (Figure 3). However, relatively few farmers are interested in monitoring geophony and anthrophony sources, other than the presence of people. The farmers indicated that people other than the farmers commit theft and, thus, they need to monitor their activities for security reasons. A substantial number of farmers (173) responded that the acoustic environment of the farm has no impact on farm production (Figure 4). These farmers may be those who cultivate tubers, bananas, and other crops that may not have pests creating obvious sounds (Table 9). Moreover, these farmers may not have perceived the question well and, indeed, 81% of those 173 farmers had only primary education. These farmers may not have thought about weather as an acoustic source; hence, their perceived ideas of the impact on farm production. However, overall, most farmers appear to understand the potential of technological solutions for monitoring farmlands. Nearly half of the respondents (48.05%) have provided positive and negative reasons as to why they consider the use of technology for monitoring the acoustic environment or not (Table 2). The relationship between farmers' consideration for using technology and sound monitoring illustrates that many of them consider the acoustic environment to monitor the happenings on the farm (Table 3).

We found that farmers who have secondary and university education are potentially more interested in technology monitoring than those with only primary education (Table 6). Farmers with a higher level of education demonstrated an understanding of the advantages of technology use in agriculture and, hence, their interest. More farmers who are engaged in commercial farming are interested in the use of technology than subsistence farmers (Table 7). These highly educated farmers affirmed that such a technology can assist them in arriving at timely information that may guide data-driven decisions to increase farm production. The responses can be explained as an understanding by the farmers that technological monitoring can provide timely information to serve as a basis for decision-making, leading to the implementation of quality control measures to mitigate against pests and diseases, which will eventually result in increased yields. This is corroborated by Raheem et al. [56] that farmers' adaptation of the right technologies would boost agriculture and make farming attractive to young Africans who are better educated than past generations.

The cost involved in adopting technology in agriculture is identified as one of the factors that play a vital role in farmers' decision to use smart systems [60]. It is, however, interesting that interacting with the farmers during the survey revealed that, given a low-cost acoustic technology, even farmers with limited technical knowledge would gladly employ such technologies in monitoring the acoustic environment within the farm. This is true for farmers at every educational level. Farmers overwhelmingly indicated that the technology should alert them with a simple alarm or message because most farmers use feature phones, not smartphones. Several works [61–63] corroborate that factors such as cost, technical know-how, and others are debilitating factors against smallholder farmers' adoption of technologies. The results suggest that, given the opportunity and training, about 77% of the farmers would acquire technology for monitoring the farm environment. This implies that in the design and development of technological solutions, user interaction must be factored in, such that the technology must be simple to operate without requiring any technical skill from the user. It is prudent for the technology to operate smartly and autonomously, requiring no human assistant to perform tasks. Furthermore, developers must consider IoT devices in the design of farm monitoring technologies that can provide low-cost systems for smallholder farmers' use.

This study provides knowledge on the useful role that the acoustic environment plays in the agricultural landscape by illustrating the benefits of understanding the impact on farm production. Farmers interact with the acoustic environment almost daily, obtaining knowledge and perception, providing insight into the characteristics of the acoustic presence. The local knowledge of the acoustic environment can provide vital information about the landscape, leading to advanced strategies for monitoring [64]. For example, understanding the acoustic characteristics can inform decisions on improved management methods for agricultural production. The farmer's perception of beneficial and non-beneficial sound sources can guide tailor-made methods for reducing the negative sounds while promoting positive sound sources to improve the health of the soil and crops and to provide good yields [65].

The concept of sustainable economic development plays a crucial role in the design and development of technologies to improve agricultural production. Taking stock of the potential use of technology and acceptance to use the new technology must be considered. Monitoring the acoustic environment of the farm provides vital implications for sustainable development in agriculture, supporting SDG 2. The acoustic environment provides valuable information about the biodiversity of the farm landscape by gaining insight into important species that are crucial for sustainable ecosystem service. In their work, Nastis et al. [66] stated that the behavior and attitude of farmers who implement sustainable farm practices are highly influenced by what they perceive to reduce risk affecting the farm. Understanding the role of the acoustic environment in reducing the risk of damaging crops will aid farm practices geared towards sustainable development.

Farmers' perception of the acoustic environment on the farm can affect agricultural practices and farm management in different ways. Understanding the dynamics of the implications can inform policy formulation and farm practices to improve production for food security. The knowledge and perception of a farmer about the acoustic environment critically affect agricultural practices. As suggested by Rayasawath [67], understanding the work environment can influence farmers' attitudes and performance in agricultural tasks. This is reiterated by Chen and Zhou [68], that farmers' perception of the agricultural landscape is vitally important for implementing sustainable development policies. A positive acoustic environment will be encouraged while efforts are made to reduce negative acoustic sources. Encouraging positive sound sources can improve crop yield. Beneficial acoustic sources can serve as a motivation for the farmer to practice improved methods in the agricultural landscape.

The theoretical implication of the acoustic environment of the farm can not be overemphasized. Farmers' knowledge of acoustic indicators can play an important role in farm management for ecological gains. This can influence farmers' decisions on integrated farm management and biodiversity. As postulated by Szymanski et al. [69], the variation in bird songs may indicate a change in the acoustic environment which suggests a change in farm practices. Policymakers and other stakeholders may design effective policies and farm practices to increase agriculture production.

Monitoring and understanding the acoustic environment of the farm has important policy implications to promote practices that can enhance biodiversity and management for sustainable development. By utilizing acoustic environment data, policymakers can understand the dynamics of the agricultural landscape and identify areas of threat to prioritize efforts that can mitigate them. The acoustic environment is a predictor of the entire health status of an ecosystem [9]. Leveraging this knowledge in the agricultural landscape provides insight for policy formulation towards improved practices among smallholder farmers and perhaps the local communities [65]. The assessment of the acoustic environment potentially provides data for the effective and efficient allocation of resources towards the timely protection of the farmlands and preventing possible disasters for sustainable development, specifically SDG 2.

Further implications of understanding how the acoustic environment influences farm production can lead to improved farm practices for economic gains. The feedback from acoustic monitoring can provide insight into farm operations that are considered noise pollution by community members. Policymakers can leverage the acoustic environment data to engage farmers and local communities to discuss management processes, leading to collaborative policy formulation for agriculture.

The survey was designed to assess the knowledge of farmers on the acoustic environment of farms in Bugesera District of Rwanda. One of the limitations of the study is access to the farm and the farmers. There are no motorable roads to the farms. When it rains, it is more difficult to access the communities for the administration of the questionnaires. The next is the misinterpretation of the questions. Some responses to the questions suggest that the respondents might have not interpreted the questions well. Another challenge faced during the survey was language barriers for those who could not read and write and, hence, the need to use enumerators. The lead investigator could not speak the local language of the farmers to interpret questions with the right intended thought, which may have contributed to a misunderstanding of the questions. The responses of some farmers suggest that they did not understand the acoustic environment of farms. The questionnaire might not have been translated to them with the appropriate meaning or they were hard of hearing. Further, incomplete response to parts of the questionnaire was another limitation. Farmers could not respond to some questions due to either misunderstanding or misinterpreting the items. Finally, the farmers' responses may differ depending on the specific crop under cultivation and the stage of the growing season at the time of the survey. There may be limitations to the interpretations derived from the survey. For example, the order of the questionnaire items made the respondents change their minds about the use of technology during the survey. Even though the survey was conducted in one farming season, the tool was designed to assess farmers' knowledge across the two farming seasons in Rwanda. The items were not related to a particular season.

5. Conclusions

The survey provides insights into the sources of acoustic activity that farmers want to monitor on their farms. The results suggest that birds are the most important acoustic source that farmers are willing to monitor. This is true for most farmers because birds make clear sounds that are unique and can be detected with technology. We found that the dominant acoustic sources on the farm are biophony-based. The biophonic sounds are of great concern to farmers since such acoustic sources are identified as contributors to significant yield loss. The negative impact of bird damage to crops is of great concern and farmers understand the potential of IoT technologies to monitor the farm environment.

The findings also suggest that farmers are willing to apply low-cost technology to monitor the crops, weather, and even theft-related issues. This willingness cuts across both commercial and subsistence farming and the educational level of the farmer. The farmers want a simple SMS alert from the technology system. We believe that this demonstrates a potential market for low-cost IoT solutions operating in near real-time for African smallholder farmers.

The information from the survey has given us some understanding of the system requirements for the monitoring technology. We must determine which frequencies of signals to monitor, what time of the day to monitor, and the number of sensors to use. We must find solutions to the type of bird to target and how to scare them from the crops. We must also determine what type of Artificial Intelligence must be employed in the system and the mode of data transmission. How the system is to be powered and for how long are some of the questions that must be addressed in the design and development of the IoT system near real-time. By understanding the system requirements will guide the design of a network of sensors for deployment on the farm field. Apart from pest attacks on crops, monitoring acoustic sources in agricultural settings may potentially provide security for the entire chain of farm production.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture15010025/s1, S1: questionnaire used for data collection, and S2: R codes for data analysis.

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