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Co-designing fodder diversification and co-products recycling fosters effectiveness, productivity and agroecological transition of dairy farms in Burkina Faso

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Introduction: Burkina Faso's dairy farms, whether extensive or semi-intensive, face major sustainability challenges. Introducing agroecological technologies offers an opportunity to optimize the use of local resources and enhance farm resilience and productivity. This study presents an innovative approach that tests and assesses, in co-design with farmers, the integration of two major agroecological technologies that underpin crop–livestock integration.
Methods: To assess the impact of these agroecological technologies, dairy farmers of the Bobo-Dioulasso milkshed implemented on-farm trials involving: (i) the introduction of dual-purpose fodder cereals (maize and sorghum) and legumes (Cowpea and mucuna) for feeding lactating cows, and (ii) the recycling of livestock and crop co-products to produce manure in covered manure pits. We employed a four-step methodological approach for co-designing agroecological innovations with 43 dairy farmers: diagnosis, co-design and experimentation, assessment, and identification of induced changes. Data from experiments and participatory assessment workshops were analyzed to compare dairy farm performance before and after the introduction of agroecological technologies. The first changes induced by these technologies were identified and characterized through participatory workshops.
Results and discussion: The introduction of dual-purpose fodder crops into production systems led to improvements in on-farm milk production. Legume fodder storage increased from 356 to 518 kg DM/farm (+45%), while cereal fodder storage decreased slightly (1,388 to 1,091 kg DM/farm). The establishment of covered manure pits enhanced manure quality, with an average increase of 4,679 kg DM/farm. Milk production rose markedly, by over 80% for mixed cows

(6.43 vs. 11.67 L/d/cow) and 12% for zebu cows (1.11 vs. 1.25 L/d/cow). Agroecological performance scores also improved particularly in diversity (38% vs. 94% after introduction of agroecological technologies), recycling (31% vs. 88%), and synergy (25% vs. 69%). These results demonstrate that a step-by-step integration of agroecological technologies can enhance their effectiveness and milk productivity, while strengthening the resilience of dairy farms, particularly in the face of climatic and economic challenges. Under conditions of prolonged dry seasons, irregular rainfall, and volatile prices of industrial inputs, the combination of these technologies ensures both the availability of fodder for livestock and manure for soil fertilization. Nevertheless, continued efforts are required to maintain and further improve this performance over time.

KEYWORDS

agroecology, dairy farming, fodder production, cow rationing, co-product recycling

1 Introduction

Livestock farming plays a major role in the economies of Sahelian countries, contributing between 11% and 18% of GDP in Mali, Niger and Burkina Faso. In these countries, milk production represents 30 to 40% of total livestock revenues (Duteurtre and Corniaux, 2013; FAO, 2018). In terms of milk availability, Burkina Faso ranks third in West Africa, with an average production of 14 liters of cow's milk per capita per year. However, locally produced milk remains poorly integrated into formal processing and marketing channels, leading to a strong dependence on imported milk powder each year. Most local milk is consumed raw, and when production is low, it is often reserved for household consumption (Duteurtre and Corniaux, 2013). In 2022, Burkina Faso imported nearly 25,000 tons of milk and dairy products (Tapsoba-Mare, 2023).

Driven by rising demand for dairy products and volatile international markets, Burkina Faso's dairy value chain is undergoing a dynamic transformation, driven by the emergence of multi-stakeholder innovation platforms, milk collection centers, mini-dairies and mini-farms (Sib et al., 2018; Duteurtre and Vidal, 2018; Vall et al., 2021, 2025). Milk production mainly relies on two livestock farming systems: pastoral and agro-pastoral systems, which predominate, and semi-intensive and intensive systems (Vall et al., 2021). Productivity remains low and highly seasonal, due to the limited genetic potential of local cows and significant feed shortages during the dry season.

Pastoral and agro-pastoral systems depend heavily on natural pastures, with only limited supplementation for cows, which are predominantly Sudanese Fulani zebus. These systems are characterized by low milk yields. They are also characterized by specific and recurrent constraints in forage availability: during the rainy season, the expansion of cultivated land reduces pasture areas, while in the dry season, available forages are of low nutritional value. Semi-intensive and intensive systems are less dependent on natural pastures. Cows, often Sudanese Fulani zebus crossbred with exotic dairy breeds, receive more substantial supplementation, characterized by greater use of feed concentrates, resulting in significantly higher milk yields than in extensive systems (Sib et al., 2018; Vall et al., 2021).

To mitigate seasonal fluctuations in milk production, dairy farmers have diversified their feeding strategies through the storage of crop residues, the use of agro-industrial co-products, and the inclusion of feed concentrates, which are often expensive and difficult to access (Sib et al., 2018; Vall et al., 2021; Sodré et al., 2022; Ouattara et al., 2024). An increasing number of dairy farmers are showing interest in fodder production, which appears to be a promising alternative, although its adoption remains limited (Sodré et al., 2022).

In this context, transitioning toward agroecology appears to be a promising pathway for ensuring the productivity, resilience, and sustainability of dairy farming systems. Considered as both a science, a set of practices, and a social movement, agroecology offers sustainable alternatives to address current agricultural challenges (Wezel et al., 2009). Grounded in principles such as recycling, input reduction, soil health, biodiversity, synergies among system components, co-creation of knowledge, and social values and diets (Wezel et al., 2020; Mottet et al., 2020), agroecology provides a relevant framework for rethinking livestock feeding in dairy systems. In this context, diversifying fodder production with high nutritional value and improving manure quality are key entry points for enhancing agroecological performance. Furthermore, the efficient use of crop and livestock co-products, combined with improved feed management on dairy farms, represents an essential lever for promoting both resilience and productivity in agroecological dairy systems. These approaches can help meet farmers' expectations while sustainably increasing milk production.

Supporting dairy farmers solely in the conceptual design of improved systems is not sufficient; it is equally crucial to assist them in implementing concrete change actions (Prost et al., 2023), through a step-by-step and iterative design process (Meynard et al., 2023; Vall et al., 2025). This approach promotes both individual and collective learning by combining scientific and empirical knowledge, making it particularly relevant for supporting the agroecological transition in cropping and livestock systems (Meynard et al., 2023).

Therefore, this study employed a methodological approach structured around four steps for the co-design of agroecological technologies: (i) diagnosis, (ii) co-design and experimentation, (iii) assessment, and (iv) identification of induced changes. The objective was to assess how the combination of agroecological practices, particularly fodder diversification and the recycling of crop and livestock co-products can enhance the effectiveness, productivity, resilience, and agroecological transition of dairy farms. This study innovates by testing and assessing, in co-design with farmers, the integration of two major agroecological technologies that underpin crop–livestock integration.

2 Materials and methods

2.1 Description of the study area

The study was carried out in the Bobo-Dioulasso milkshed area, which extends over a 50 km radius around the city of Bobo-Dioulasso (Figure 1). This city is located in the Hauts-Bassins region in Western Burkina Faso. The region covers a total area of 25,574 km^2 and is home to 2,239,840 people, i.e. 10.9% of the country's total population. Divided into 3 administrative provinces, it boasts a total of 33 communes, three of which have the status of 'urban commune': Bobo-Dioulasso for the Houet province, Orodara for Kénédougou and Houndé for Tuy (MATD, 2021; INSD, 2022). The climate in the Hauts-Bassins region is Sudano-Sahelian, between isohyets 800 mm and 1,100 mm, with an alternating pattern of the dry season (November to May) and rainy season (June to October) during the course of the year. Maximum rainfall occurs in August. Faced with variable weather conditions, rainfall in the region is irregular, with uneven space-time distribution within the same crop season and from one crop season to the next. The average diurnal temperature ranges from 22 °C in cooler months (November to February) to 37 °C in hotter months (March to May). Soils are 61.3% tropical ferruginous (Conseil régional des Hauts-Bassins, 2018).

2.2 General methodological approach

To assess the impact of fodder diversification and the recycling of crop and livestock co-products on dairy farms effectiveness, productivity and agroecological transition, we employed a four-step methodological approach: (i) diagnosis, (ii) co-design and experimentation of innovations, (iii) assessment of these innovations, and (iv) identification of the induced changes (Figure 2). This methodological approach falls within the framework of participatory research, organized in a stepwise process (Meynard et al., 2023; Vall et al., 2025). The sample consisted of 43 dairy farmers: 10 for an overview of livestock and crop co-products management; 43 for the implementation of agroecological technologies (43 for fodders demo-plots, 15 for dairy production units, and 12 for covered manure pits); and 20

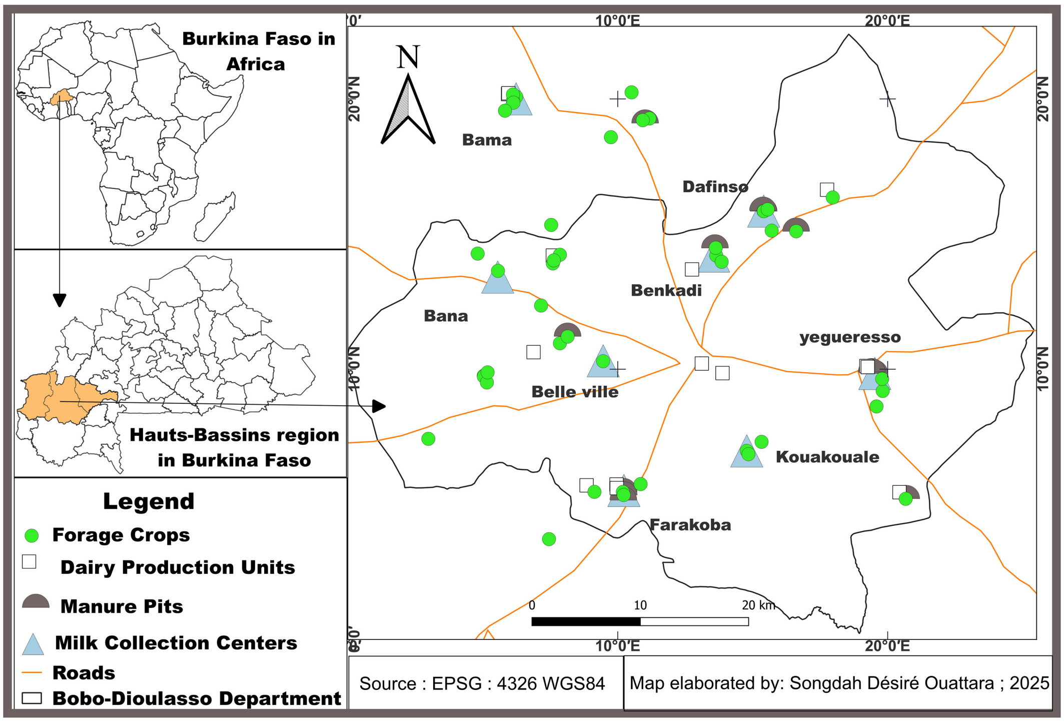

FIGURE 1
Map of the study area, showing where agroecological technologies were introduced.

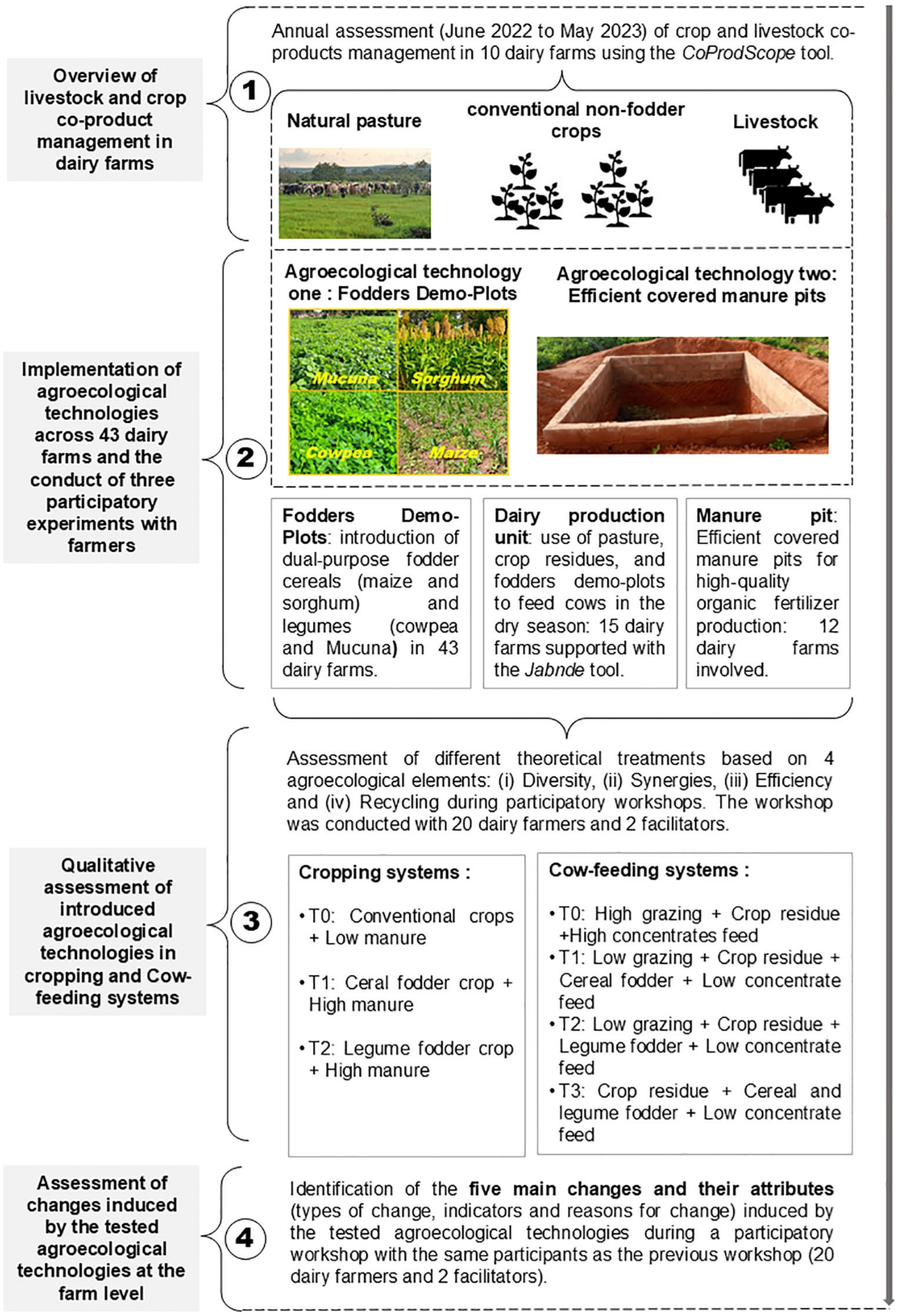

FIGURE 2
Summary of the methodological approach.

for the qualitative assessment of the introduced agroecological technologies in cropping and cow-feeding systems, as well as for assessing the changes induced at the farm level. Although the sample size varied across stages, the same individuals were involved throughout the process. All of these dairy farmers were affiliated with the eight milk collection centers of the Bobo-Dioulasso dairy innovation platform.

2.2.1 Step 1: overview of livestock and crop co-product management in dairy farms

The *CoProdScope* (CPS: https://coprodscope.cirad.fr/; Google playstore: https://play.google.com/store/apps/details?id=fr.cirad.coprodscope&hl=fr) tool was used to establish the annual balance (June 2022 to May 2023) of livestock and crop co-product management at the dairy farm level for a sample of 10 key dairy farmers. Designed for agropastoral farms of the savanna zones of West and Central Africa, CPS is a decision-support tool for managing crop and livestock co-products, based on the interaction between an agricultural advisor and an agropastoral farmer (Zoungrana et al., 2023).The tool is designed, first, to assess the contribution of crop and livestock co-products to meet fodder, manure, and mulch requirements on an agropastoral farm during the previous agricultural season (year N). Second, it supports co-designed advice with farmers to improve the management of these co-products for the following year (year N + 1).

For this study, the Microsoft Excel version of the tool was applied to conduct the assessment stage. For each dairy farmer, the shares of fodder and manure requirements covered by on-farm crop and livestock co-products were entered into an Excel file to build the database. Average values were then calculated for each requirement.

2.2.2 Step 2: participatory experiments with dairy farmers

During the 2023/2024 crop season, two agroecological technologies were introduced and tested on dairy farms: (i) dual-purpose fodder cereals (Espoir maize and Grinkan sorghum) and legumes (Tiligré cowpea and *Mucuna pruriens* var. *deeringiana*) for feeding lactating cows, and (ii) the recycling of livestock and crop co-products to produce high-quality manure in covered manure pits. These technologies were selected through a participatory co-design workshop held with the milk collection centers.

Initially, only cowpea and *mucuna* were proposed for the fodder demo-plot crops, but dairy farmers expressed interest in also including maize and sorghum. This participatory process resulted in the selection of all four crops and the voluntary participation of 43 dairy farmers to test both technologies.

A characterization survey of cropping and cow-feeding systems was then conducted among the 43 volunteer dairy farmers. Crop production data referred to the 2022/2023 crop season, while milk production data focused on the 2023 dry season (January to March). Data on the cropping system were collected from 47 maize plots, 28 sorghum plots, 22 cowpea plots, and 6 *mucuna* plots.

All experimental and characterization survey data collection sheets were digitized. Forms were first prepared in CSV format using Excel and then uploaded to the KoboToolbox platform. Using KoboCollect, they were deployed on tablets, and the collected data were sent back to KoboToolbox before being exported as Excel files for analysis (Nampa et al., 2020).

2.2.2.1 Establishment of fodders demo-plots

During the 2023/2024 crop season, the 43 volunteer dairy farmers received support for establishing the fodder crops, which included seeds and technical training. The quantities of seeds allocated per dairy farmer were 3 kg for maize, 1.5 kg for sorghum, 2 kg for cowpea, and 4 kg for *mucuna*, corresponding to an average cultivated area of 0.125 ha per crop (Sanou, 2006; Botorou and Niaba, 2011; CIRAD-CIRDES-UPPCT-INADES, 2012; NAFASO, 2013). Not all dairy farmers were able to cultivate all of their fodder crops due to limited sowing area, labor constraints, and localized droughts. This primarily resulted in an imbalance in the number of plots among the four crops: 36 for maize, 32 for *mucuna*, and 24 each for sorghum and cowpea.

Monitoring of the cultivated fodder crops provided data on crop management practices and yield performance. Fodder yields were determined using yield quadrats and the integral harvesting method (Levang and Grouzis, 1980). Five $4m^2$ quadrats were established in each plot prior to grain harvest, four positioned along the diagonals and one at the center. The yields from these quadrats were averaged and extrapolated to a per-hectare basis (Sodre, 2022). Dry matter content (% DM) was determined by weighing after oven-drying at 55 °C for 72 hours. By the end of the crop season, complete data on the total quantity of fodder (from fodder and non-fodder crops) and stored concentrates could only be assessed for 25 dairy farmers. Data collection for the remaining dairy farmers was not possible due to direct grazing of some fodder plots, relocation of some dairy farmers for safety reasons, and the inability to store fodder because grain ripening coincided with a rainy spell.

Comparative analyses were performed using R software version 4.3.3 (R Core Team, 2024) to assess the performance of cropping systems in a baseline situation (using survey data, see 2.2.2), and subsequently after the introduction of fodders demo-plots. The variables considered in the analysis were the quantities (kg DM) of stored quality fodder (cowpea and *mucuna*), stored coarse fodder (maize and sorghum), and crop grain yields (kg/ha). The Wilcoxon test was used for mean comparisons at the 5% significance level.

2.2.2.2 Establishment of a dairy production unit

During the 2024 dry season (January to March), 15 dairy farmers (12 with zebu cows and 3 with mixed cows) were selected from the initial sample to receive support in establishing pilot dairy production units. Selection criteria included: availability of a large stock of fodder, presence of lactating cows, willingness to test rations based on fodder crops, easy access to the farm for monitoring purposes, and dairy farmers' ability to maintain a dairy unit monitoring sheet. An average of two cows per dairy unit were monitored for 21 days (14-days adaptation period followed by 7 days of data collection). The *Jabnde* tool (https://jabnde.cirad.fr/; Google playstore: https://play.google.com/store/apps/details?id=com.zhou_tn.jabnde_mobile) was used to provide technical, economic, and environmental advice for developing appropriate rations for selected lactating cows (Lecomte and Vall, 2022). The aim was to set up efficient dry-season rations, i.e., balanced and economically acceptable for dairy farmers.

Each volunteer dairy farmer participated in the implementation and adaptation of the co-designed rations, as well as in assessing their effects on the performance of the dairy cows monitored on their farm. During the adaptation period, the farmers received support on the first two days of each of the first two weeks (i.e., on days 1, 2, 8, and 9 of the experiment), after which they managed the rations independently. Using a daily monitoring sheet, the following information was recorded: (i) quantities of feed offered to the cows; (ii) the level of feed intake; (iii) daily grazing duration; and (iv) quantity of milk produced per cow per day, measured with a graduated bottle. The amount of milk consumed by the calf was not included. After the experimental phase, interviews were conducted with the dairy farmers to gather their perceptions of the rations' effects on milk production.

Average daily milk yield per cow per dairy farm was compared between the baseline situation (using survey data; see 2.2.2) and after the establishment of dairy units supplied with fodder from the fodder demo-plots. The analysis was performed using R software, and mean differences were tested with the Student's t-test at the 5% significance level.

2.2.2.3 Establishment of covered manure pits

Lastly, manure pits from 12 dairy farmers were closely monitored from construction to manure production. The selected dairy farmers were those who had established fodder crops and had completed the digging, filling, and covering of their manure pits in 2024, using co-products from their dairy production units. Each pit had a planned volume of 9 m^3 (3 m × 3 m × 1 m) with constructed borders. The pits were continuously supplied with crop and livestock co-products from the dairy farms and were regularly watered. After filling, the pits were covered to accelerate decomposition. The volunteer dairy farmers received support for constructing covered manure pits using cement and tarpaulins. Monitoring enabled the assessment of total manure production.

Before emptying the manure pits, samples were collected using an auger at five points along the two diagonals of each pit, at depths of 0–30, 30–60, and 60–90 cm. For each pit, a composite sample was then prepared for each depth. The dry matter content (% DM) of the samples was determined by weighing after oven-drying at 60 °C for 72 hours. The three average samples per depth from each pit used for manure characterization were analyzed in the Soil-Water-Crop Laboratory of the Institute of Environment and Agricultural Research of Farako-Ba (Burkina Faso). The measured parameters included: pH in water, organic carbon, organic matter, total nitrogen, carbon-to-nitrogen ratio, total phosphorus, total potassium, total calcium, and total magnesium.

For the chemical composition analysis, the mean and standard deviation were calculated for each physicochemical parameter across all samples. The chemical composition of manure from covered pits was systematically compared with values reported by Blanchard et al. (2014), who characterized manures produced by farmers in agropastoral systems in western Burkina Faso.

2.2.3 Step 3: assessment of cropping and cow-feeding systems including the two introduced agroecological technologies

Participatory assessment workshops were conducted to characterize the alignment of cropping and cow-feeding systems integrating the introduced agroecological technologies on four agroecological elements: (i) Diversity, (ii) Synergy, (iii) Recycling, and (iv) Efficiency. Twenty dairy farmers, selected from the initial group of 43 experimental volunteers, took part in a plenary session to carry out this assessment. The participants were randomly selected, with at least two farmers from each milk collection center, considering the project's logistical capacity to provide support for feed and transportation.

Since not all dairy farmers were able to implement all four fodder crops, the fodder production technology was categorized into different treatments to assess the degree of agroecological transition in cropping and cow-feeding systems with regard to the four agroecological elements. The treatments described below were proposed by the researchers and defined qualitatively. In each treatment, agroecological technologies were combined with other practices commonly used by farmers. The detailed modalities and rationale for each treatment are explained in Table 1.

With regard to the cropping system, three treatments were assessed (introduced agroecological technologies are shown in **<u>bold and underlined</u>**):

- T0: Non-fodder crops (maize, sorghum, cowpea) + Low **<u>use (*) of manure</u>**;
- T1: Introduction of **<u>fodder cereal plots</u>** (Espoir maize and Grinkan sorghum) + Extensive **<u>use (*) of manure</u>**;
- T2: Introduction of **<u>fodder legume plots</u>** (Tiligré cowpea and *Mucuna pruriens* var. *deeringiana*) + Extensive **<u>use of manure</u>**.

With regard to the cow-feeding system, the following treatments were assessed:

- T0: Extensive natural grazing + Non-fodder crop residues + High use (*) of concentrates;
- T1: Little natural grazing + Crop residues + **<u>Cereal fodder</u>** + Low use of concentrates;
- T2: Little natural grazing + Crop residues + **<u>Legume fodder</u>** + Low use of concentrates;
- T3: Crop residues + **<u>Cereal and legume fodder</u>** + Low use of concentrates (Table 1).

(*) The terms "low use" and "high or extensive use" do not refer to measurable or standardized quantities but rather represent a qualitative assessment intended to differentiate agricultural practices according to the presumed intensity of input use.

For each agroecological element (Diversity, Synergy, Recycling, and Efficiency), four indices (Table 2) were assessed using a Likert-type scale ranging from 0 to 4. Workshop participants assigned a score to each index of a given treatment based on the assessment grid of agroecological transition indicators proposed by Mottet et al. (2020) and FAO (2021) (Tables 3–6). In cases where consensus could not be reached, a vote was held, and the score adopted corresponded to the majority decision. Two facilitators oversaw the conduct of the workshop. To assess different treatments, the scores for the four indices were standardized on a scale from 0 to 100% in order to produce an overall score for each agroecology element of a treatment, which facilitated comparison between treatments.

2.2.4 Step 4: identification of changes induced by agroecological technologies tested

The same 20 dairy farmers who had participated in the assessment of the agroecological transition of cropping and cow-feeding systems were mobilized during a second workshop. The

TABLE 1 Description of the various treatments assessed.

Treatments	Descriptions
Cropping system	
T0: Non-fodder crops (maize, sorghum, cowpea) + Low use of manure	The control treatment is not part of the trial here, but reflects the current main practice in the region to feed the herd in a highly constrained environment. Most farmers grow conventional non-fodder crops such as maize, sorghum or cowpea and use low manure. If these crops do produce biomass in addition of the grain production, they are not selected to optimize this biomass production, in contradiction to fodder crop.
T1: Introduction of fodder cereal plots (Espoir maize and Grinkan sorghum) + Extensive use of manure	This both technologies, have been implemented on-farm according to farmers' condition and access to mechanization, mineral fertilizer, labor, pesticide use, etc. Cereal fodder crops are a very promising technology in the region because it has a high capacity to generate biomass if sufficient inputs are provided, which also explain why the technology is tested with increased use of manure. Legume fodder crop has tested because they allow both to increase biomass production and increase soil nitrogen due to symbiotic fixation.
T2: Introduction of fodder legume plots (Tiligré cowpea and *Mucuna* pruriens var. deeringiana) + Extensive use of manure	
Cow-feeding system	
T0: Extensive natural grazing + Non-fodder crop residues + High use of concentrates	The control treatment in this case is the current feed ration of cattle in the region of Bobo-Dioulasso. Cattle mainly rely on grazing land when available; crop residue stored by the farmers or grazed in other farmers' field (free grazing is the rule in the region and cattle are authorized to graze on field after harvest period); and finally concentrate feed such as cotton seedcake when no more fodder is available.
T1: Little natural grazing + Crop residues + Cereal fodder + Low use of concentrates	This agroecological technology assumes that the extra biomass produced by the cereal fodder crop will allow the farmers to reduce its expenses in concentrate feed (highly expensive feed) and its dependency on grazing land. Indeed, due to expansion of agricultural land, grazing land are less accessible and more herders concentrates on them. Depending on grazing land is thus a non-resilient strategy that should be overcome with on-farm biomass production. In addition, if cows stay close to the farm with accessible biomass, the manure produced will be more easily optimize in the cropland, in contrary to the manure deposited in grazing land, considered as lost for the farmers (but useful to sustain soil fertility of these grazing land though).
T2: Little natural grazing + Crop residues + Legume fodder + Low use of concentrates	Added value of this agroecological technology is based on the same assumption as the T1 described below (reduced use of concentrate feed and reduce access to grazing land). In addition to these added values, this agroecological technology suggest to use legume, instead of cereals to produce biomass. By doing so, this technology will not only increase biomass production, but also increase soil nitrogen through symbiotic fixation. In this environment where access to mineral fertilizer is very limited, legume can help to sustain soil fertility, in addition of significant inputs of organic matter. Finally, Legume fodder crop is highly nutrient fodder complementary to cereal fodder crop richer in fiber.
T3: Crop residues + Cereal and legume fodder + Low use of concentrates	In this agroecological technology, both type of fodder are grown (cereals and legumes), in addition of low use of concentrate feed and crop residue. The amount of biomass produced is sufficient to avoid grazing land, which allows the farmers to optimize manure collection and therefore improve its soil fertility management. In order to be completely self-sufficient in biomass, it will important to have enough land size to grow both cereals and legume fodder crop.

workshop first focused on identifying the full range of changes induced by the introduced agroecological technologies, and then aimed to characterize the attributes of these changes, including the types of change, relevant indicators, and the reasons behind them. Finally, the five most significant changes were identified. This method is inspired by the principles of the outcome harvesting (Wilson-Grau and Britt, 2012) limited to the identification of outcomes. Two facilitators led the session, posing questions to participants to stimulate reflection and guide the identification of observed changes. The questions asked were as follows:

- We have worked together on integrating agroecological practices into your farms. Where have you observed changes occurring?
- Who is doing things differently than before as a result of our joint work on milk production?
- Consider all types of changes that may have occurred: changes in your farming practices, or in your relationships with your clients or suppliers.
- Have there been any changes in milk production?
- Have there been changes in the production, storage, or distribution of fodders?
- Have there been changes in cows feeding management, or in the management of farm co-products for fodder conservation, manure production, and maintaining soil cover?
- Have there been changes in the way manure is produced and used?
- Are there any other changes you would like to mention?

Each response was written down by the facilitators on a post-it note and read aloud to ensure that the idea had been accurately

TABLE 2 Indices of agroecological elements.

Agroecology elements	Agroecological transition characterization indices
Diversity	• Crop • Animal • Trees and other perennials • Diversity of activities, products and services
Synergies	• Crop-livestock integration • Soil-plant system management • Three-way integration (agroforestry, silvopastoralism, agrosilvopastoralism) • Connectivity between elements of the agroecosystem and the landscape
Efficiency	• Use of external inputs • Management of soil fertility • Management of pests and diseases • Productivity and household's needs
Recycling	• Recycling of biomass and nutrients • Water saving • Management of seeds and breeds • Renewable energy and production

understood. The attributes of the changes identified during the previous session were then characterized by the participants. To this end, the facilitators prepared a table on a large sheet of kraft paper displayed in front of the group (Figure 3) to be completed jointly with the participants. After recording the label of each change in the first cell, the facilitators filled in the corresponding rows with the participants' responses.

Once the attributes of the changes were characterized, participants were asked to assign a score from 1 to 5 cowries to each change, ranking them from the most to the least important. The number of cowries assigned to each change was then counted, with the change receiving the highest number ranked first, and so on. Finally, the five most significant changes, receiving the highest number of cowries, were selected and validated by the participants.

3 Results

3.1 Contribution of crop and livestock co-products to meet fodder and manure needs

The *CoProdScope* tool revealed a low contribution of grazed and stored crop co-products to meet the fodder requirements of dairy farms (8.5 ± 5.38%). In contrast, with an average herd size of 49.3 ± 27.6 Tropical Livestock Units (TLU; 1 TLU = 250 kg liveweight) and a mean farm area of 2.84 ± 1.45 ha, the manure produced (pen manure) covered 141 ± 82% of the farms' fertilizer needs.

3.2 Improvement of quality fodder availability in dairy farms

The introduction of fodder crops contributed to an increase of more than 45% in the total amount of stored quality fodder (legume haulms), while reducing the quantities of coarse fodder (cereal fodder) and feed concentrates. The amount of stored quality fodder increased from 355.72 ± 334 to 517.84 ± 374.40 kg DM/farm, whereas coarse fodder decreased from 1,387.91 ± 1,545.04 to 1,091.17 ± 801.75 kg DM/farm. Similarly, the amount of feed concentrate decreased from 2,040 ± 2,166.49 to 1,518 ± 1,481.59 kg DM/farm (Table 7). However, no significant difference was found between the amount of feed stored before and after the introduction of agroecological technologies ($P > 0.05$). The fodder yields of the introduced dual-purpose crops were 3,332.70 ± 1,553.20; 3,903.86 ± 1,889.14; 1,909.43 ± 1,441.84 and 2,531.26 ± 1,010.05 kg DM/ha for maize, sorghum, cowpea, and *mucuna*, respectively.

Moreover, grain yields from the fodder demo-plots were slightly higher than those obtained prior to the introduction of agroecological technologies, although the differences were not statistically significant ($P > 0.05$). Maize grain yield increased

TABLE 3 Rating grid of agroecology indices for the diversity element.

Indices	0	1	2	3	4
Crops	Monoculture (or no crops cultivated)	One crop covering more than 80% of cultivated area	Two or three crops	More than 3 crops adapted to local and changing climatic conditions	More than 3 crops and varieties adapted to local conditions. Spatially diversified farm by multi-, poly- or inter-cropping
Animals (including fish and insects)	No animals raised	One species only	Several species, with few animals	Several species with significant number of animals	High number of species with different breeds well adapted to local and changing climatic conditions
Trees (and other perennials)	No trees (nor other perennials)	Few trees (and/or other perennials) of one species only	Some trees (and/or other perennials) of more than one species	Significant number of trees (and/or other perennials) of different species	High number of trees (and/or other perennials) of different species integrated within the farm land
Diversity of activities, products and services	One productive activity only (e.g. selling only one crop)	Two or three productive activities (e.g. selling 2 crops, or one crop and one type of animals)	More than 3 productive activities	More than 3 productive activities and one service (e.g. processing products on the farm, ecotourism, transport of agricultural goods, training etc.)	More than 3 productive activities, and several services

TABLE 4 Rating grid of agroecology indices for the synergy element.

Indices	0	1	2	3	4
Crop-livestock-aquaculture integration	No integration: animals, including fish, are fed with purchased feed and their manure is not used for soil fertility; or no animal in the agroecosystem.	Low integration: animals are mostly fed with purchased feed; their manure is used as fertilizer.	Medium integration: animals are mostly fed with feed produced on the farm and/or grazing; their manure is used as fertilizer.	High integration: animals are mostly fed with feed produced on the farm, crop residues and by-products and/or grazing, their manure is used as fertilizer and they provide traction.	Complete integration: animals are exclusively fed with feed produced on the farm, crop residues and by-products and/or grazing, all their manure is recycled as fertilizer and they provide more than one service (food, products, traction, etc.).
Soil-plants system management	Soil is bare after harvest. No intercropping. No crop rotations (or rotational grazing systems). Heavy soil disturbance (biological, chemical or mechanical).	Less than 20% of the arable land is covered with residues or cover crops. More than 80% of the crops are produced in mono and continuous cropping (or no rotational grazing).	50% of soil is covered with residues or cover crops. Some crops are rotated or intercropped (or some rotational grazing is carried out).	More than 80% of soil is covered with residues or cover crops. Crops are rotated regularly or intercropped (or rotational grazing is systematic). Soil disturbance is minimized.	All the soil is covered with residues or cover crops. Crops are rotated regularly and intercropping is common (or rotational grazing is systematic). Little or no soil disturbance.
Integration with threes (agroforestry, silvopastoralism, agrosilvopastoralism)	No integration: trees (and other perennials) don't have a role for humans or in crop or animal production.	Low integration: small number of trees (and other perennials) only provide one product (e.g. fruits, timber, forage, medicinal or biopesticides substances…) or service (e.g. shade for animals, increased soil fertility, water retention, barrier to soil erosion…) for humans crops and/or animals.	Medium integration: significant number of trees (and other perennials) provide at least one product or service.	High integration: significant number of trees (and other perennials) provide several products and services.	Complete integration: many trees (and other perennials) provide several products and services.
Connectivity between elements of the agroecosystem and the landscape	No connectivity: high uniformity within and outside the agroecosystem, no semi-natural environments, no zones of ecological compensation.	Low connectivity: a few isolated elements can be found in the agroecosystem, such as trees, shrubs, natural fences, a pond or a small zone of ecological compensation.	Medium connectivity: several elements are adjacent to crops and/or pastures or a large zone of ecological compensation.	Significant connectivity: several elements can be found in between plots of crops and/or pastures or several zones of ecological compensation (trees, shrubs, natural vegetation, pastures, hedges, channels, etc.).	High connectivity: the agroecosystem presents a mosaic and diversified landscape, many elements such as trees, shrubs, fences or ponds can be found in between each plot of cropland or pasture, or several zones of ecological compensation.

from 1,243.67 ± 600.73 kg/ha to 1,358.09 ± 763.89 kg/ha after the introduction of agroecological technologies. For sorghum, the yield increased from 787 ± 473.31 to 1,015 ± 1,050.83 kg/ha. In the case of legumes, cowpea grain yield improved slightly from 299.46 ± 213.72 to 334.91 ± 127.31 kg/ha, whereas for *mucuna*, the yield increased from 467.28 ± 418.28 to 794.84 ± 674.82 kg/ha.

3.3 Improvement of milk production in dairy farms

Milk production from mixed cows (6.43 ± 3.12 L/d/cow) before the introduction of agroecological technologies was significantly lower ($P < 0.05$) than that of cows rationed with fodder crops (11.67 ± 0.23 L/d/cow). For zebu cows, milk production increased from 1.11 ± 0.46 L/d/cow before the introduction of agroecological technologies to 1.25 ± 0.46 L/d/cow after the introduction of agroecological technologies ($P > 0.05$; Figure 4), representing an increase of more than 12%. Experimenting dairy farmers reported having achieved their milk production targets for 86% of mixed cows and 20% of zebu cows following the use of fodder crops in their dairy units. Regarding zebu cows, they considered that milk production was close to expectations in 70% of cases. Overall, dairy farmers indicated that milk production had increased significantly for 41% of the cows, increased slightly for 55% of the cows and remained stable for 4% of the cows.

TABLE 5 Rating grid of agroecology indices for the efficiency element.

Indices	0	1	2	3	4
Use of external inputs	All inputs are purchased from the market.	The majority of the inputs is purchased from the market.	Some inputs are produced on farm/within the agroecosystem or exchanged with other members of the community.	The majority of the inputs is produced on farm/within the agroecosystem or exchanged with other members of the community.	All inputs are produced on farm/within the agroecosystem or exchanged with other members of the community.
Management of soil fertility	Synthetic fertilizers are used regularly on all crops and/or grasslands (or no fertilizers are used for lack of access, but no other management system is used).	Synthetic fertilizers are used regularly on most crops and some organic practices (e.g. manure or compost) are applied to some crops and/or grasslands.	Synthetic fertilizers are used on a few specific crops only. Organic practices are applied to the other crops and/or grasslands.	Synthetic fertilizers are only used exceptionally. A variety of organic practices are the norm.	No synthetic fertilizers are used; soil fertility is managed only through a variety of organic practices.
Management of pests & diseases	Chemical pesticides and drugs are used regularly for pest and disease management. No other management is used.	Chemical pesticides and drugs are used for a specific crop/animal only. Some biological substances and organic practices are applied sporadically.	Pests and diseases are managed through organic practices but chemical pesticides are used only in specific and very limited cases.	No chemical pesticides and drugs are used. Biological substances are the norm.	No chemical pesticides and drugs are used. Pests and diseases are managed through a variety of biological substances and prevention measures.
Productivity and household's needs	Household's needs are not met for food nor for other essentials.	Production covers only household's needs for food. No surplus to generate income.	Production covers household's needs for food and surplus generates cash to buy essentials but doesn't allow savings.	Production covers household's needs for food and surplus generates cash to buy essentials and to have sporadic savings.	All household's needs are met both for food and for cash to buy all essentials needed and to have regular savings.

TABLE 6 Rating grid of agroecology indices for the recycling element.

Indices	0	1	2	3	4
Recycling of biomass and nutrients	Residues and by-products are not recycled (e.g. left for decomposition or burnt). Large amounts of waste are discharged or burnt.	A small part of the residues and by-products is recycled (e.g. crop residues as animal feed, use of manure as fertilizer, production of compost from manure and household waste, green manure). Waste is discharged or burnt.	More than half of the residues and by-products is recycled. Some waste is discharged or burnt.	Most of the residues and by-products are recycled. Only a little waste is discharged or burnt.	All of the residues and by-products are recycled. No waste is discharged or burnt.
Water saving	No equipment nor techniques for water harvesting or saving.	One type of equipment for water harvesting or saving (e.g. drip irrigation, tank).	One type of equipment for water harvesting or saving and use of one practice to limit water use (e.g. timing irrigation, cover crops).	One type of equipment for water harvesting or saving and various practices to limit water use.	Several types of equipment for water harvesting or saving and various practices to limit water use.
Management of seeds and breeds	All seeds and/or animal genetic resources (e.g. chicks, young animals, semen) are purchased from the market.	More than 80% of seeds/animal genetic resources are purchased from the market.	About half of the seeds are self-produced or exchanged, the other half is purchased from the market. About half of the breeding is done with neighboring farms.	The majority of seeds/animal genetic resources are self-produced or exchanged. Some specific seeds are purchased from the market.	All seeds/animal genetic resources are self-produced, exchanged with other farmers or managed collectively, ensuring enough renewal and diversity.
Renewable energy and production	No renewable energy is used nor produced.	The majority of the energy is purchased from the market. A small amount is self-produced (animal traction, wind, turbine, hydraulic, biogas, wood…).	Half of the energy used is self-produced, the other half is purchased.	Significant production of renewable energy, negligible use of fuel and other non-renewable sources.	All of the energy used is renewable and/or self-produced. Household is self-sufficient for energy supply, which is guaranteed at every time. Use of fossil fuel is negligible.

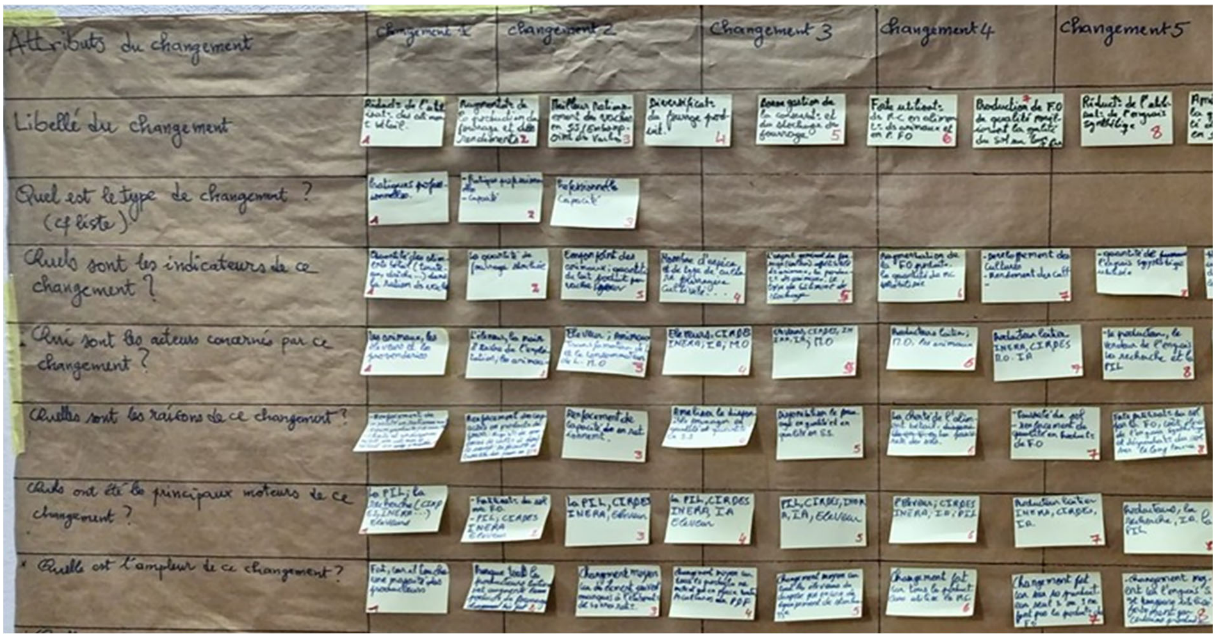

FIGURE 3
Framework for identifying changes induced by agroecological technologies.

3.4 Improved manure production using manure pits

The manure pits, with an average capacity of 13.67 ± 3.84 m^3, were installed at an average distance of approximately 58 m from the barns. After 118 ± 62 days, the pits were filled and covered. Crop co-products accounted for 17% of the inputs, while livestock co-products represented 83%. The average duration from the start of filling to manure removal was approximately 238 days. The recorded manure production was 316.95 ± 203.59 kg DM/m^3, corresponding to a total of 4,678.77 ± 3,827.37 kg DM per pit. The produced manure had a pH of 8.0 ± 0.3, with an organic carbon content of 22.5 ± 6.5%, total nitrogen of 1.3 ± 0.3%, and a carbon-to-nitrogen ratio of 17.7 ± 2.5. The organic matter content averaged 44.5 ± 13.3%, while total phosphorus and potassium contents were 0.3 ± 0.1% and 0.1 ± 0.3%, respectively. Finally, total calcium and magnesium contents were 0.1 ± 0.5% and 0.5 ± 0.1%, respectively (Table 8).

3.5 Participatory assessment of agroecological technologies in cropping systems

The cropping systems including stronger modalities of agroecological technologies introduced (T1 and T2) received a positive assessment compared with the reference cropping system (T0). Treatments T2 and T1 were ranked higher than treatment T0 on all four criteria (Figures 5, 6). The scores for the Diversity element were 38%, 63% and 81% for treatment T0, T1, and T2, respectively. For Synergy, the corresponding scores were 25%, 50%, and 63%. The Efficiency element recorded scores of 31%, 44%, and 63% for T0, T1 and T2, respectively. For Recycling the corresponding scores were 38%, 56%, and 69% for T0, T1 and T2, respectively. Among all elements, farmers have attributed to Diversity the highest scores.

3.6 Participatory assessment of agroecological technologies in milk production units

Dairy farmers gave a positive assessment of the three cow-feeding systems including the agroecological technologies introduced (T1, T2 and T3) compared with the reference cows-feeding system (T0). Treatments T3, T2, and T1 were ranked higher than T0 according to the four criteria (Figures 7, 8). The scores for the Diversity element were 38%, 63%, 63%, and 94% for treatment T0, T1, T2, and T3, respectively. For Synergy, the corresponding scores were 44%, 63%, 56%, and 69%. The Efficiency element recorded scores of 31%, 44%, 50%, and 63% for T0, T1, T2, and

TABLE 7 Quantities of fodders and concentrates stored in dairy farms.

Feed stocks	Concentrates (kg GM/farm)	Coarse fodder (kg DM/farm)	Quality fodder (kg DM/farm)
At the beginning of the operation	2,040 ± 2,166.49	1,387.91 ± 1,545.04	355.72 ± 334
At the end of the operation	1,518 ± 1,481.59	1,091.17 ± 801.75	517.84 ± 374.40
P-value	P > 0.05	P > 0.05	P > 0.05

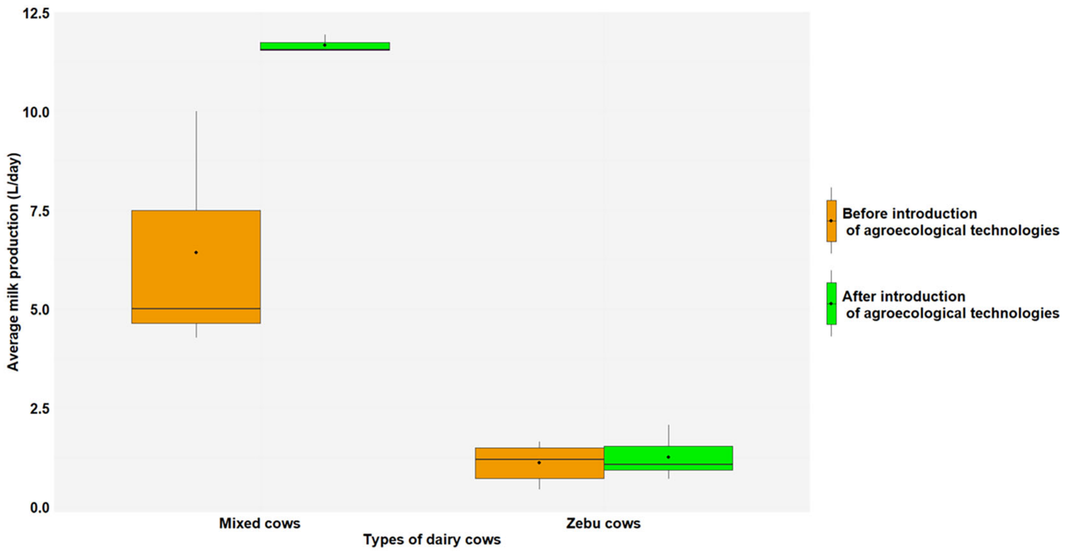

FIGURE 4
Dairy unit milk performance.

T3, respectively. For the Recycling the corresponding scores were 31%, 56%, 63%, and 88% for T0, T1, T2, and T3 respectively. Here again, farmers gave the highest score to the diversity criterion.

3.7 Changes driven by the agroecological technologies

For dairy farmers, the five main changes resulting from the introduction of agroecological technologies were: (i) an expansion of the area dedicated to fodder production; (ii) diversification of fodder crops; (iii) a better awareness of the need for rational management of dairy farm co-products; (iv) greater use of crop residues for livestock feeding and for producing high-quality manure; and (v) improved cow selection for milk production. Most of these changes were related to farmers' working practices (Table 9).

4 Discussion

4.1 Cross-effects of agroecological technologies on dairy farm performance

The fodder demo-plots contributed to improve the availability of quality fodder on dairy farms, reducing the use of concentrate

TABLE 8 Chemical composition of manures from covered pits vs. reference manures.

Elements (%DM)	Manure from covered manure pit	Medium-quality manure (Blanchard et al., 2014)	Manure with high amendment value (Blanchard et al., 2014)
Dry matter content	64.4 ± 6.1	76.1 ± 0.1	70.0 ± 0.2
pH in water	8.0 ± 0.3	8.1 ± 0.9	8.0 ± 0.7
Organic Carbon	22.5 ± 6.5	9.5 ± 4.2	20.4 ± 8.7
Total Nitrogen	1.3 ± 0.3	0.5 ± 0.2	1.1 ± 0.4
Carbon/Nitrogen (Unit)	17.7 ± 2.5	23.2 ± 11.2	18.4 ± 4.7
Total Phosphorus	0.3 ± 0.1	0.2 ± 0.1	0.5 ± 0.3
Organic Matter	44.5 ± 13.3	—	—
Total Potassium	0.1 ± 0.3	—	—
Total Calcium	0.1 ± 0.5	—	—
Total Magnesium	0.5 ± 0.1	—	—

—: Data not available.

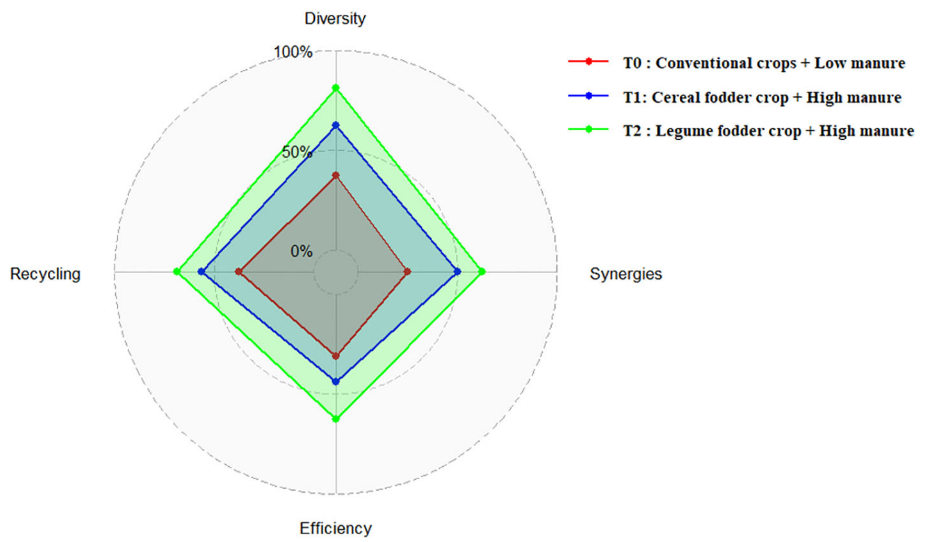

FIGURE 5
Alignment of cropping systems according to agroecological elements.

feed by more than 25% and coarse fodder by 21%. This significant reduction in concentrate use is likely to lower milk production costs and enhance production security, especially since concentrates are expensive and not always readily accessible (Deffo et al., 2009; Sib et al., 2018; Gaye et al., 2020).

The integration of fodder demo-plots into dairy production systems thus presents strong adoption potential. In addition to improving the quality of stored fodder, these plots enabled slightly higher grain yields from the very first experimental season compared with non-fodder crops from the previous season. Although these

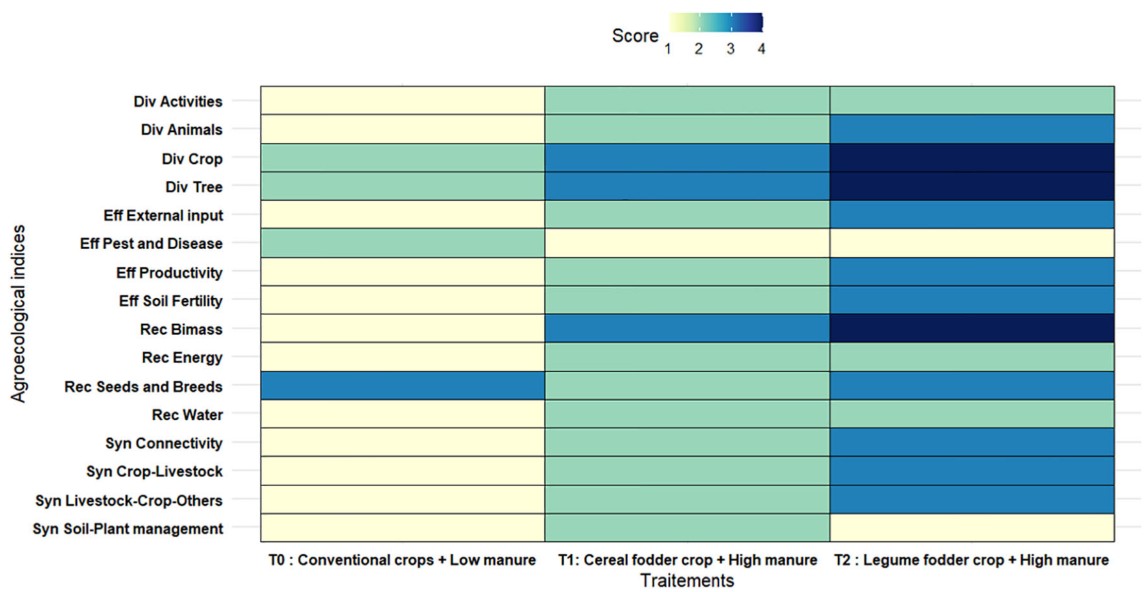

FIGURE 6
Heatmap of cropping systems alignment based on agroecological element indices. Div Activities = Diversity of activities, products and services; Div Animals = Diversity of animals; Div Crop = Diversity of crops; Div Tree = Diversity of trees and other perennials; Eff External input = Efficiency of use of external inputs; Eff Pest and Disease = Efficiency of management of pests and diseases; Eff Productivity = Efficiency of productivity and household's needs; Eff Soil Fertility = Efficiency of management of soil fertility; Rec Biomas = Recycling of biomass and nutrients; Rec Energy = Renewable energy and production; Rec Seed and Breeds = Management of seeds and breeds; Rec Water = Water saving; Syn Connectivity = Connectivity between elements of the agroecosystem and the landscape; Syn Crop-Livestock = Crop livestock integration; Syn Livestock-Crop-Others= Three-way integration (agroforestry, silvopastoralism, agrosilvopastoralism); Syn Soil-Plant management = Synergies of soil-plant system management.

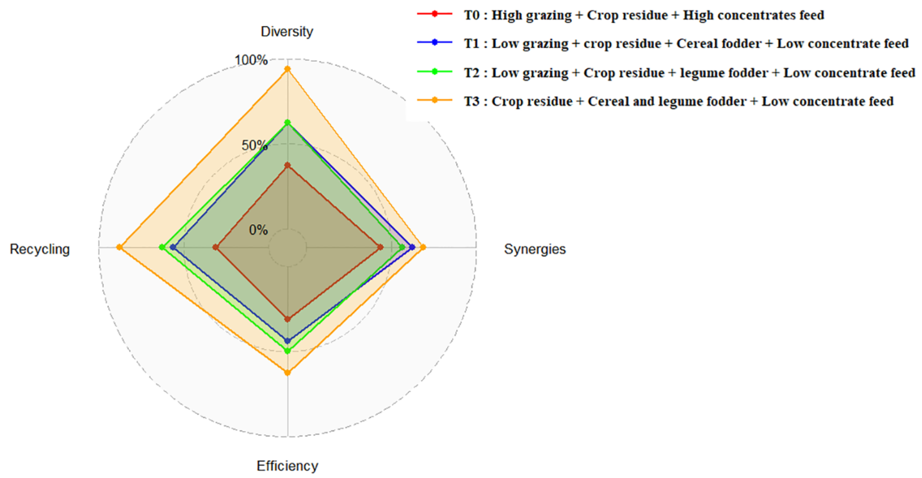

FIGURE 7
Alignment of cow-feeding systems according to agroecological elements.

yields remain lower than potential values reported in technical data sheets (Sanou, 2006; Botorou and Niaba, 2011; CIRAD-CIRDES-UPPCT-INADES, 2012; NAFASO, 2013), they are significant in the current context characterized by delayed rainfall onset, reduced and poorly distributed precipitation, localized droughts, recurrent flooding, and strong winds that degrade soil fertility and compromise yield stability (Dayamba et al., 2019).

Combining this agroecological fodder production technology with the use of the *Jabnde* tool for dairy cow feeding significantly improved milk production during the dry season. Milk yield of mixed cows increased by over 80% (6.43 vs. 11.67 L/cow/day), while that of zebu cows increased by more than 12% (1.11 vs. 1.25 L/cow/day). These production levels, corresponding to the quantities of milk actually milked, are particularly noteworthy in a regional context where zebu cow yields typically range between 0.8 and 1.7 L/cow/day (Sodré et al., 2022) and 1.4-3.1 L/TLU/day (Vall et al., 2021), while mixed cows average 7.3 L/TLU/day (Vall et al., 2021). Supplementing grazing cows with quality fodders remains essential for sustaining milk production, as reported by several studies (Sib et al., 2018; Vall

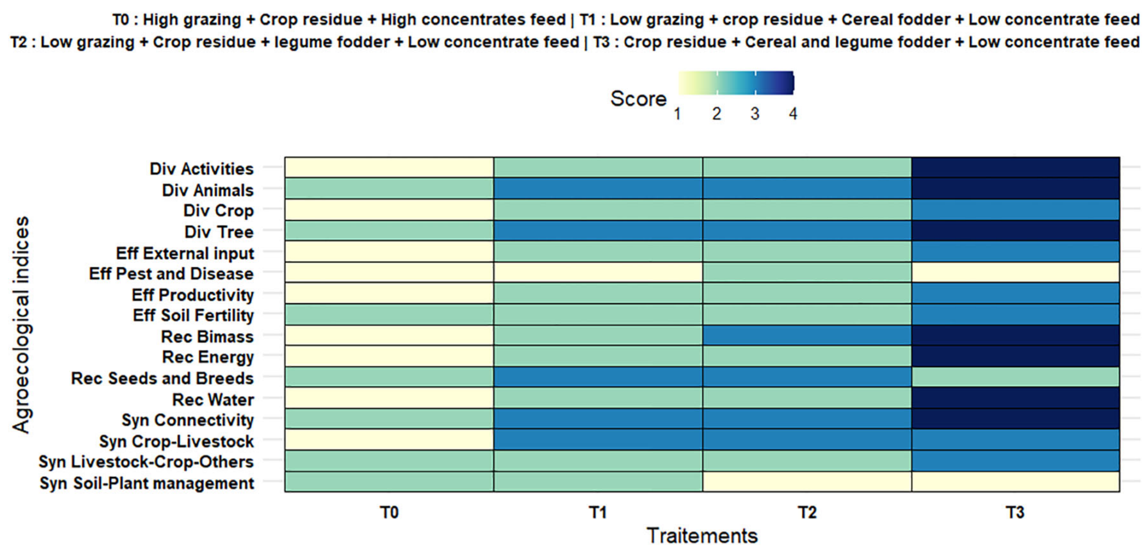

FIGURE 8
Heatmap of cow-feeding systems alignment based on agroecological element indices. Div Activities = Diversity of activities, products and services; Div Animals = Diversity of animals; Div Crop = Diversity of crops; Div Tree = Diversity of trees and other perennials; Eff External input = Efficiency of use of external inputs; Eff Pest and Disease = Efficiency of management of pests and diseases; Eff Productivity = Efficiency of productivity and household's needs; Eff Soil Fertility = Efficiency of management of soil fertility; Rec Biomas = Recycling of biomass and nutrients; Rec Energy = Renewable energy and production; Rec Seed and Breeds = Management of seeds and breeds; Rec Water = Water saving; Syn Connectivity = Connectivity between elements of the agroecosystem and the landscape; Syn Crop-Livestock = Crop livestock integration; Syn Livestock-Crop-Others= Three-way integration (agroforestry, silvopastoralism, agrosilvopastoralism); Syn Soil-Plant management = Synergies of soil-plant system managementTables.

TABLE 9 Main changes driven by agroecological technologies for farmers.

Designations	Change 1	Change 2	Change 3	Change 4	Change 5
Change description	Expansion of the area dedicated to fodder production	Diversification of fodder crops	A better awareness of the need for rational management of dairy farm co-products;	Greater use of crop residues for livestock feeding and for producing high-quality manure	Improved cow selection for milk production.
Change type	Working practice/Capacity	Working practice/ Capacity	Attitudes/Mindsets/ Opinion	Working practice/ Behavior	Working practice
Indicators	Quantity of fodder stored; quantity of milk produced; fodder crop area; types of fodder available	Number of fodder crop varieties and types grown	Existence of manure pits; manure sharing (fields and household manure pits)	Increase in the amount of manure produced and the quantity of crop residues used	Amount of milk produced per cow; types of co-products or ingredients used for cow rationing
Reasons for change	Capacity-building in fodder production; acquisition of dual-purpose fodder seeds; shortage of fodder in the dry season; conflicts between arable and livestock farmers	Improving fodder availability in both quantity and quality during the dry season	Training; meetings; support and advice	High livestock feed prices and poor soil conditions	Training; support and advice; farm monitoring

et al., 2021; Sodre, 2022; Ouedraogo et al., 2023). The added value of this study lies in the integration of fodder production and its use in dairy cow rationing through a dedicated tool, as recommended by these authors, whose findings were mainly based on survey data.

4.2 Quality of manure from efficient covered manure pits

The covered manure pits effectively recycled crop and livestock co-products from dairy farming, contributing to soil amendment and increasing the availability of high-quality manure within dairy farms. This agroecological technology enabled the production of manure that qualifies as a high-value amendment, as defined by Blanchard et al. (2014).

The chemical composition of manure from covered manure pits, compared with high-value amendment manure reported by Blanchard et al. (2014), showed slightly higher values for organic carbon (22.5 ± 6.5 vs. 20.4 ± 8.7% DM) and total nitrogen (1.3 ± 0.3 vs. 1.1 ± 0.4% DM), with a similar pH (8.0 ± 0.3 vs. 8.0 ± 0.7). While phosphorus content (0.3 ± 0.1% DM) was slightly lower than that of the high-value manure (0.5 ± 0.3% DM), it remained higher than that of medium-quality manure (0.2 ± 0.1% DM). The carbon-to-nitrogen ratio of manure from covered manure pits (17.7 ± 2.5) was slightly lower than that of high-value manure (18.4 ± 4.7) (Table 8). This manure exhibits characteristics that promote humus formation while enhancing soil physicochemical and biological properties, including structure, water-holding capacity, nutrient retention, and stimulation of soil flora and fauna (Chabalier et al., 2006; Blanchard et al., 2014; Coly et al., 2018).

Production of manure through covered manure pits also offers a relevant alternative to mineral fertilizers, whose quality is often low and whose accessibility is limited by high costs and low purchasing power in sub-Saharan Africa (Dimkpa et al., 2023). This innovation is particularly important in a context of progressive soil fertility decline due to climate change impacts, intensive chemical fertilization practices, and land-use intensification following the abandonment of fallow systems (Adebiyi et al., 2019; Dimkpa et al., 2023). Furthermore, covered manure pits can help reduce greenhouse gas (GHG) emissions. The cover acts as a physical barrier, limiting manure exposure to external conditions (rain, oxygen) that promote NH_3; volatilization and CH_4 and N_2O production, similar to membrane cover systems (Varga et al., 2024). Lemes et al. (2023) demonstrated that manure cover systems reduced ammonia emissions by over 92%.

4.3 Complexity and effectiveness of a four-step co-design approach in dairy farming

The co-design and simultaneous testing of two agroecological technologies within dairy systems proved complex, as it required aligning practices with different technical requirements, managing potential interactions, and adapting implementation. Conducting the experiment directly on dairy farms also demanded addressing contextual variability, both in data collection and in result assessment (Lacombe et al., 2018; Toillier et al., 2022; Giannini and Marraccini, 2023). The sampling process notably showed variations in sample size across different stages. In this context, flexibility was essential for achieving the expected outcomes (Méndez et al., 2017; Lema et al., 2021; Giannini and Marraccini, 2023). Despite the challenges, the approach led to significant and lasting changes. Its relevance for supporting the agroecological transition is widely recognized due to its timeframe, its ability to fill knowledge gaps through learning, its contribution to farmer empowerment, and its capacity to tailor solutions to local specificities (Meynard et al., 2023; Prost et al., 2023; Vall et al., 2025). The quantitative assessment, based on a before-and-after comparison of agroecological technologies, and the qualitative assessment, relying on outcome harvesting methodology, proved complementary. The qualitative analysis confirmed the quantitative results, in which observed differences were not always statistically significant. Vall et al. (2025) emphasize that the methodology of change identification (outcome harvesting) tends to provide richer information than that obtained through direct surveys.

The combined implementation of agroecological fodder production (fodder demo-plots) and the recycling of crop and livestock co-products positively impacted four pillars of agroecology: diversity, synergy, efficiency, and recycling, at both the cropping system and dairy cow feeding levels. Regarding diversity, these technologies promoted the production of various fodder crops that support both livestock feeding and household food needs through grain production. In terms of synergy, efficiency, and recycling, they enabled nearly complete integration of crop and livestock systems, with a substantial share of inputs produced within the agroecosystem, thereby reducing reliance on external inputs. This strong crop–livestock integration is a key lever for advancing the agroecological transition in West African agro-silvo-pastoral systems (Vall et al., 2023), while contributing to sustainable milk production (Vidal et al., 2020). Furthermore, this integrated system helps reduce pollution and lowers costs associated with waste treatment (Dumont et al., 2013).

4.4 Study limitations and contributions

The methodological approach involved a limited number of dairy farmers in the Bobo-Dioulasso milkshed area, which may constrain the representativeness of the results and limit their generalization to other areas or groups of dairy farmers. The introduced agroecological technologies were not assessed from economic (profitability of practices), environmental (effects on soil fertility and quality), or social (inclusion of women and youth) perspectives. Moreover, the participatory assessment was conducted after a single crop season, which does not allow for a full appreciation of the long-term effects or sustainability of the observed changes. On-farm experiments, surveys, and the use of digital tools (*Jabnde* and *CoProdScope*) provided valuable data; however, variability in farming practices and environmental conditions may have influenced the results. In addition, the digital tools have certain limitations, notably their restricted capacity to model agroecological technologies beyond those tested. Finally, the methodological process requires long-term commitment and substantial financial resources to ensure the continuity and coherence of all steps.

Despite these limitations, the study offers important insights into agroecological transitions in dairy systems. Through the integration of co-design, on-farm experimentation, digital advisory tools, and participatory assessment, it demonstrates that combining fodder diversification with the recycling of crop and livestock co-products into manure enhances both the productivity and resilience of dairy farms within an integrated crop–livestock system. These technologies strengthen farm resilience, particularly in the face of climatic and economic challenges. Indeed, under conditions of prolonged dry seasons, irregular rainfall, and volatile prices of industrial inputs, the combination of these technologies ensures both the availability of fodder for livestock and manure for soil fertilization. Finally, the approach enhanced farmer engagement, knowledge exchange, and practical capacity to implement agroecological practices.

5 Conclusion

This study highlights the efficiency of agroecological technologies, including dual-purpose fodder cereals (maize and sorghum) and legumes (cowpea, *mucuna*) for feeding lactating cows, as well as the recycling of livestock and crop co-products to produce manure in covered pits on dairy farms. After one year of experimentation, these technologies were found to improve dairy farm yields, increase stocks of quality fodder during the dry season, and enhance milk production. They position dairy farms on an agroecological transition pathway grounded in the principles of Diversity, Synergy, Efficiency, and Recycling. Regarding cropping systems, the introduction of dual-purpose legume fodder crops combined with extensive manure application (T2), and for cow-feeding systems, the use of quality and coarse fodder with low concentrate input during the dry season (T3), led to better agroecological performance.

The methodological approach for co-designing agroecological innovations structured in four steps: diagnosis, co-design and experimentation, assessment, and identification of induced changes, remains complex but has enabled systemic transformations that enhance the productivity and resilience of dairy farms. This approach is innovative in that it tests and assesses, in co-design with farmers, the integration of two major agroecological technologies that underpin crop–livestock integration.

To consolidate and disseminate the study's achievements, concerted efforts are needed in several areas: enhanced technical guidance, access to suitable inputs and seeds, support for the local dairy value chain in terms of equipment and structuring, and the development of viable economic models aligned with agroecology principles. These conditions are crucial for embedding sustainable and resilient dairy systems within local communities over the long term.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Ethics statement

Ethical approval was not required for the study involving humans in accordance with the local legislation and institutional requirements. The participants provided their informed consent to participate in this study.

Author contributions

SDO: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing, Validation. OS: Conceptualization, Methodology, Supervision, Validation, Resources, Project administration, Funding acquisition, Writing – review & editing. BMO: Methodology, Investigation, Validation, Writing – review & editing. SS: Methodology, Investigation, Validation, Writing – review & editing. VMCB-Y: Conceptualization, Validation, Supervision, Writing – review & editing. EV: Conceptualization, Methodology, Validation, Supervision, Resources, Project administration, Funding acquisition, Writing – review & editing.

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Conflict of interest

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

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