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Sustainable intensification of smallholder maize production in northern Ghana: The case of cowpea living mulch technology

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Abstract

Several agricultural technologies have been promoted to intensify smallholder farming systems in Ghana, but there is limited literature on sustainability assessment of these technologies. A 2-year (2017–2018) on-farm study was conducted to evaluate the sustainability of using cowpea [*Vigna unguiculata* (L.) Walp.] living mulch (CPLM) technology to intensify smallholder maize (*Zea mays* L.) production in northern Ghana. Four treatments (control, CPLM planted with maize on the same day, CPLM planted 1 week after maize, and CPLM planted 2 weeks after maize) were laid in RCBD with four replications per treatment. We used Sustainable Intensification Assessment Framework (SIAF) to assess the sustainability of the above treatments based on five domains (productivity, economic, environment, human, and social). We conducted the assessment in the following three steps: (1) measured selected indicators from the five SIAF domains, which were useful to answering research question; (2) converted measured values of the indicators into scores using a scale of 0–1; and (3) calculated sustainability index using geometric rules considering each SIAF domain as an edge of a pentagon. The sustainability indices for the CPLM increased by 143%–300% compared with the control treatment. The sustainability indices for the CPLM were >1, indicating better sustainability relative to the control treatment, which recorded sustainability index of <1. This suggests that smallholder farmers in northern Ghana and similar agroecologies can intercrop cowpea 1–2 weeks after planting maize as living mulch for better sustainability of their maize production and well-being through its effect on yield, income, food security, nutrition, and gender equity.

Abbreviations: AP, available phosphorus; BCR, benefit–cost ratio; CPLM, cowpea living mulch; CSDM, cowpea living much planted with maize on the same day; C1WAM, cowpea living mulch planted 1 week after maize; C2WAM, cowpea living mulch planted 2 weeks after maize; OC, organic carbon; ROI, return on investment; SI, sustainable intensification; SIAF, Sustainable Intensification Assessment Framework; TN, total nitrogen.

1 | INTRODUCTION

Agriculture is a major source of livelihood for more than 50% of the work force in Africa. Its production in Africa is primarily rainfall dependent and on subsistence basis, with an average land holding of less than 5 ha (Jayne et al., 2014). The subsistent farmers produce about 80% of the food consumed in the region (Chauvin et al., 2012). The productivity of the subsistent farms is low due to several biophysical factors, such as degrading natural resources (low and declining soil fertility), limited use of external inputs, climate change, pests and diseases, unfavorable policies, markets, and institutional arrangements. Africa's population is projected to be doubled from 1.3 to 2.5 billion by 2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2017). This will increase the demand for food from these subsistent farms to feed the growing population and land use for both agricultural and non-agricultural use in the region (Brandt et al., 2017). The current per capita increase in food production in Africa is from conversion of grazing and marginal lands to productive arable lands, which is now becoming limited and unsustainable due to an increase in demand for land use (World Bank, 2007). Sustainable intensification (SI) of farming systems in Africa is a must to meet the growing food demand to feed the increasing human population growth in the region (Vanlauwe et al., 2017). SI of farming system involves the use of agricultural technology that improves productivity per unit area of land in an economically sound manner and reduces negative environmental, human, and social impacts (Pingali, 2012; Pretty et al., 2011; Loos et al., 2014; Musumba et al., 2017). SI of farming system is key to achieving sustainable development goals on ending hunger, malnutrition, and poverty in Africa. Garnett and Godfray (2012) reported that SI of agriculture should be used as a conceptual framework for guiding discussions on achieving balanced outcomes. Sustainable Intensification Assessment Framework (SIAF) was developed to provide a systematic guide and an objective-oriented approach on assessing the sustainability of agricultural technology (Musumba et al., 2017). The SIAF helps to identify the objectives of agricultural innovation and indicators associated with the objectives to assess the performance of the innovation in a balanced approach across five domains (productivity, economic, environment, human, and social). Recent studies have successfully applied the SIAF for sustainability assessment of several agricultural innovations (Abdul Rahman et al., 2020; Fischer et al., 2024; Kotu et al., 2022; Snapp et al., 2018).

Snapp et al. (2018) reported that the SIAF provided systematic means to consider tradeoffs and opportunities associated with maize–legume intercropping systems in Malawi. Abdul Rahman et al. (2020) reported that the SIAF provided a systematic approach for sustainability indexing of intensification practices in groundnut production in northern Ghana. Another study reported that the SIAF helped identify heterogeneity between genders for farmers preferences for SI attributes of maize production in Ghana (Kotu et al., 2022). The study by Fischer et al. (2024) also reported that the SIAF helps identify social components in developing gender-transformative innovation for SI and the importance of having equitable arrangement for both social and technical components of developing gender transformative innovation. There is the need for continuous application of the framework to provide practical evidence of its application dynamics with different innovations at different scales to the scientific community, policy makers, and other relevant stakeholders. There is also limited literature on SI indexing for comparing technologies and addressing this contributes to literature. In this study, we adopted and modified the SI indexing approach by Abdul Rahman et al. (2020) to assess the sustainability of cowpea living mulch (CPLM) technology for smallholder maize production.

Core Ideas

- The Sustainable Intensification Assessment Framework provides a systematic guide for assessing agricultural sustainability.
- Cowpea living mulch recorded higher sustainability scores relative to that of the control treatment.
- Cowpea living mulch sustainably has intensified smallholder maize production.

Living mulch is a cover crop planted either before, same day with, or after the main crop and maintained as cover throughout the cropping season or longer (Hartwig & Ammon, 2002). It creates good soil ecosystem conditions for the main crop to thrive well depending on the type of crop used as living mulch. The use of leguminous crops as living mulch improves soil organic carbon (OC), nitrogen, phosphorus, microbial biomass, bacterial structure, soil moisture retention, infiltration, bulk density, temperature, and erosion relative to non-leguminous crop or control treatment (Hartwig & Ammon, 2002; Qian et al., 2015; Safari et al., 2021; Trail et al., 2016). CPLM is the planting of cowpea as living mulch on the same day with maize or 1–2 weeks after planting maize in a maize-based cropping system (Abdul Rahman et al., 2022). They also reported that CPLM improves soil quality and productivity of smallholder maize in northern Ghana. However, the sustainability of the CPLM for improving smallholder maize productivity is unknown. In this study, we tested the hypothesis that CPLM can sustainably intensify smallholder maize production in northern Ghana. The objective of this study is to assess sustainability of CPLM for smallholder maize production in northern Ghana.

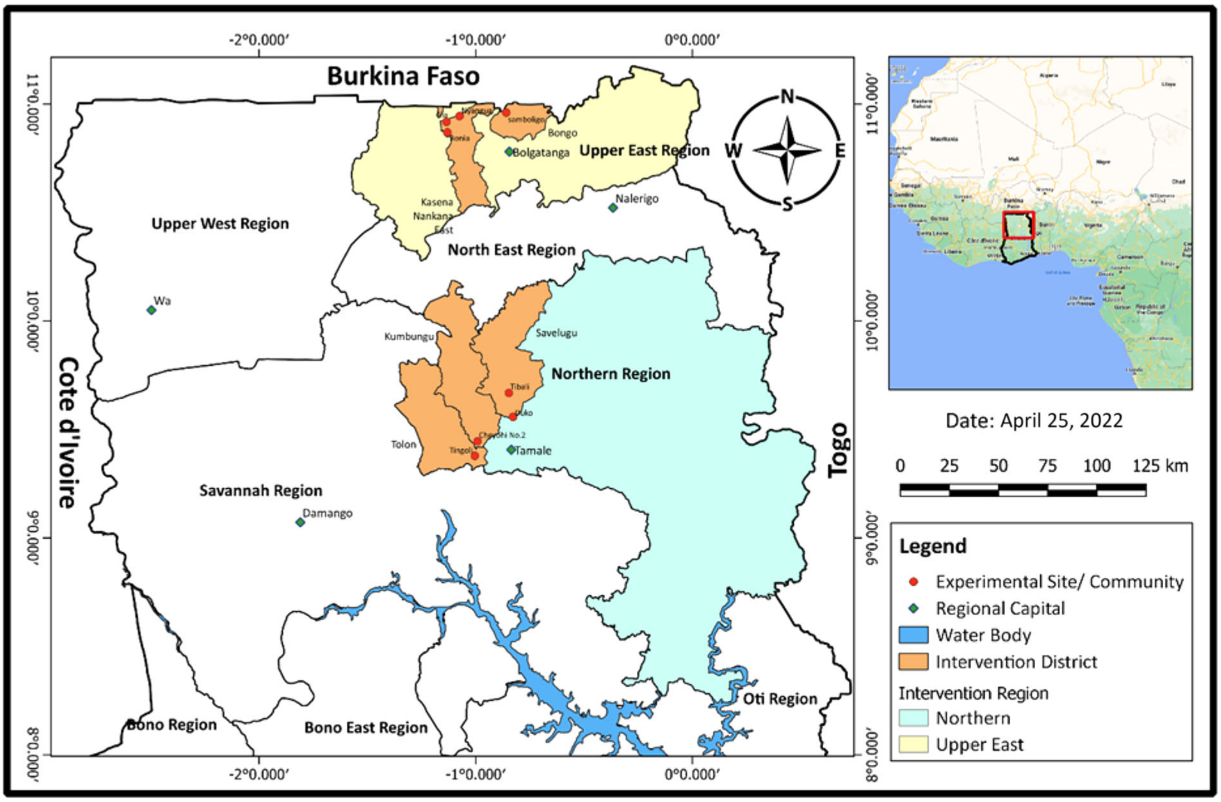

FIGURE 1 Map of Ghana showing experimental sites in the intervention communities.

2 | MATERIALS AND METHODS

2.1 | Study area

The experiment was conducted in Cheyohi No. 2, Tingoli, Duko, and Tibali communities of the Northern Region, and Samboligo, Nyangua, Gia, and Bonia communities in the Upper East Region of northern Ghana during the 2017 and 2018 cropping seasons (Figure 1 and Table S1). The rainfall pattern in these areas is monomodal, which starts from March, peaks in August–September, and ends in October–November. In Northern Region, the total amount of rainfall recorded during cropping seasons (June–October) was 692.4 mm for 2017 and 850.5 mm for 2018 with mean daily temperatures of 23.6–31.7˚C for 2017 and 22.4–30.9˚C for 2018 (Abdul Rahman et al., 2022). The same authors reported that in the Upper East Region, the total amount of rainfall received during 2017 and 2018 was 565.5 and 796.3 mm, respectively, while the daily mean temperatures were 22.2–34.3˚C in 2017 and 23.6–31.1˚C in 2018. The soils of study areas in the Northern Region were developed from sand stones with topsoil properties (0–20 cm) of OC (5.5–9.5 g kg^{-1}) and total nitrogen (TN) (0.5–0.9 g kg^{-1}) (Tetteh et al., 2016). They also reported that the soils of study areas in Upper East Region were developed from granite and Upper Birimian phyllite with topsoil (0–20 cm) properties of OC (4.1–7.5 g kg^{-1}) and TN (0.3–0.4 g kg^{-1}). Details of the initial soil properties for each of the experimental community are presented in Table S1.

2.2 | Experimental design and agronomic management

At each site, four CPLM treatments were laid in a randomized complete block design with four communities as replications. The same fields and communities were used as replications for the 2-year period of the study. The CPLM treatments were no mulch or control (farmer practice, which involves sole maize with no CPLM), cowpea living mulch planted with maize on the same day (CSDM), cowpea living mulch planted 1 week after maize (C1WAM), and cowpea living mulch planted 2 weeks after maize (C2WAM). The cowpea variety used as living mulch was a spreading type with 65 physiological maturity days and a landrace called "Nandambaya." Three maize varieties were used in this study, and details about the maize varieties are reported by Abdul Rahman et al. (2022).

A tractor was used to plough the experimental fields in the Northern Region, while a bullock was used to plough those of the Upper East Region in line with common land preparation practice in each region. The maize plants were planted at a spacing of 75 cm × 40 cm at three seeds per hill and thinned to two seeds per hill after 14 days to achieve a plant density of 66,667 plants ha^{-1} in line with the recommended plant density for maize (Adu et al., 2014). The cowpea plants were planted in the middle of maize rows at an intra-spacing of 20 cm and two seeds per hill to attain a recommended plant density of 133,333 plants ha^{-1} (Omoigui et al., 2018). A compound NPK (15-15-15 N-P_2O_5-K_2O) fertilizer was applied 14 days after planting to the maize plants at 40 kg ha^{-1} NPK. The maize plants were top-dressed with ammonium sulphate (20 kg ha^{-1} N) 21 days after application of compound fertilizer. Hoe weeding was done once 14 days after planting in all the treatment plots and 21 days after first weeding in the control plots.

2.3 | Sustainable intensification assessment

The SIAF was used as a guide to assess the sustainability of the CPLM systems (Abdul Rahman et al., 2020; Musumba et al., 2017). The SIAF is a multi-disciplinary framework that assesses the sustainability of agricultural technology under five domains (productivity, economic, environment, human, and social). The SIAF provides a systematic guide of its application to users, and its application involves the following three main steps: (1) selection and measurement of indicators under the five domains that are key to answering research questions, (2) transformation of these measured indicators into unitless scores to bring indicators with different units onto one scale, and (3) aggregation of indicators under each of the five domains.

2.4 | Selection and measurement of indicator by domains

Considering that the causes of low yield of maize on farmers' fields include low soil fertility and weed infestation, the objective of the CPLM technology is to smoother weed growth and improve soil quality to increase productivity of maize (Abdul Rahman et al., 2022). We selected the following indicators under the five domains of SIAF.

2.4.1 | Productivity

Maize grain and stover yields, cowpea grain yield, and weed biomass were selected and measured in this domain. The maize and cowpea grain yields were selected because of their importance as food. The maize stover was selected because of its use as livestock feed and biochar for soil fertility improvement. The weed biomass was also selected to measure the effect of the living mulch on weed control. Maize cobs from the two middle rows of each treatment plot were harvested at physiological maturity, dehusked, shelled, oven-dried at 65˚C to a moisture content of 13%, and weighed as maize grain yield. The maize plants in the two middle rows from which the cobs were harvested were cut at ground level, oven-dried at 65˚C to a constant weight, and weighed as stover yield. The pods of cowpea plants in the two middle rows of each treatment plot were harvested at physiological maturity, threshed, winnowed, oven-dried at 65˚C to a moisture content of 12%, and weighed as cowpea grain yield. A quadrat of 1 × 1 m^2 was randomly placed three times in each treatment. The weeds species in the quadrate were cut at ground level, oven-dried at 65˚C to constant weight, and weighed as weed biomass.

2.4.2 | Economic

The economic profitability of agricultural technology is a key factor that motivates farmers to adopt new agricultural technologies and to determine the profitability of the CPLM technology. We calculated net income, benefit–cost ratio (BCR), and return on investment (ROI) under this domain. We used secondary data on grain price for maize and cowpea from the Tamale Metropolitan main market (about 20 km from study communities in the Northern region) and Navrongo main market (about 10 km from study communities in Upper East) for the period of October–December of 2017 and 2018 to compute the total revenue of the output. The prices of the grain retrieved from the markets were retail prices and were adjusted to 80% as farmgate prices for the grains (Brooks et al., 2007). We computed total cost of production as cost of inputs and labor used for production. The cost of inputs was the cost of seed and fertilizer. Maize and cowpea prices were also obtained from Seed Production Association Ghana (SEEDPAG) within the respective study areas. The price data of fertilizers (NPK and ammonium sulphate) were collected from Ghana fertilizer dashboard (https://vifaaghana.org/#/ghana/home). The costs of labor included cost for ploughing, planting, weeding, fertilizer application, harvesting, and processing. The cost of labor was obtained using key informant interviews with selected farmers within the experimental communities. The net income was calculated as the difference between total revenue and total cost of production, and the BCR was computed as a ratio of the total revenue and total cost of production (Kahraman et al., 2000). The ROI was also computed in percentage as ratio of net income and total cost of production (Murdoch et al., 2007).

2.4.3 | Environment

Soil physical properties (soil temperature and moisture at the tasseling stage of maize) and chemical properties (OC, TN, and available phosphorus [AP]) were measured in this domain. The above soil physical properties were selected to measure the effect of the CPLM on soil moisture retention for maize, especially at the reproductive stage (tasseling and silking) where moisture is critical for dry matter production. The soil chemical properties were also selected because they are major plant nutrient sources and the most limiting nutrients in the soils of northern Ghana. A soil thermometer (HI 98501; Hanna Instrument Inc.) was randomly placed at five different spots along the diagonals of each treatment plot to measure soil temperature at the tasseling stage of maize. A galvanized iron cores of 4.5-cm inner diameter and 25-cm high were used to take five core samples along the diagonals of each treatment plot to measure moisture content at the tasseling stage of maize (Anderson & Ingram, 1993). After harvesting the maize crops in each cropping season, a composite surface soil (0- to 15-cm depth) samples were taken at five different spots along the diagonals of each plot. The composite soil samples were air-dried, ground, sieved, and analyzed for OC (titration method), TN (Kjeldahl distillation and titration method), and AP (Bray 1 extraction solution and colorimetric method) as outlined by Anderson and Ingram (1993).

2.4.4 | Human

In this domain, we calculated the total calorie and protein production of each treatment as a measure of food security and nutrition indicators. The quantity of grain yield produced by a treatment contributes to the total calorie and protein production. We used secondary data on the calorie and protein content of maize and cowpea from the United States Department of Agriculture, Agriculture Research Services National Nutrient Database for Standard Reference to estimate the total calorie and protein production of each treatment (https://fdc.nal.usda.gov/fdc-app.html#/?query=corn%20grain).

2.4.5 | Social

Community field days were organized at the experimental fields at physiological maturity of the crops for farmers to share experiences among themselves, get feedback from farmers, and allow participating farmers to select their preferred treatment. The evaluation of the treatments was done in two separate groups, the male and female groups. This was done to allow the female farmers to feel comfortable among themselves in expressing their opinion about the technologies. A total of 509 (2017 = 249 and 2018 = 260) farmers evaluated the treatments in the Northern Region. In 2017, the farmers were 51% female and 49% male, while in 2018, their composition was 42% female and 58% male. Similarly, in the Upper East Region, a total of 304 (2017 = 160 and 2018 = 144) farmers participated in the evaluation treatments. In 2017, the composition of the farmers was 54% female and 46% male, while in 2018, their composition was 62% and 38% for female and male farmers, respectively.

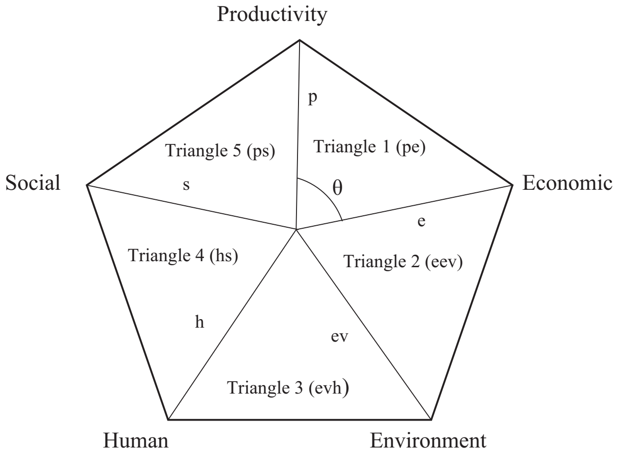

FIGURE 2 Triangles in pentagon representing the five sustainable intensification domains.

2.5 | Transformation, aggregation of indicators, and sustainability indexing

We converted the measured indicators into scores using a linear scoring function of more is better or less is better method (Abdul Rahman et al., 2022; Andrews et al., 2002). For "more is better" indicators, each of the measured value of an indicator was divided by the highest measured value, such that the highest measured value received a score of 1. For "less is better" indicators, the lowest value of a measured indicator was divided by each of the measured values of the indicator, such that the lowest measured value received a score of 1. The scale used for the scoring was in the range of 0–1 with 0 as the least and 1 as the highest indicator of strength. The transformation of measured indicators with different units into unitless scores helped in the aggregation of indicators across domains. Transformed values of indicators (scores) were aggregated under each of the five domains using the arithmetic mean approach (Pollesch & Dale, 2015). Considering each SIAF domain as an edge of a pentagon with a known angle θ and distance (p, e, ev, h, and s) from the center of the pentagon to form five triangles (Figure 2). We calculated sustainability index using geometric rules for calculating the area of the pentagon using Equation (4) (Abdul Rahman et al., 2020; Kang et al., 2005):

$$\text{Sustainability index} = \frac{1}{2}\sin\theta\ [\text{Triangles}\ (1+2+3+4+5)] \tag{1}$$

$$\text{Sustainability index} = \frac{1}{2}\sin\theta\ (pe + eev + evh + hs + ps) \tag{2}$$

$$\theta = \frac{2\pi}{5} = \frac{360}{5} = 72 \tag{3}$$

$$\text{Sustainability index} = \frac{1}{2}\sin 72\ (pe + eev + evh + hs + ps) \quad (4)$$

They also reported that, for a technology to be sustainable, the sustainability index should always be positive, above the score limit (>1), and higher the value, the more sustainable the technology.

2.6 | Statistical analysis

We used Statistical Analysis System for windows (SAS Institute, 2015) to analyze the data from the measured indicators under the productivity, economic, environment, and human domains of the SIAF (Tables 1 and 2). The above data were analyzed on year basis using the model in Equation (5).

$$Y_{ijk} = \mu + B_i + C_j + e_{ijk} \quad (5)$$

where Y_{ijk} is an observation, μ is the experimental mean, B_i is the block (community) effect, C_j is the CPLM effect, and e_{ijk} is the error. Treatment means of significant difference were separated using least significant difference (LSD) test at a probability level of 0.05.

3 | RESULTS AND DISCUSSION

3.1 | Productivity

Maize grain yield showed significant response to CPLM during 2017 and 2018 in both regions (Tables 1 and 2). In Northern Region, maize grain yield for CPLM treatments on the average increased ($p < 0.05$) by 34% during 2017 and 37% during 2018 compared with the control treatment (Table 1). Similarly, in the Upper East Region, maize grain yield for CPLM treatments on average significantly increased by 84% relative to that of the control treatment (Table 2). However, during 2018 in the Upper East Region, maize grain yield decreased with CPLM, and the maize grain yield for control treatment increased ($p < 0.01$) compared with that of CSDM but was not significantly different from that of CPLM at 1–2 weeks after maize (Table 2). The difference in the grain yield data observed in the two regions could be explained by the difference in the soil properties (OC and TN) measured and rainfall pattern in the two regions. The Northern Region is reported to have higher rainfall, better soil properties, and higher average regional maize grain yield relative to that of the Upper East Region (Abdul Rahman et al., 2022; MoFA [Ministry of Food and Agriculture], 2017). The variation in grain yield between the control treatment and CPLM could be explained by the benefits of the CPLM on soil moisture, OC, TN, and AP properties. The improvement in the above soil nutrients by the CPLM, especially during tasseling and silking of maize plant is critical for accumulation and partition of dry matter into yield. In line with this result, other studies have reported an increase in grain yield of living mulch field relative to that of a control field (Abdul Rahman et al., 2022; Caamal-Maldonado et al., 2001; Jamshidi et al., 2013; Trail et al., 2016).

Cowpea grain yield was significantly affected by the time of planting CPLM (Tables 1 and 2). The cowpea grain yield for CPLM with maize on the same day was higher ($p < 0.01$) than that of the CPLM at 2 weeks after maize in both regions. The cowpea grain yield declined by 17% during 2018 relative to that of 2017 in the Northern Region (Table 1). However, in the Upper East Region, the cowpea grain yield increased by 19% during 2018 compared with the grain yield of 2017 (Table 2). The variation in cowpea grain yield among the CPLM could be due to the differences in the time of planting the CPLM, shading effect of the maize plants on the growth of cowpea plants. Planting CPLM at 2 weeks after maize gives the maize competitive advantage for nutrients, light, and water over the cowpea. This result is consistent with the finding that planting cowpea late in maize–cowpea intercropping reduces the grain yield of the cowpea due to the shading effect of the maize plants (Adipala et al., 2002). The contrasting results of cowpea grain yield observed in both regions could be partly explained by the performance of the maize in the CPLM system as the year with high maize grain yield recorded low cowpea grain yield and vice versa. In consonance with this result, other studies have reported similar contrasting results of cowpea grain yield when intercropped with maize or other cereals on the same field for more than 1 year (Abdul Rahman et al., 2021; Trail et al., 2016).

The weed biomass showed significant response to CPLM during 2017 and 2018 in both regions (Tables 1 and 2). The CPLM treatments reduced ($p < 0.01$) weed biomass by 42%–46% in the Northern Region and 38%–51% in the Upper East Region relative to the control treatment. The reduction in weed biomass by the CPLM could be explained by the limited niche in terms of light, water, and nutrients available for weed growth in the CPLM due to the cowpea growth and canopy cover. This result supports the findings that the use of cowpea, velvet bean, and red clover as living mulch in maize production reduces weed growth relative to control treatment (Caamal-Maldonado et al., 2001; Jamshidi et al., 2013; Youngerman et al., 2018).

3.2 | Economic

The CPLM had a significant effect on the BCR, net income, and ROI in both years and regions (Tables 1 and 2). In the Northern Region, the CPLM treatments recorded higher ($p < 0.05$) BCR, net income, and ROI than that of the control

TABLE 1 Cowpea living mulch effect on measured indicators of sustainable intensification in the Northern Region of Ghana, 2017 and 2018.

		2017						**2018**					
Indicator by domain	**Metrics**	**Control**	**CSDM**	**C1WAM**	**C2WAM**	**SEM**	***p*-value**	**Control**	**CSDM**	**C1WAM**	**C2WAM**	**SEM**	***p*-value**
	Productivity												
Crop productivity	Maize grain yield (kg ha^{-1})	1605.6b	2223.3a	2277.8a	1946.7ab	150.65	**	2092.2b	2742.2a	2915.6a	2947.8a	213.58	*
	Cowpea grain yield (kg ha^{-1})	–	490.9a	491.7a	565.5a	66.38	ns	–	571.7a	476.0a	237.0b	44.26	***
	Stover yield (kg ha^{-1})	4027.2a	4406.1a	4271.7a	4382.8a	244.57	ns	3945.0a	4020.2a	4266.5a	4237.3a	323.90	ns
	Weed biomass (g m^{-2})	8.8a	4.9b	5.0b	5.5b	0.37	***	13.2a	6.2b	7.4b	7.8b	0.89	***
	Economic												
Profitability	Cost of production (GHS[a] ha^{-1})	1639.7b	2317.8a	2323.1a	2368.2a	58.54	***	1936.9c	2757.3a	2674.7a	2431.7b	43.61	***
	Revenue from production (GHS ha^{-1})	1332.6b	3224.8a	3272.1a	3204.6a	201.16	***	1903.9c	4176.1a	4052.6a	3379.3b	222.65	***
	Net income (GHS ha^{-1})	−307.1b	907.0a	949.0a	836.5a	144.38	***	−33.0b	1418.8a	1377.9a	947.6a	190.55	***
	Benefit cost ratio	0.8b	1.4a	1.4a	1.3a	0.06	***	1.0b	1.5a	1.5a	1.4a	0.07	***
	Return on investment (%)	−19.7b	37.1a	38.4a	33.9a	6.33	***	−2.2b	49.1a	51.5a	38.3a	6.87	***
	Environment												
Soil physical quality	Temperature (°C)	28.2a	27.1c	27.6b	28.0a	0.12	***	29.4a	28.3c	28.6bc	28.9b	0.13	***
	Moisture (cm^3 cm^{-3}, × 10^{-2})	5.8b	9.7a	8.2a	9.6a	0.63	***	2.8b	5.7a	6.0a	5.7a	0.38	***
Soil chemical quality	Organic carbon (g kg^{-1})	4.8b	6.2a	5.9a	6.1a	0.34	*	5.5b	6.5a	7.1a	6.9a	0.29	***
	Total nitrogen (g kg^{-1})	0.5b	0.7a	0.7a	0.6a	0.03	**	0.6b	0.7a	0.7a	0.7a	0.03	*
	Available phosphorus (mg kg^{-1})	4.6b	6.5a	6.5a	6.8a	0.41	**	5.0b	9.4a	10.2a	9.2a	0.66	***
	Human												
Food security	Calorie production (kcal ha^{-1}, × 10^4)	586.0b	976.5a	996.6a	900.5a	57.26	***	763.7b	1193.0a	1224.1a	1155.6a	78.75	***
Nutrition	Protein production (g ha^{-1}, 10^3)	151.2b	324.9a	330.2a	316.4a	19.20	***	197.1b	392.8a	386.6a	333.4a	21.88	***
	Social												
Gender equity	Technology rating by gender (no. of farmers)												
	Female	14	19	39	55	–	–	18	25	40	25		
	Male	15	25	53	29	–	–	40	42	38	32		

Note: Means with same letter(s) within row under a metric are not significantly different from each other according to least significant difference (LSD) test.

Abbreviations: CSDM, cowpea living mulch planted with maize on the same day; C1WAM, cowpea living mulch planted 1 week after maize; C2WAM, cowpea living mulch planted 2 weeks after maize; SEM, standard error of mean.

[a] Ghana cedis (\$1 = 11.91 Ghana cedis, Bank of Ghana 2024).

$^{ns}p > 0.05$; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

TABLE 2 Cowpea living mulch effect on measured indicators of sustainable intensification in the Upper East Region of Ghana during 2017 and 2018.

		2017						2018					
Indicator by domain	**Metrics**	**Control**	**CSDM**	**C1WAM**	**C2WAM**	**SEM**	***p*-value**	**Control**	**CSDM**	**C1WAM**	**C2WAM**	**SEM**	***p*-value**
	Productivity												
Crop productivity	Maize grain yield (kg ha^{-1})	1084.4b	2120.5a	1881.5a	1991.1a	178.97	***	1462.9a	742.4b	1079.9ab	1324.2a	143.77	**
	Cowpea grain yield (kg ha^{-1})	–	582.0a	334.2b	212.4c	26.24	***	–	606.1a	463.6b	273.7c	30.87	***
	Stover yield (kg ha^{-1})	2176.3a	2118.5a	2785.2a	2203.0a	243.2	ns	2538.9a	2522.2a	2922.2a	2977.8a	223.1	ns
	Weed biomass (g m^{-2})	4.5a	2.1c	2.7bc	3.5ab	0.45	**	8.6a	3.8b	4.2b	4.5b	0.40	***
	Economic												
Profitability	Cost of production (GHS[a] ha^{-1})	1923.9d	2707.4a	2452.8b	2350.4c	30.13	***	2145.7c	2785.4a	2692.7a	2546.3b	35.15	***
	Revenue from production (GHS ha^{-1})	1084.4c	3668.6a	2770.5b	2556.2b	198.36	***	1623.8b	2406.1a	2408.6a	2184.2a	167.5	**
	Net income (GHS ha^{-1})	−839.5c	961.2a	317.7b	205.8b	168.76	***	−521.9a	−379.4a	−284.1a	−362.2a	143.11	ns
	Benefit cost ratio	0.6c	1.4a	1.1b	1.1b	0.06	***	0.7a	0.8a	0.9a	0.9a	0.07	ns
	Return on investment (%)	−44.0c	34.9a	12.3b	7.5b	6.38	***	−25.3a	−15.0a	−10.8a	−14.7a	6.61	ns
	Environment												
Soil physical quality	Temperature (°C)	29.7a	28.1c	28.6b	29.0b	0.17	***	30.2a	29.5b	29.3bc	29.0c	0.14	***
	Moisture (cm^3 cm^{-3}, × 10^{-2})	4.2b	7.2a	6.9a	8.8a	0.71	***	3.9b	7.2a	6.9a	7.4a	0.39	***
Soil chemical quality	Organic carbon (g kg^{-1})	4.5b	5.4a	5.6a	5.5a	0.22	**	4.4b	5.3a	5.5a	5.1a	0.22	**
	Total nitrogen (g kg^{-1})	0.6b	0.7a	0.8a	0.7a	0.04	**	0.6c	0.7b	0.7b	0.8a	0.03	***
	Available phosphorus (mg kg^{-1})	4.2b	9.1a	8.2a	8.8.a	0.94	**	5.5b	9.4a	8.3a	10.2a	0.82	***
	Human												
Food security	Calorie production (kcal ha^{-1}, × 10^4)	395.8b	969.5a	799.0a	798.1a	67.01	***	534.0a	474.6a	549.9a	575.3a	51.00	ns
Nutrition	Protein production (g ha^{-1}, 10^3)	102.2c	336.6a	255.8b	237.5b	18.53	***	137.8b	212.5a	210.8a	189.1a	14.42	**
	Social												
Gender equity	Technology rating by gender (no. of farmers)												
	Female	15	18	21	32	–	–	4	17	32	37		
	Male	13	16	27	18	–	–	4	12	14	24		

Note: Means with same letter(s) within row under a metric are not significantly different from each other according to least significant difference (LSD) test.

Abbreviations: CSDM, cowpea living mulch planted with maize on the same day; C1WAM, cowpea living mulch planted 1 week after maize; C2WAM, cowpea living mulch planted 2 weeks after maize; SEM, standard error of mean.

[a] Ghana cedis ($1 = 11.91 Ghana cedis, Bank of Ghana 2024).

$^{ns}p > 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

treatment in both years (Table 1). A similar trend of results was also observed in the Upper East Region where the BCR, net income, and ROI values of the CPLM treatments increased ($p < 0.05$) relative to that of the control treatment (Table 2).

The significant increase in BCR, net income, and ROI could be attributed to the higher revenue returns generated from the CPLM, which was able to offset the additional cost of production from the CPLM. For example, in the Northern Region, an additional cost of 684–697 Ghana cedis required to practice CPLM generates a revenue of 1901–1965 Ghana cedis (Table 1). Similarly, in the Upper East Region, an additional cost of 529–580 Ghana cedis for CPLM generates a revenue of 709–1914 Ghana cedis (Table 2). In consonance with these results, other studies have reported significant increase in profitability of maize–legume intercropping systems relative to sole maize (Abdul Rahman et al., 2021; Kamara et al., 2019).

3.3 | Environment

In the Northern Region, the CPLM reduced ($p < 0.01$) soil temperature by 2%–3%, increased ($p < 0.01$) soil moisture by 59%–107%, soil OC by 24%–27%, TN by 17%–40%, and AP by 43%–92% relative to that of the control treatment during 2017 and 2018 (Table 1). Similarly, in the Upper East Region, the soil temperature of CPLM declined ($p < 0.01$) by 3%–4% but increased ($p < 0.01$) soil moisture (81%–85%), OC (20%–22%), TN (17%–33%), and AP (69%–107%) compared with that of the control treatment during 2017 and 2018 (Table 2).

The significant effect of CPLM on soil temperature and moisture in all years and regions could be attributed to the presence of the cowpea as a living mulch. The cowpea canopy covers the soil surface against direct sunlight and evaporation from the soil, which in turn affects soil temperature and soil moisture. The variation in soil temperature among the CPLM could also be explained by the time of planting the cowpea as a living mulch and its effect on the growth of the cowpea canopy. The results are in line with findings from earlier studies that mulched fields reduce soil temperature and improve soil moisture retention (Abdul Rahman et al., 2022; Safari et al., 2021; Trail et al., 2016). The effect of CPLM on soil OC, TN, and AP in both years and regions could be explained by (i) the addition and decomposition of leaves and stalks of the cowpea; (ii) the ability of the cowpea to add external source of nitrogen into the soil through biological nitrogen fixation; and (iii) the improved soil microclimate for microbial activity by the CPLM, which enhances the release of nutrients in the soil. In line with this result, other studies have reported significant increase in soil OC, TN, and AP with the use of leguminous crops as living mulch (Abdul Rahman et al., 2022; Hartwig & Ammon, 2002; Qian et al., 2015).

3.4 | Human

The calorie production varied among the treatments with the control treatment recording the least calorie production relative to the CPLM in both years and regions (Tables 1 and 2). The protein production showed significant response to CPLM in both regions. In the Northern Region, the protein production was not statistically different among the CPLM treatments during 2017, but in 2018, the protein production for CPLM with maize on the same day and CPLM at 1 week after maize was significantly higher than that of the CPLM at 2 weeks after maize (Table 1). In the Upper East Region, the protein production for CPLM with maize on the same day was higher ($p < 0.01$) than that of the CPLM at 1–2 weeks after maize in both years (Table 2). Similarly, the protein production for CPLM at 1 week after maize was statistically different from that of CPLM at 2 weeks after maize during 2017 and 2018 in the Upper East Region (Table 2).

The significant increase in calorie and protein production of the CPLM treatments relative to that of the control treatment could be attributed to the effect of the CPLM on grain yield of the maize and cowpea. In line with our results, other studies have reported significant increase in calorie and protein production from intercropping maize with legume relative to that of sole maize (Li et al., 2023; Mukhala et al., 1999). The significant variation in protein production among the CPLM systems could be explained by the difference in the time of planting the CPLM and its effect on growth and grain yield of the cowpea.

3.5 | Social

The farmers rating of the treatments varied across the two regions (Tables 1 and 2). In the Northern Region, majority (83%–88%) of the female farmers preferred the CPLM relative to the control treatment during both years (Table 1). Similarly, most (88%) of the male farmers rated the CPLM treatments above the control treatment in 2017, but this was not the case during 2018 (Table 1). In the Upper East Region, majority of both female (82%–96%) and male (82%–93%) farmers rated the CPLM treatments above the control treatment in both years (Table 2).

Some of the key reasons most of the farmers gave for their choice of CPLM treatments over the control treatment were as follows: higher grain harvest from the cowpea and maize, less risk of total crop failure in terms of bad weather or pest and disease attack, the cowpea canopy cover suppresses weed growth and improves soil moisture retention, and the cowpea also fixes biological nitrogen into soil, which helps to improve the soil fertility. This result is in line with the findings of a follow-up study to scale the CPLM technology beyond

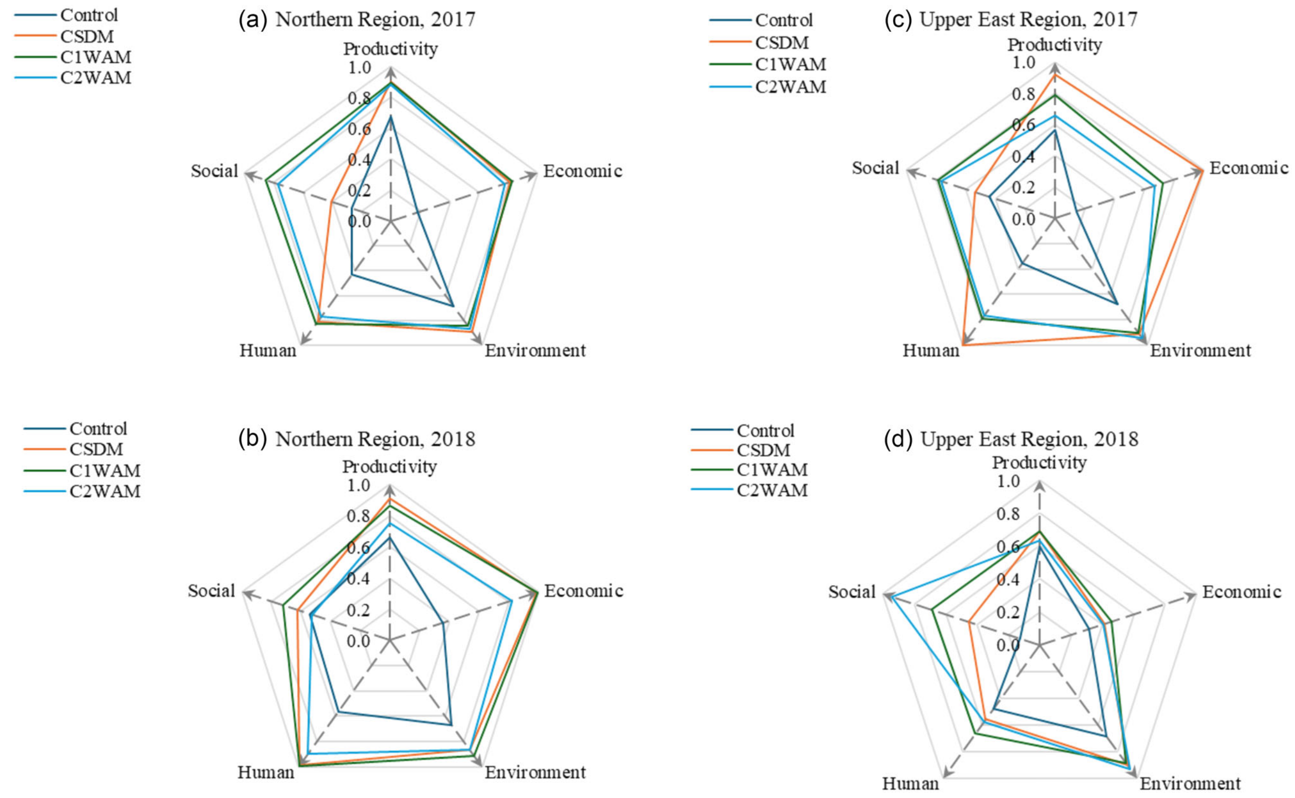

FIGURE 3 Cowpea living mulch effect on sustainable intensification assessment domains in Northern Region, (a) 2017 and (b) 2018, and Upper East Region, (c) 2017 and (d) 2018, of Ghana. CSDM, cowpea living mulch planted with maize on the same day; C1WAM, cowpea living mulch planted 1 week after maize; C2WAM, cowpea living mulch planted 2 weeks after maize.

the intervention districts and regions of this study in northern Ghana (Abdul Rahman et al., 2023). Other studies have also reported significant increase in farmer preference for cover crop intercropping systems relative to other cropping systems in other parts of the world (Jourdain et al., 2020; Nong et al., 2021; Ortega et al., 2016).

3.6 | Sustainability

In the Northern Region, the CPLM recorded higher scores relative to that of the control treatment under productivity, economic, environment, human, and social domains during 2017 and 2018 (Figure 3a,b). Similarly, in the Upper East Region, the CPLM showed consistently higher scores under the five SIAF domains compared with the control treatment during 2017 (Figure 3c). However, during 2018 in the Upper East Region, the CPLM recorded higher scores under four domains (productivity, economic, environment, and social) out of the five domains (Figure 3d). Figure 4 shows the sustainability indices of the CPLM treatments during 2017 and 2018 in both regions. In the Northern Region, the control treatment recorded sustainability index of <1 in both years, while the CPLM recorded indices of >1 in both years (Figure 4a,b). During 2017 in the Upper East Region, the sustainability indices for the CPLM treatments were >1, while that of the control was <1 (Figure 4c). However, in 2018, the sustainability indices for CPLM at 1–2 weeks after maize were >1, while that of the control treatment and CSDM were <1 (Figure 4d).

The 13%–39% increase in productivity score for CPLM relative to the control treatment across the two regions could be attributed to the effect of the CPLM on measured environmental indicators, which translated into an increase in grain yield and reduction in weed biomass. The CPLM canopy cover on soil surface reduces evaporation from the soil, which improves soil moisture retention, leaf litter, and biological nitrogen fixing activity of the cowpea from the CPLM also adds nutrient (carbon, nitrogen, and phosphorus), which are important for development and partition of maize dry matter into yield. The canopy cover of CPLM also reduces niches in terms of light, water, and nutrients available for weed growth, which reduces the growth of weeds in the CPLM systems. In line with these results, other studies have reported significant effect of living mulch on the selected productivity and environmental indicators used in this study (Abdul Rahman et al., 2022; Caamal-Maldonado et al., 2001; Jamshidi et al., 2013; Trail et al., 2016; Youngerman et al., 2018).

The 34% to fourfold increase in economic domain score for the CPLM compared with the control treatment over the

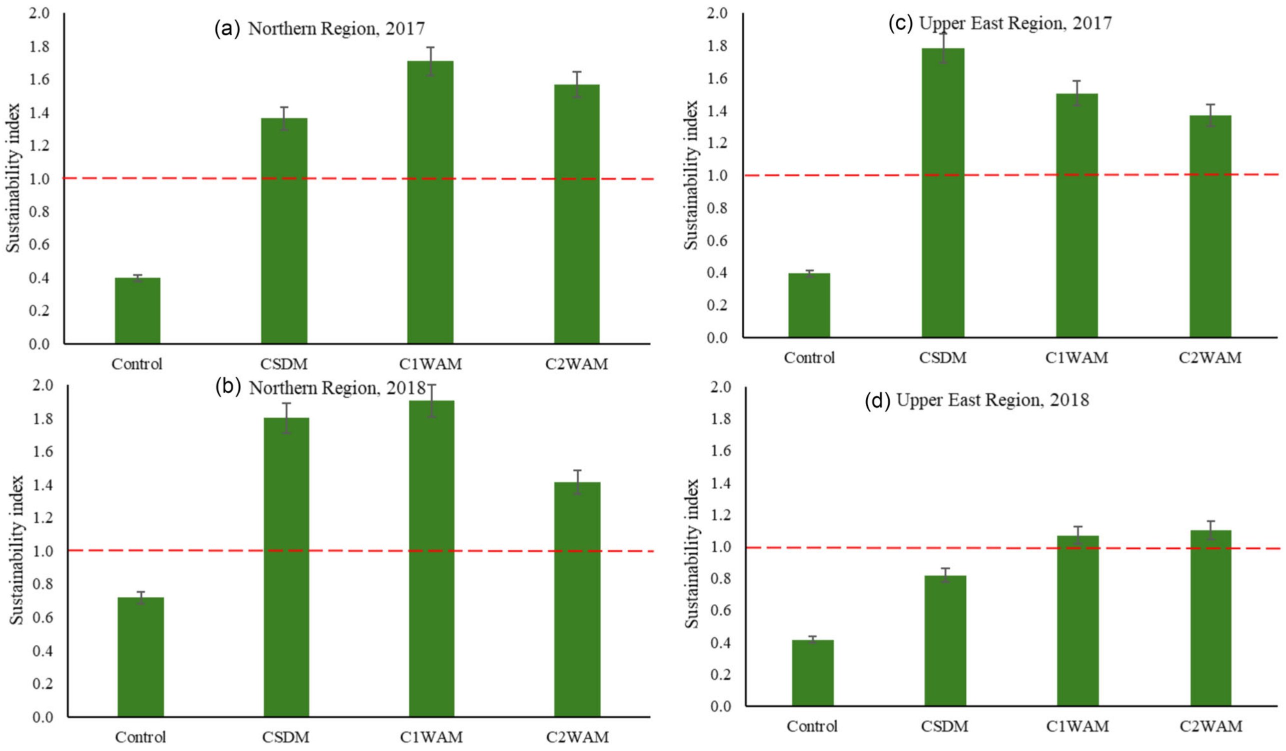

FIGURE 4 Sustainability index as affected by cowpea living mulch in Northern Region, (a) 2017 and (b) 2018, and Upper East Region, (c) 2017 and (d) 2018, of Ghana. CSDM, cowpea living mulch planted with maize on the same day; C1WAM, cowpea living mulch planted 1 week after maize; C2WAM, cowpea living mulch planted 2 weeks after maize. Bars represent standard error, and red broken line indicates sustainability threshold.

two regions could possibly be due to the increase in grain yield of maize and cowpea, which was able to offset the additional cost of production. The grain yield is direct function of profitability, and the revenue generated from the production of grain yield of CPLM was 17%–143% higher than the cost of production of grain yield of CPLM. Similarly, the 25%–136% increase in the human domain score for the CPLM relative to that of the control could also be explained by the differences in the grain yield of maize and cowpea obtained by the treatments. The calorie and protein indicators of the human domain were estimated from the maize and cowpea grain yields. Thus, an increase in maize and cowpea grain yields has a direct effect on calorie and protein production and vice versa. In line with the above findings, Dominguez-Hernandez et al. (2018) reported productivity domain as the key influential attribute in measuring sustainability of agricultural technology, as the yield determines how efficient the technology is and its influence on other domains.

The 26%–36% variation in the environmental domain scores between the CPLM and control treatment could be due to the effect of the CPLM on the measured indicators of the environmental domain. The canopy cover, leaf litter, and biological nitrogen fixing activity of the CPLM improved soil moisture, OC, TN, and AP indicators of the environmental domain. This result supports reports from earlier studies that mulching systems improve soil properties relative to non-mulching system (Abdul Rahman et al., 2022; Hartwig & Ammon, 2002; Qian et al., 2015; Safari et al., 2021; Trail et al., 2016). The majority of the female (82%–96%) and male (82%–93%) farmers showed their preference for the CPLM over the control treatment, and the key reason for their decision was due to the higher grain yield and the improvement of soil microclimate conditions such as soil moisture retention and fertility for the maize crop to thrive well. The reasons given by the farmers for their decisions were in line with the data measured in the productivity and environment domains.

The increase in sustainability indices for the CPLM relative to that of the control treatment could be explained by the effect of CPLM on the measured indicators of the study. The CPLM improved grain yield, weed control, soil moisture, OC, TN, AP, calorie, and protein production, which resulted in higher scores obtained by the CPLM relative to that of the control treatment. The sustainability indices of >1 recorded by the CPLM indicate that CPLM is sustainable for smallholder maize production in northern Ghana. The sustainability indices of <1 recorded by the control treatment in both years and regions also indicate that control treatment is not sustainable for smallholder maize-based cropping in northern Ghana. These findings are in consonant with reports from other studies that, for a technology to be sustainable, the sustainability index should always be positive, above the higher score limit (greater than one), and higher the index, the more sustainability of the technology (Abdul Rahman et al., 2020; Kang et al., 2005).

4 | CONCLUSION

Generally, the SIAF provided a systematic guide and approach for assessing the sustainability of the CPLM technology for smallholder maize-based cropping system in northern Ghana. The sustainability indices for the CPLM were 143%–275% higher than that of the control treatment in Northern Region during 2017 and 2018. A similar trend was observed in the Upper East Region with the CPLM recording 150%–300% increase in sustainability indices relative to that of the control treatment during both years. The sustainability index of the control treatment was <1 (below the maximum score limit) in both years as well as regions, and this index indicates that the control treatment is not sustainable for smallholder maize production in both regions. The sustainability indices recorded by the CPLM were above the maximum score limit (greater than one), which indicates better sustainability system for smallholder maize production in northern Ghana. The results suggest that smallholder maize farmers in northern Ghana and similar agroecologies can intercrop cowpea, especially at 1–2 weeks after planting maize as living mulch for better sustainability of their maize production and well-being through its effect on yield, income, food security, nutrition, and gender equity.

AUTHOR CONTRIBUTIONS

Nurudeen Abdul Rahman: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing—original draft; writing—review and editing. **Asamoah Larbi**: Conceptualization; formal analysis; investigation; methodology; supervision; validation; visualization; writing—original draft; writing—review and editing. **Fred Kizito**: Formal analysis; investigation; methodology; supervision; validation; visualization; writing—original draft; writing—review and editing. **Bekele Hundi Kotu**: Formal analysis; methodology; supervision; validation; visualization; writing—original draft; writing—review and editing. **Irmgard Hoeschle-Zeledon**: Methodology; project administration; resources; software; supervision; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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