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Greenhouse Farming Adoption: Determinants and Impacts on Dietary Diversity, Food Consumption and Insecurity in Ghana

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ABSTRACT

Food and nutrition insecurity remains a pressing challenge in many emerging economies. This study examines the heterogeneous impacts of greenhouse farming (GHF) on household food insecurity, dietary diversity, and food consumption in Ghana. Using survey data from 400 vegetable-producing households and applying marginal and policy-relevant treatment effect (MTE and PRTE) models, the analysis reveals significant heterogeneity in gains from GHF, shaped by both observable and unobservable household characteristics. Overall, GHF adoption is associated with increased dietary diversity and food consumption, as well as reduced food insecurity. The PRTE estimates indicate that improving farmers' access to produce markets could raise household dietary diversity and food consumption by 42% and 41%, respectively, while lowering food insecurity by 25%. By quantifying both the heterogeneous impacts of GHF and the role of market access, this study provides new evidence on how climate-smart agricultural technologies can enhance household nutrition and food security in sub-Saharan Africa.

1 | Introduction

Globally, food and nutrition insecurity remains a pressing challenge, particularly in emerging economies. In 2020, between 720 and 811 million people faced hunger (FAO et al. 2024). Progress toward reducing food insecurity has been undermined by recent global shocks, including the COVID-19 pandemic, the Russia–Ukraine war (Osendarp et al. 2022), and extreme climatic events (Hall et al. 2021; Abu Hatab 2022). These shocks, compounded by rising food and energy prices, have intensified undernourishment and household food insecurity.

Urbanisation further complicates food security by reshaping consumption patterns and placing pressure on production and supply systems. The rapid expansion of cities and the emergence of megacities require reliable food provision in environments traditionally unsuitable for agriculture. While infrastructure improvements may enhance physical access, financial access remains constrained. Unlike rural households that often produce part of their food, urban and peri-urban populations are highly dependent on markets and therefore vulnerable to price volatility (Szabo 2015; De Bruin and Holleman 2023). Price increases frequently force households to cut other expenditures,

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leading to inadequate or poor-quality diets and growing reliance on inexpensive street foods, which are often unhygienic and pose health risks. With projections suggesting that seven in ten people will live in cities by 2050 (De Bruin and Holleman 2023), urbanisation and rural–urban migration of agricultural labour are expected to heighten pressures on food availability, processing, and distribution, thereby worsening food and nutrition insecurity.

These concerns have sparked debate on the potential role of urban food production in strengthening agri-food systems. Greenhouse farming (GHF) has been proposed as a promising alternative to conventional agriculture, offering opportunities for year-round production and efficient use of scarce urban resources (Shamshiri et al. 2018; El Bilali et al. 2019; Yeşil and Tatar 2020; Torsu et al. 2024). However, in most developing countries, including Ghana, GHF has yet to feature prominently in urban policy agendas addressing food and nutrition insecurity. Rising urbanization, coupled with persistent food insecurity and demographic shifts, underscores the need for policymakers, researchers, and urban planners to consider GHF in local food systems.

In Ghana, the government has begun to integrate GHF into its food security strategy through initiatives such as the GhanaVeg Programme, in collaboration with Wageningen UR Centre for Development and Innovation, the Ministry of Food and Agriculture, the Ghana Export–Import Bank, and Agri-Impact Consult. These efforts have focused on installing greenhouses in urban centres and providing subsidies to agribusinesses adopting GHF, thereby promoting efficient, year-round food production (Van Asselt et al. 2018; Torsu et al. 2024). Ghana's progress positions GHF as a potential game-changer for addressing climate vulnerability and food insecurity in Africa (Forkuor et al. 2022).

Existing studies highlight the climate-smart potential of GHF. For example, Achour et al. (2021) show that GHF enables control of internal climatic conditions, while Kesavan and Swaminathan (2018) emphasize the role of smart technologies in enhancing adaptation and mitigation. Evidence also suggests that GHF stabilizes yields and boosts productivity (Reddy 2016; Thiye et al. 2017; Musayev et al. 2018; Banerjee et al. 2022), largely through water-efficient technologies and climate control measures. Additional benefits include pest and disease management (Yeo et al. 2022) and reductions in methane and CO₂ emissions (Valdez et al. 2016). In southern Ghana, GHF adoption has also been linked to improved per capita household expenditure (Torsu et al. 2024).

Despite these promising findings, research has largely focused on the environmental benefits of GHF (Valdez et al. 2016; Kesavan and Swaminathan 2018; Achour et al. 2021; Yeo et al. 2022), with limited attention to its socioeconomic implications. By contrast, other climate-smart agricultural (CSA) practices—such as crop diversification (Frimpong et al. 2022; Belay et al. 2024), improved varieties (Belay et al. 2024), irrigation management (Owusu-Sekyer et al. 2021), and soil and water conservation (Di Falco et al. 2011)—have been extensively studied in relation to yield, income, and food security outcomes. Few studies have examined GHF's impact on household food security. Exceptions

include Forkuor et al. (2022), who explored large-scale GHF promotion, and Stemmler and Meemken (2023), who assessed its effects on labor demand, particularly among women. However, no study has yet investigated its direct impact on food and nutrition security or dietary diversity.

This study addresses that gap by examining the effects of GHF on household food and nutrition security in southern Ghana. Specifically, we analyse its impact on dietary diversity, food consumption, and food insecurity using the Household Dietary Diversity Score (HDDS), Food Consumption Score (FCS), and Household Food Insecurity Access Scale (HFIAS) (Swindale and Bilinsky 2006; Coates et al. 2007; Leroy et al. 2015; Marivoet et al. 2019; Nunoo et al. 2023). Our contributions are threefold. First, we provide empirical evidence on the socioeconomic impacts of GHF adoption, expanding the literature on CSA practices. Second, we inform debates on achieving SDG 2—ensuring year-round access to safe, nutritious, and sufficient food (Target 2.1) and eliminating all forms of malnutrition (Target 2.2)—as well as integrating climate action into national policies (Target 13.2). Third, from a methodological perspective, we apply a marginal treatment effects (MTE) framework, which accounts for both observable and unobservable factors influencing adoption. Unlike local average treatment effects (LATEs), MTE allows estimation of treatment effects across the full population (Heckman and Vytlacil 2007; Andresen 2018) and enables policy simulations on how adoption incentives can improve food security outcomes.

The rest of the paper is structured as follows: section two presents the methodology, and the subsequent section presents the results and discussions of the study. Conclusions and implications are presented in the last section.

2 | Methodology

2.1 | Conceptual and Empirical Specification

Given the potential benefits of GHF (e.g., Karanisa et al. 2022; Stemmler and Meemken 2023; Torsu et al. 2024), we assume that a household's decision to use greenhouse farming is premised on the anticipated gains. Rationally, a household will use greenhouse farming if the anticipated gains are greater than the gains from conventional farming practices. The household's decision to adopt GHF is expected to affect the food consumption, dietary diversity, and food insecurity experiences (Frimpong et al. 2022; Belay et al. 2024). We let Q denote the outcome variables, including HDDS, FCS, and HFIAS scores. Also, H_i denotes the adoption decision of the i -th household. If a household adopts GHF, then $H_i = 1$, and $H_i = 0$, if otherwise. Household i will adopt GHF if the anticipated gains (Q_{i1}) are greater than the gains from non-GHF (Q_{i0}), such that $H_i = 1$, if $H_i^* = Q_{i1} - Q_{i0} \geq 0$, otherwise $H_i = 0$. Empirically, we express the relationship between Q and measured covariates as:

$$Q_{ig} = \alpha_g X_i + \delta R_i + \epsilon_{ig} \quad (1)$$

where X_i denotes a vector of socioeconomic (e.g., household size, education) and institutional (e.g., access to credit, extension, climate information, market information) factors of

household i , R_i is the regional dummies, α and δ are parameters to be estimated, and ϵ_i is the error term. The subscript g represents the participation decision, where $g = 1$ is for GHF adopters and $g = 0$ is for GHF non-adopters. Engagement in GHF is not random, and as such, households select themselves into participation in GHF based on observed and unobserved variables. Hence, the decision to farm using GH technology is endogenous. Since the anticipated gains (H_i^*) from participating in GHF is not directly measured, it is expressed as a function of observed factors:

$$H_i = f_n(X_i, V_i) - U_i \quad (2)$$

where X_i is as defined above and V_i denotes the exclusion restriction for model identification. In this study, we used the perceived benefit of greenhouse technology as the identifying instrument for the selection equation of the MTE model. U_i captures the unobserved heterogeneity in the household's tendency to engage in GHF. The negative sign attached to U_i implies that unseen resistance limits households from participating in GHF (Andresen 2018). The selection rule in equation (2) can be transformed using the specification in equation (3):

$$f_n(X_i, V_i) - U_i \geq 0 \Leftrightarrow f_n(X_i, V_i) \geq U_i \Leftrightarrow h_u[f_n(X_i, V_i)] \geq h_u(U_i) \quad (3)$$

where h_u represents the cumulative distribution function of U_i , $h_u[f_n(X_i, V_i)]$ represents the likelihood that household i with observable socioeconomic and institutional factors X_i and the instrument V_i will engage in GHF. $h_u(U_i)$, represented by $h_u(U_i) \equiv \epsilon_{H_i}$, denotes the distribution quantiles of unseen resistance to engage in GHF (U_i) (Cornelissen et al. 2018). Following Andresen (2018) and Cornelissen et al. (2018), the heterogeneous anticipated gains subject to observable and unobservable factors are expressed as:

$$\begin{aligned} Q_i &= H_i Q_{1i} + (1 - H_i) Q_{0i} \\ &= Q_{0i} + H_i (Q_{1i} - Q_{0i}) \\ &= X_i \alpha_0 + H_i \underbrace{[X_i (\alpha_1 - \alpha_0) + \epsilon_{1i} - \epsilon_{0i}]}_{\Delta_i \equiv Q_{1i} - Q_{0i} = X_i (\alpha_1 - \alpha_0) + \epsilon_{1i} - \epsilon_{0i}} + \epsilon_{0i} \end{aligned} \quad (4)$$

The variables in equations (2) and (4) are identified by satisfying the basic conditional independence IV assumption that $\epsilon_{1i}, \epsilon_{0i}, \epsilon_{H_i}$ are statistically independent of the perceived benefit of greenhouse technology (V_i), given the socioeconomic, institutional, and location specific characteristics. Following Cornelissen et al. (2016), the MTE, which is a function of the treatment effects (TE) at any given ϵ_{H_i} is specified as

$$\begin{aligned} \text{MTE}(X_i = x, \epsilon_{H_i} = \epsilon_h) \\ = E[\Delta_i / X_i = x, \epsilon_{H_i} = \epsilon_h] \end{aligned} \quad (5a)$$

The TE of a given household with observable socioeconomic and institutional factors $X_i = x$ at ϵ_h -th, where the threshold of the unobserved heterogeneity takes a propensity score of $\rho(X_i, V_i) = \epsilon_h$. Considering that the MTE is composed of observable and unobservable parts, we can re-specify the MTE equation as:

$$\text{MTE}(x, \epsilon_h) = E[\Delta_i / X_i = x, \epsilon_{H_i} = \epsilon_h] = \underbrace{x(\alpha_1 - \alpha_0)}_{\text{observable part}} + \underbrace{E(\epsilon_1 - \epsilon_0 / \epsilon_{H_i} = \epsilon_h)}_{\text{unobservable part}} \quad (5b)$$

Based on equation (4) and the propensity score, we now express and estimate the outcome equation as:

$$E(Q_i / X_i = x, \rho(X_i, V_i) = \rho) = X_i \alpha_0 + X_i (\alpha_1 - \alpha_0) \rho + D(\rho) \quad (6)$$

where Q_i captures the gains from GHF for households with varying observable socioeconomic and institutional factors ($X_i = x$), propensity score ρ , and a non-linear function of ρ denoted by $D(\rho)$. As noted by Carneiro et al. (2017) and Cornelissen et al. (2016), equation (6) can be differentiated with respect to ρ to obtain the MTE below:

$$\begin{aligned} \text{MTE}(X_i = x, \epsilon_{H_i} = \rho) &= \frac{\partial E(Q_i / X_i = x, \rho(X_i, V_i) = \rho)}{\partial \rho} \\ &= x(\alpha_1 - \alpha_0) + \frac{\partial D(\rho)}{\partial \rho} \end{aligned} \quad (7)$$

Analytically, the joint estimation of the MTE model starts with equation (2) using a probit model, and is then followed by the estimation of the outcome equation as in equation (8):

$$Q_i = X_i \alpha_1 + X_i (\alpha_1 - \alpha_0) \hat{\rho} + \sum_{d=1}^D \varphi_d \hat{\rho}^d + \lambda_i \quad (8)$$

We compute an MTE curve from equation (8) by differentiating it with respect to $\hat{\rho}$. This curve explains the role of unobserved variables influencing uptake of GHF. In plotting the curves, the TE of adopting GHF on the outcome variables are expressed as a function of the unobservables. As a robustness check for our estimation, we compared different polynomial orders $d = 1, \dots, 4$, to check the sensitivity of the plotted MTE curves. In this study, we focused on the average treatment effect (ATE), average treatment effect on the treated (ATT), and the average treatment effect on the untreated (ATU) for the adoption of GHF on the outcome variables (Q) of interest. These are expressed as:

$$\begin{aligned} \text{ATE} &= E[Q_{1i} - Q_{0i}] = E[\alpha_1(X_i) - \alpha_0(X_i)] \\ \text{ATT} &= E[Q_{1i} - Q_{0i} / H_i = 1] + E[\epsilon_1 - \epsilon_0 / H_i = 1] = E[\alpha_1(X_i) - \alpha_0(X_i) / H_i = 1] + E[\epsilon_1 - \epsilon_0 / H_i = 1] \\ \text{ATU} &= E[Q_{1i} - Q_{0i} / H_i = 0] + E[\epsilon_1 - \epsilon_0 / H_i = 0] = E[\alpha_1(X_i) - \alpha_0(X_i) / H_i = 0] + E[\epsilon_1 - \epsilon_0 / H_i = 0] \end{aligned} \quad (9)$$

Considering the policy relevance of the success of implementing a sustainable and viable GHF programme, as well as its adoption, we extend our analysis in the present study to include policy-relevant treatment effects (PRTE) to examine how the impact of the adoption of GHF will differ in the baseline scenario and alternative policy. In particular, the policy variable included in this study is access to market information. Linking farmers to relevant markets is very crucial for producers of fresh produce from GHF. Postharvest loss is still a major challenge in SSA, partly due to a lack of proper marketing channels and networks for perishable products (FAO et al. 2019). Therefore, we examine the impact of a 20% increase in access to market information

on the outcome variables. The simulated increase—from a baseline average of 62% to 82%—was determined through qualitative discussions with stakeholders along the vegetable value chain, including producers, marketers, and GHF promoters. The PRTE equation is specified as:

$$\text{PRTE}(X) = \frac{E[Q_i / X_i = x, \text{alternate policy}] - E[Q_i / X_i = x, \text{baseline policy}]}{E[H_i / X_i = x, \text{alternate policy}] - E[H_i / X_i = x, \text{baseline policy}]} \quad (10)$$

2.2 | Measurement of Outcome Variables

In this study, the outcome variables we examined regarding the adoption of GHF include the HDDS, FCS, and HFIAS scores. These outcome indicators were used to capture food and nutrition security within the households (Swindale and Bilinsky 2006; Coates et al. 2007; Leroy et al. 2015; Marivoet et al. 2019). The HDDS reveals the ability of the households to access twelve categories of food items (see Table 1). Following Swindale and Bilinsky (2006), each food category is given a value of 1 if consumed during the past 7 days, or otherwise 0. In this study, we further asked how many days in a typical week did the household consume each of food groups. Responses ranged from 0 to 7 days. For a given household, the computed HDDS is the sum of the scores for each of the food categories. The FCS collates household-level data on the diversity and frequency of food categories consumed. Weights are assigned to the food categories based on the relative nutritional content (see the 2nd column of Table 1). The food items consumed by the households are grouped into the eight food categories under the FCS indicator. The consumption frequencies of the food items under each category are summed up and multiplied by their corresponding weights. The FCS is

finally computed by summing the weighted food categories. It is important to mention that HDDS and FCS are correlations (Coates et al. 2007; Leroy et al. 2015). HFIAS measures the prevalence of household food insecurity (access) and identifies variations in the household food insecurity condition over a period. The HFIAS comprises 9 ‘occurrence’ and 9 ‘frequency-of-occurrence’ questions. The households were asked to answer the questions based on their food security experience in the past month. The HFIAS was measured as a continuous variable by scoring each of the 9 questions from 0 to 3. The scores are summed up such that the final HFIAS scores range from 0 to 27 (Coates et al. 2007).

2.3 | Identification Strategy

The MTE framework requires an instrumental variable that influences the likelihood of adopting GHF but does not directly affect the outcome variables. Given the increasing prominence of GHF, awareness of its environmental, economic, and sustainability benefits is a prerequisite for adoption. Accordingly, this study employs the perceived benefit of greenhouse technology as the identifying instrument. Consistent with expected utility theory (Peasgood 2014), farmers weigh the anticipated benefits before making adoption decisions. Thus, perceived benefits are expected to influence adoption but not directly affect HDDS, FCS or HFIAS, except through adoption. While perceptions of climate-resilient agricultural practices may evolve, such changes primarily shape future adoption decisions. Prior studies (Di Falco and Veronesi 2013; Owusu-Sekyere et al. 2021; Torsu et al. 2024) similarly find that perceived benefits do not directly affect outcomes such as yield, income, or farm performance.

To measure this instrument, twelve statements on potential benefits of GHF were included in the survey, measured on a five-point Likert scale, and derived from the literature (Karanisa et al. 2022; Savic and Ilin 2022). Confirmatory factor analysis was employed to validate the measurement model and assess whether the observed variables adequately represented the latent construct. Using eigenvalues with varimax rotation, a single factor was retained and labeled perceived benefit of GHF (Table 2).

Sampling adequacy and reliability were confirmed by the Kaiser–Meyer–Olkin test and reliability coefficients. Instrument relevance was tested using a Wald test in the first-stage adoption model, while instrument validity was assessed by regressing the instrument on the outcome variables via OLS (see Table S2).

2.4 | Sampling and Data Collection

The data used in the study was obtained from three regions in Ghana. The regions were Greater Accra, Ashanti, and the Central Region. Using a multistage sampling approach, first, the regions were purposively selected based on the concentration of greenhouse technologies in the regions. Again, we purposively selected two suburbs from Greater Accra Region (Dwahanya and Lakeside), three from the Ashanti Region (Ayeduaase,

TABLE 1 | Food categories used to compute HDDS and FCS indicators.

HDDS indicator		FCS indicator	
No.	Food category	Food category	Weight
1.	Cereals	Main staples	2
2.	Roots and tubers	Pulses	3
3.	Fruits	Vegetables	1
4.	Vegetables	Fruit	1
5.	Meat, offal and poultry	Meat and fish	4
6.	Eggs	Milk	4
7.	Fish and seafood	Sugar	0.5
8.	Pulses, nuts and legumes	Oil	0.5
9.	Milk and milk products		
10.	Oils and fats		
11.	Sugar and honey		
12.	Miscellaneous		

Source: Swindale and Bilinsky (2006); World Food Program (2008).

TABLE 2 | Confirmatory factor analysis results for perceived benefit of greenhouse farming.

Statements	Factor loadings (varimax)	KMO
1. Temperatures and humidity are easily controlled in GHF	0.6	0.88
2. Crops are protected against adverse weather, pest, and disease under GHF	0.71	0.93
3. GHF unlike rain-fed farming, allows all year-round crop production	0.65	0.92
4. GHF in the urban area can help in purifying the air	0.67	0.91
5. GHF requires small land area for production	0.53	0.88
6. GHF minimizes carbon dioxide emission	0.58	0.88
7. Greenhouse covers can change the direction of the sun's ray	0.58	0.88
8. No use of fossil fuels is required in GHF	0.61	0.88
9. GHF makes farming attractive To the youth and women	0.69	0.89
10. GHF produces higher yields	0.57	0.87
11. GHF is highly profitable	0.57	0.92
12. Crops from GHF are clean and safe for consumption	0.64	0.91
Eigenvalue of perceived benefit		4.72
Overall Kaiser–Meyer–Olkin (KMO)		0.89
Scale reliability coefficient		0.86

Source: Authors computation.

Akumadan and Ejisu-Asinipong), and two from the Central Region (Jukwaa and Asemasa). In determining the sample size, there was a need to assume a given margin, confidence interval, and power value. We used a margin of error of 0.05 at a 95% confidence interval and a power value of 90% to ensure that a test has high power. Using 90% power, the required sample size was 216 and 265 for the one-sided and two-sided tests, respectively. From a sample frame of greenhouse farmers, there was a total of 209 GHF adopters and 191 non-adopters, for a total of 400 respondents. Using proportional sampling, we selected 227, 111 and 62 respondents from Greater Accra, Ashanti and the Central Region, respectively. The difference in the number of samples is proportionally based on the number of GHF and

vegetable producers in the study areas. Our sample size is above the representative sample according to the estimated number of vegetable producers in the urban settings and the power calculation estimates.

3 | Results and Discussion

3.1 | Descriptive Results

Table 3 reports the descriptive statistics of variables used in the regression models. Approximately 52% of farmers in the sample have adopted GHF. Significant differences between adopters and non-adopters are observed across several characteristics, including age, marital status, household size, education, experience, awareness, farm size, farm ownership, livestock production, FBO membership, market information, market distance, fertilizer use, seeding rate, and region. Compared with non-adopters, adopters are younger, better educated, less experienced in farming, and more engaged in non-farm income activities. They also operate smaller farms, own fewer livestock, live in smaller households, and are more likely to be single and members of FBOs. Adopters report less access to markets and travel longer distances to reach them, apply more fertilizer, use improved seed varieties, and are less likely to reside in the Ashanti Region.

With respect to perceived benefits, adopters hold positive views of GHF technology, while non-adopters report negative perceptions. Table 4 presents the summary statistics of outcome variables for both groups. Apart from the food insecurity score, differences in food security outcomes between adopters and non-adopters are statistically insignificant. These differences, however, do not account for unobserved heterogeneity that may influence dietary diversity, food consumption, and food insecurity.

3.2 | Empirical Findings

3.2.1 | Determinants of Adoption of GHF

In this section, we present the probit estimates from the selection equation of the MTE model, which examines the determinants of GHF adoption (Table 5). The results indicate that the perceived benefits of GHF exert a positive and statistically significant influence on adoption decisions. With respect to socio-economic variables, age is negatively and significantly associated with adoption, suggesting that older farmers are less likely to adopt GHF than younger farmers, who tend to be less risk averse. Gender is positive and significant, indicating that male farmers are more likely to adopt GHF, a finding consistent with the demographic composition of farmers across the three study regions, where men predominate (GSS 2018). Farming experience is negatively associated with adoption, implying that farmers with longer agricultural experience are less inclined to adopt GHF, possibly due to their greater risk aversion and preference for traditional farming systems. Awareness of greenhouse technology shows a positive and significant effect, underscoring the importance of access to information in facilitating the adoption of agricultural

TABLE 3 | Descriptive statistics of the variables examined in the regression models.

Variables	Variable definition	Pooled mean	Adopters mean	Non-adopters mean	Mean difference
Adoption	1 if GHF adopter, 0 otherwise	0.52 (0.03)			
Socioeconomic factors					
Age	Years	36.81 (0.57)	32.29 (0.60)	41.74 (0.87)	−9.45***
Gender	1 if male farmer, 0 otherwise	0.79 (0.02)	0.80 (0.03)	0.79 (0.03)	0.01
Marital status	1 if married, 0 otherwise	0.56 (0.02)	0.43 (0.03)	0.71 (0.33)	−0.28***
Household size	Number of members in the household	5.33 (0.11)	4.83 (0.12)	5.86 (0.18)	−1.04***
Education	Number of years in formal education	10.69 (0.25)	11.72 (0.35)	9.55 (0.32)	2.16**
Experience	Number of years in farming	6.57 (0.25)	4.32 (0.15)	9.03 (0.43)	−4.71***
Awareness	1 if farmer is aware, 0 otherwise	0.71 (0.02)	0.96 (0.01)	0.42 (0.04)	0.54**
Farm size	Size of the farm under cultivation in hectares	0.21 (0.01)	0.14 (0.01)	0.29 (0.02)	−0.15
Individual owned land	1 if farmer owned, 0 otherwise	0.32 (0.02)	0.41 (0.03)	0.23 (0.03)	0.17
Family owned	1 if farmer owned, 0 otherwise	0.19 (0.01)	0.06 (0.02)	0.35 (0.03)	0.28***
Non-farm income	The total amount of off-farm income in GH¢	991.84 (114.86)	1924.84 (205.73)	87.65 (35.29)	1837.18***
Off farm employment	1 if farmer has off farm job, 0 otherwise	0.07 (0.01)	0.09 (0.02)	0.04 (0.01)	0.05
Livestock production	1 if farmer rears, 0 otherwise	0.07 (0.01)	0.01 (0.01)	0.12 (0.02)	−0.11***
Institutional factors					
Extension access	1 if a farmer has access, 0 otherwise	0.32 (0.25)	0.29 (0.04)	0.28 (0.04)	0.01
Climate information	1 if a farmer has access to climate information, 0 otherwise	0.70 (0.03)	0.86 (0.03)	0.59 (0.04)	0.22
Credit access	1 if a farmer has access to credit, 0 otherwise	0.61 (0.02)	0.72 (0.03)	0.48 (0.04)	0.25
FBO membership	1 if a farmer is a member of farmer-based organization, 0 otherwise	0.81 (0.02)	0.87 (0.03)	0.74 (0.03)	0.13*
Labour (man days)	Number of hired farm labourers	5.76 (0.06)	5.69 (0.10)	5.84 (0.08)	−0.15

(Continues)

TABLE 3 | (Continued)

Variables	Variable definition	Pooled mean	Adopters mean	Non-adopters mean	Mean difference
Market information	1 if a farmer has access to market information, 0 otherwise	0.62 (0.03)	0.04 (0.04)	0.54 (0.04)	−0.50***
Market distance	Distance from farm to food market in kilometres	26.09 (1.26)	20.34 (1.52)	31.65 (1.89)	−11.31***
Support schemes access	1 if a farmer has access to support schemes, 0 otherwise	0.61 (0.02)	0.72 (0.03)	0.48 (0.04)	0.24
Assets	Number of assets owned by the farmer	8.61 (0.07)	9.42 (0.08)	7.73 (0.09)	1.69
Technological factors					
Improved seeds	1 if the farmer has access to improve seeds, 0 otherwise	0.77 (0.02)	0.89 (0.02)	0.63 (0.03)	0.26
Fertiliser application	Quantity of fertiliser applied per kilograms per year	27.03 (1.75)	30.74 (2.63)	23.44 (2.30)	7.29***
Seed rate	Quantity of seeds sown in grams per year	1252.11 (83.89)	1478.54 (147.23)	1032.66 (80.08)	445.89**
Irrigation access	1 if the farmer has access to irrigation, 0 otherwise	0.83 (0.01)	0.93 (0.12)	0.72 (0.03)	0.21
Location dummies					
Greater Accra region	1 if the farm is located in greater Accra region, 0 otherwise	0.58 (0.03)	0.62 (0.04)	0.54 (0.04)	0.07
Ashanti region	1 if the farm is located in the Ashanti region, 0 otherwise	0.27 (0.02)	0.24 (0.03)	0.31 (0.04)	−0.07**
Central region	1 if the farm is located in the Central region, 0 otherwise	0.15 (0.02)	0.15 (0.15)	0.15 (0.03)	0.00
Perceived benefit of GHF	Perception about GHF technology. Continuous variable from CFA	1.45 (0.94)	0.49 (0.07)	−0.54 (0.04)	−1.03***

Note: ***, ** and * indicate significance at 1%, 5% and 10% levels respectively. Values in parentheses are standard deviations.

Source: Authors' own computation.

innovations. Farm size, however, is negatively associated with adoption. This may reflect the prohibitive costs of establishing greenhouse infrastructure on larger farms.

Similarly, both individually owned and family-owned land are negatively associated with adoption, contrary to expectations. This outcome may be explained by the complex land tenure arrangements in Ghana, which discourage long-term investments in infrastructure-intensive technologies such as GHF (Abdulai et al. 2011; Torsu et al. 2024). Labour is also negatively and significantly associated with adoption, suggesting

that higher labour requirements reduce the likelihood of GHF uptake. This finding aligns with the dual nature of GHF's labour effects: while initial investment demands substantial labour, operational labour requirements (e.g., weed and pest management) decline once the system is established (Graetz et al. 2022). Access to market information is positively related to adoption, reflecting the critical role of reliable markets in sustaining year-round production facilitated by GHF. Regarding technological factors, fertiliser application is negatively and significantly associated with adoption. This may be linked to rising global fertiliser prices following the COVID-19

TABLE 4 | Mean differences for outcome indicators.

Variables	Pooled sample	Adopters	Non-adopters	Mean difference
HDDS	76.75 (1.40)	88.43 (1.66)	63.97 (1.93)	24.46
FCS	82.65 (1.32)	94.57 (1.46)	69.62 (1.83)	24.93
HFIAS	1.73 (0.11)	1.52 (0.13)	1.96 (0.18)	−0.44**
Food consumption score categories				
Main staple	5.84 (0.07)	6.27 (0.08)	5.36 (0.11)	0.91
Vegetable	−1.25 (0.14)	6.39 (0.07)	5.15 (0.12)	1.25
Fruit	4.71 (0.11)	5.62 (0.12)	3.71 (0.16)	1.91
Pulse	5.02 (0.09)	5.61 (0.12)	4.36 (0.13)	1.25
Meat and fish	5.72 (0.08)	6.37 (0.08)	5.00 (0.13)	1.36
Milk	4.38 (0.13)	5.49 (0.14)	3.16 (0.18)	2.34
Oils	5.08 (0.10)	5.78 (0.11)	4.31 (0.15)	5.08
Sugars	4.98 (0.11)	5.66 (0.14)	4.24 (0.16)	1.42

Note: Values in brackets are standard deviations.

Source: Authors' own computation. ** indicates significance at 5% level.

pandemic and the Russia–Ukraine war (Abu Hatab 2022), which reduce the appeal of farming systems requiring intensive fertiliser inputs. Conversely, asset ownership is positively associated with adoption, highlighting the substantial resource requirements of GHF and the greater capacity of wealthier farmers to make such investments.

Finally, location exerts a significant influence on adoption decisions. Farmers in the Central Region are more likely to adopt GHF compared with those in Greater Accra. This may be explained by the higher poverty incidence among farming households in the Central Region (GSS 2018), which could make GHF adoption an attractive strategy for improving livelihoods.

3.2.2 | Factors Affecting HDDS, FCS and HFIAS

Table 6 reports the second-stage estimates of controlled factors influencing household outcomes. Age is positively associated with HFIAS for non-adopters, indicating that older farmers outside GHF are more food insecure. Gender effects show that male non-adopters record lower dietary diversity and food consumption than their counterparts, highlighting gender disparities in technology adoption and its nutritional impacts (Teklewold et al. 2020). Farm size is positively associated with HDDS and FCS among adopters, consistent with evidence that larger plots enable more diverse production and consumption (Hu et al. 2022). The negative association with HFIAS further reinforces this link, as higher diversity and food consumption reduce food insecurity. Land tenure also matters: individually owned plots are positively associated with all three outcomes for adopters, suggesting that secure rights encourage investment in technologies such as GHF (Agyei-Holmes et al. 2020). In contrast, individual ownership is negatively associated with HDDS and FCS for non-adopters, possibly reflecting limited access to the incentives tied to GHF initiatives.

Family land ownership is positively correlated with HFIAS among adopters, likely because food or income from such plots must be shared among multiple household members, thereby constraining producers' food security. Access to market information significantly reduces food insecurity among non-adopters, underscoring its role in improving household resilience. Livestock ownership further enhances food consumption and reduces food insecurity among adopters, while engagement in off-farm employment appears to constrain food consumption, possibly due to reduced time and resources for farming.

Institutional factors show mixed effects. Extension access unexpectedly reduces dietary diversity and food consumption among non-adopters, suggesting that conventional extension services may not effectively promote dietary improvements in this group (Amrullah et al. 2023). In contrast, access to government support schemes improves dietary diversity, highlighting the potential of targeted policy interventions. Technological adoption, particularly the use of fertilizer, improved seed varieties, and irrigation, consistently improves dietary diversity and food consumption, especially among non-adopters. These findings reinforce prior evidence that technological inputs increase yields and incomes, thereby reducing food insecurity (Asfaw et al. 2019). However, asset ownership is negatively associated with dietary diversity and food consumption among adopters, consistent with earlier findings that asset accumulation does not always translate into improved nutrition (Ansah et al. 2022). Finally, location matters: adopters in the Ashanti Region exhibit higher dietary diversity and lower food insecurity than those in the Central Region, reflecting stronger market opportunities and income prospects linked to GHF in Ghana's commercial hub.

3.2.3 | Marginal Treatment Effects (MTE) Estimates

Figure 1 presents the MTE curve estimates with 95% confidence intervals, obtained from 500 bootstrap replications. For

TABLE 5 | Probit estimates of determinants of GHF adoption: selection equation.

Variable	Coefficient	R standard errors	z- statistics
Socioeconomic factors			
Age	−0.028**	0.014	−2.05
Gender	0.446*	0.229	1.95
Education	0.004	0.021	0.19
Experience	−0.102***	0.037	−2.76
Household size	0.025	0.053	0.48
Marital status	−0.009	0.227	−0.04
Awareness of GHF	1.418***	0.291	4.87
Farm size	−0.146**	0.058	−2.51
Individual owned land	−0.736*	0.396	−1.86
Family-owned land	−0.538*	0.280	−1.92
Distance to market	−0.094	0.111	−0.85
Labour (man days)	−0.246***	0.087	−2.82
Off farm employment	0.177	0.409	0.43
Livestock production	−0.653	0.515	−1.27
Non-farm income	0.013	0.032	0.40
Institutional factors			
Extension access	0.296	0.245	1.21
FBO membership	−0.015	0.279	−0.06
Credit access	−0.283	0.269	−1.05
Climate information	0.004	0.221	0.02
Market information	0.539**	0.211	2.55
Access to support scheme	−0.172	0.311	−0.55
Technological factors			
Seed rate	0.025	0.072	0.35

(Continues)

TABLE 5 | (Continued)

Variable	Coefficient	R standard errors	z- statistics
Fertilizer application	−0.210*	0.111	−1.89
Improved seeds	−0.225	0.328	−0.68
Irrigation access	−0.653	0.358	−0.05
Assets	0.349***	0.756	4.62
Location variables			
Ashanti region	0.002	0.245	0.01
Central region	0.817**	0.275	2.97
Instrumental variable			
Perceived benefit of GHF (F1)	0.734***	0.159	4.62
Constant	0.258	1.162	0.22
Observation	400		
Pseudo- R^2	0.64		
Chi-squared	218.45***		

Note: ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively.
Source: Authors' own computation.

HDDS and FCS (Figure 1a,b), the MTE curves increase with unobserved resistance to adoption, indicating inverse selection: households most likely to adopt GHF derive the greatest gains in dietary diversity and food consumption. This pattern of essential heterogeneity is statistically significant at the 5% level (Table 6). For HFIAS, the MTE curve exhibits a similar upward trend, suggesting that households more inclined to adopt GHF benefit most in terms of reduced food insecurity. However, this heterogeneity is not statistically significant at conventional levels. Even so, the direction of the effect underscores the potential of GHF adoption to strengthen household food security. These findings suggest that policies designed to incentivize adoption—particularly targeting households more predisposed to GHF—can yield substantial improvements in dietary diversity, food consumption, and overall food security.

3.2.4 | Impact of Adopting GHF on HDDS, HFIAS, and FCS

Table 7 presents the estimated impacts of GHF on HDDS, FCS, and HFIAS under the baseline model. The ATE and ATU estimates are statistically significant across all three outcomes. On average, GHF adoption increases dietary diversity and food consumption by about 40% and reduces food insecurity by 51%.

TABLE 6 | MTE estimates on determinants of outcome indicators: outcome equations.

Adoption	HDDS		FCS		HFIA5	
	Adopters (standard error)	Non-adopters (standard error)	Adopters (standard error)	Non-adopters (standard error)	Adopters (standard error)	Non-adopters (standard error)
Constant	75.01** (35.97)	21.27 (19.32)	77.23** (34.12)	32.29* (18.33)	7.60* (4.06)	−1.57 (2.18)
Socioeconomic factors						
Age	−0.33 (0.35)	−0.13 (0.15)	−0.09 (0.32)	−0.22 (0.15)	−0.06 (0.04)	0.03** (0.01)
Gender	5.52 (6.04)	−7.85** (4.01)	3.67 (5.73)	−7.06* (3.80)	0.09 (0.68)	0.19 (0.45)
Education	−0.01 (0.58)	0.39 (0.38)	0.04 (0.55)	−0.01 (0.37)	0.01 (0.07)	0.01 (0.04)
Experience	0.52 (0.91)	−0.28 (0.31)	0.26 (0.86)	−0.13 (0.29)	0.04 (0.10)	−0.01 (0.04)
Household size	0.09 (1.13)	0.74 (0.68)	0.14 (1.12)	0.63 (0.64)	−0.01 (0.13)	−0.03 (0.08)
Awareness of GHF	−19.25 (17.02)	4.02 (4.74)	−25.19 (16.16)	3.22 (4.50)	−1.66 (1.92)	−0.31 (0.54)
Farm size	3.77** (1.41)	0.09 (0.91)	3.60* (1.34)	−0.14 (0.86)	−0.36** (0.16)	0.05 (0.10)
Individual owned	15.49* (9.14)	−20.51*** (4.82)	17.08** (8.67)	−18.31*** (4.58)	−2.49** (1.03)	−0.64 (0.54)
Family-owned land	−3.49 (8.56)	−4.85 (3.62)	0.75 (8.12)	−5.66 (3.44)	1.59* (0.97)	−0.31 (0.41)
Market information	1.05 (5.36)	−3.74 (3.32)	3.62 (5.09)	−4.24 (3.15)	−0.66 (0.61)	−0.82** (0.37)
Distance to market	−1.69 (2.66)	3.02 (1.88)	−0.61 (2.53)	1.86 (1.78)	−0.07 (0.30)	−0.19 (0.21)
Labour (man days)	−2.42 (2.11)	3.64** (1.59)	−1.35 (1.99)	3.18** (1.51)	−0.05 (0.24)	0.13 (0.18)
Off farm employment	−11.03 (8.94)	3.09 (7.34)	−14.01* (8.48)	7.44 (6.97)	−0.27 (1.01)	0.83 (0.83)
Livestock ownership	24.62 (15.69)	5.07 (4.84)	27.04** (14.88)	6.46 (4.59)	−4.92** (1.77)	2.57*** (0.55)
Non-farm income	0.64 (1.04)	0.99 (0.86)	0.39 (0.99)	0.80 (0.81)	0.13 (0.12)	−0.22** (0.09)
Institutional factors						
Extension access	6.71 (5.33)	−10.59** (3.62)	6.83 (5.06)	−7.33** (3.43)	−0.66 (0.60)	0.42 (0.41)
FBO membership	−0.89 (5.35)	0.14 (3.29)	1.57 (5.08)	0.22 (3.12)	0.75 (0.60)	0.01 (0.37)
Credit access	7.58 (5.80)	2.67 (3.54)	0.03 (0.66)	0.03 (0.66)	0.03 (0.65)	0.37 (0.40)
Climate information	5.67 (5.46)	−1.74 (3.42)	4.92 (5.18)	−0.82 (3.25)	−2.20*** (0.62)	0.920** (0.386)
Support scheme	−1.60 (6.88)	13.89*** (3.65)	0.35 (6.53)	12.03** (3.46)	−0.80 (0.78)	−0.26 (0.41)
Technological factors						
Seed rate	−0.54 (1.55)	−0.64 (0.94)	0.12 (1.47)	−0.61 (0.89)	0.08 (0.29)	0.02 (0.11)
Fertilizer application	−2.28 (2.43)	5.25** (1.59)	−2.25 (2.31)	4.71** (1.51)	−0.16 (0.28)	−0.10 (0.18)

(Continues)

TABLE 6 | (Continued)

Adoption	HDDS		FCS		HFIAS	
	Adopters (standard error)	Non-adopters (standard error)	Adopters (standard error)	Non-adopters (standard error)	Adopters (standard error)	Non-adopters (standard error)
Improved seeds	17.50* (9.03)	10.93** (3.89)	17.13** (8.57)	8.58** (3.69)	0.28 (1.02)	−1.02** (0.44)
Irrigation access	1.29 (8.87)	3.24 (3.67)	−6.76 (8.48)	6.32* (3.48)	−0.14 (1.00)	0.27 (0.41)
Assets	−5.30** (2.59)	0.42 (1.52)	−5.29** (2.36)	1.05 (1.44)	0.05 (0.29)	0.20 (0.17)
Location dummies						
Ashanti region	12.61** (5.83)	−1.66 (3.48)	9.82 (5.53)	−0.23 (3.30)	−1.12* (0.66)	−0.07 (0.39)
Central region	−3.10 (7.35)	1.24 (4.90)	−6.66 (6.97)	5.15 (4.65)	−0.87 (0.83)	0.30 (0.55)
Test of observable heterogeneity	0.01		0.00		0.00	
Test of essential (unobserved) heterogeneity	0.03		0.03		0.66	
Test for joint significant of excluded instrument	104.22***		107.54***		110.12***	

Note: ***, ** and * indicate significance at 1%, 5% and 10% levels, respectively. Values in brackets are standard errors.

Source: Authors' own computation.

For non-adopters, the ATU results suggest even larger potential gains: adoption would raise dietary diversity and food consumption by 52% and 55%, respectively, while reducing food insecurity by 80%. The higher ATU values relative to the ATEs indicate negative selection on unobserved benefits.

The ATT estimates are only significant for HFIAS, showing that adopters experience a 57% reduction in food insecurity. This result highlights that while current adopters benefit primarily through reduced food insecurity, the potential gains for non-adopters—particularly in dietary diversity and food consumption—remain substantial.

3.2.5 | Policy Relevant Results for 20% Increase in Market Information Access

Table 8 presents the PRTE estimated after the MTE baseline specification. The simulation considers an increase in GHF participation from the current 52% to 72% in areas targeted by government and private investment. Consistent with the ATT results, expanding adoption requires complementary measures, particularly improved access to produce markets and marketing channels. Without these, scaling participation and achieving positive outcomes would be difficult. To address this, we simulate a 20% increase in access to market information. The results indicate that such an intervention could raise dietary diversity (HDDS) and food consumption (FCS) by 42% and 41%, respectively, while reducing food insecurity

(HFIAS) by 25%. The MTE curves for this alternative policy scenario (Figure 2) confirm these gains, showing substantial improvements in food security outcomes under enhanced access to market information.

The MTE curves for HDDS and FCS (Figure 2) are downward sloping, indicating that the benefits of GHF adoption diminish as resistance to adoption increases. This pattern reflects positive selection on benefits: households more inclined to adopt GHF experience greater improvements in dietary diversity and food consumption. The positive and significant PRTE estimate aligns with Carletto et al. (2017), Ogutu et al. (2019), and Manda et al. (2020), who found that stronger market orientation and access to marketing channels influence production, consumption, and poverty reduction. These results reinforce the importance of aligning farming households with produce markets to maximise gains from GHF adoption.

As a robustness check, we explored alternative model specifications. First, we disaggregated household consumption into staple foods (cereals, roots and tubers), vegetables and fruits (Table S1). The MTE curves (Figure S1) reveal patterns consistent with those observed for HDDS and FCS, confirming significant positive effects of GHF on these food groups. Second, we re-estimated the baseline model using a polynomial functional form (Figures S2–S4). These results further corroborate the robustness of our baseline findings, showing that GHF adoption consistently enhances household food consumption and dietary diversity.

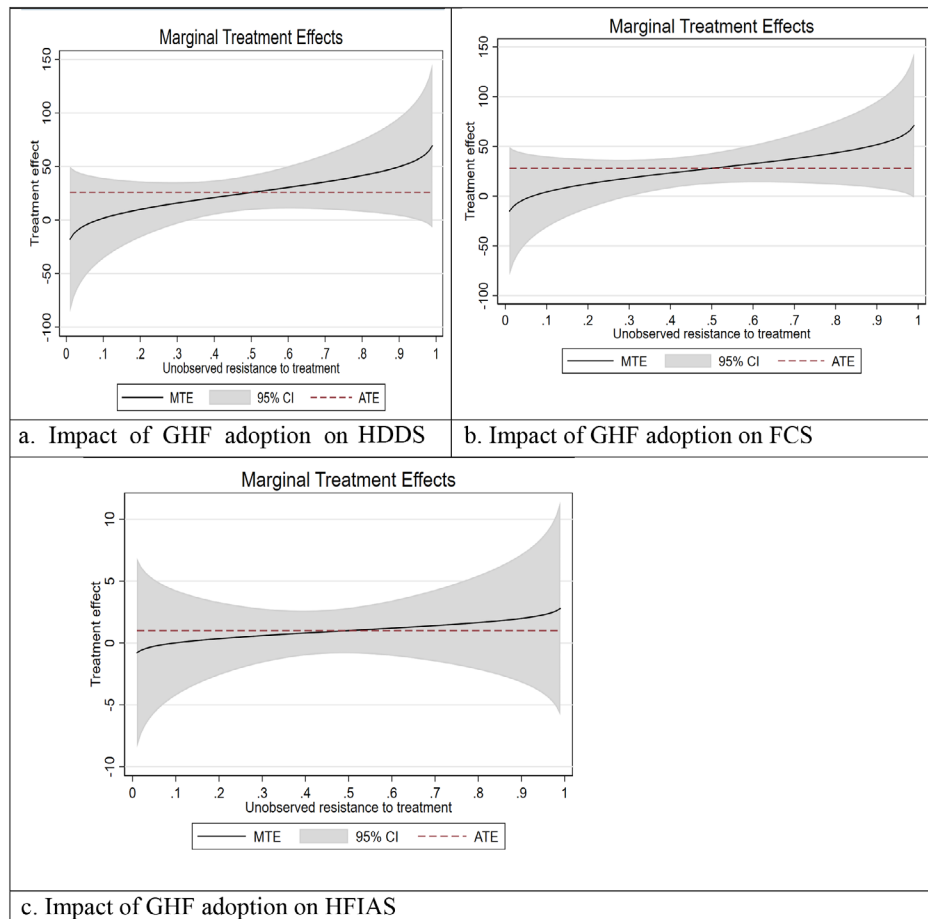


FIGURE 1 | Marginal treatment effect (MTE) curves showing impact of GHF on outcome indicators. (a) Impact of GHF adoption on HDDS; (b) impact of GHF adoption on FCS; (c) impact of GHF adoption on HFIAS. *Source:* authors' own construction.

TABLE 7 | Treatment effects of adoption of GHF as CSA practice on outcome indicators.

Parameters	HDDS		FCS		HFIAS	
	Coefficient	% change	Coefficient	% change	Coefficient	% change
ATE	25.75** (8.26)	40.25	27.96*** (7.84)	40.16	-1.00*** (0.13)	-51.02
ATT	6.82 (9.84)	10.66	6.13 (9.33)	8.80	-1.11** (0.49)	-56.63
ATU	46.36** (17.00)	52.43	51.73** (16.13)	54.70	-1.56* (0.92)	-79.59

Note: ***, ** and * indicate significance at 1%, 5% and 10% levels, respectively. The standard errors in parentheses were bootstrapped with 500 replications.
Source: Authors' own computation.

TABLE 8 | Average treatment effects of adoption of GHF as CSA practice on outcome indicators.

Parameters	HDDS		FCS		HFIAS	
	Coefficient	% change	Coefficient	% change	Coefficient	% change
PRTE	26.66** (12.64)	41.68	28.44** (11.96)	40.85	-1.43** (0.63)	-25.00

Note: ** indicate significance at 5% level. The standard errors in parentheses were bootstrapped with 500 replications.
Source: Authors' own computation.

4 | Conclusions and Implications

Global efforts to combat food and nutrition insecurity remain central to development agendas but face persistent

threats from climate change, the COVID-19 pandemic, and the Russia–Ukraine war. This study provides evidence, based on MTE, that GHF has the potential to improve household dietary diversity, food consumption, and food security. However,

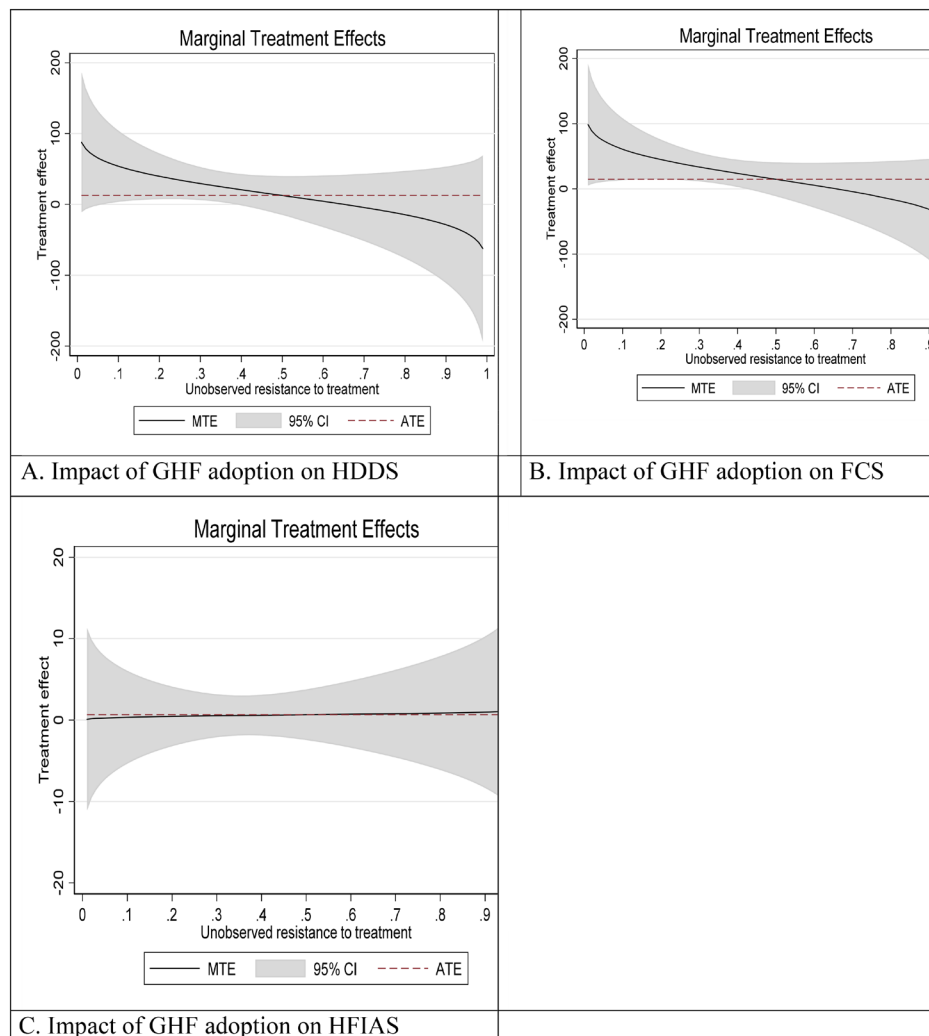


FIGURE 2 | Marginal treatment effect (MTE) curves for alternative policy. (a) Impact of GHF adoption on HDDS; (b) impact of GHF adoption on FCS; (c) impact of GHF adoption on HFIAS.

the benefits of GHF are not uniform. Adoption decisions and associated gains are heterogeneous across observable and unobservable socio-economic, institutional, and technological characteristics. The findings reveal inverse selection with respect to household characteristics, indicating that those most likely to adopt GHF also gain the most in terms of dietary diversity and food consumption. The estimated ATE confirms that GHF adoption significantly improves household food and nutrition security. Moreover, the estimated ATU suggests that non-adopting vegetable producers would also experience substantial improvements in dietary diversity and food consumption if they adopted GHF.

From a policy perspective, since adoption requires substantial upfront investment, policymakers should facilitate access to affordable credit through agricultural banks, microfinance institutions, and government-backed loan guarantee schemes. Subsidies for greenhouse kits, drip irrigation systems, and renewable energy-powered water pumps would further lower barriers to entry. Our findings underscore the importance of awareness creation. Initiatives should emphasize not only the dietary and nutritional benefits of GHF but also its environmental advantages. Governments and NGOs should invest in targeted

extension services and training programs that demonstrate the nutritional, economic, and environmental benefits of GHF. This could include farmer field schools, demonstration plots, and the integration of GHF modules into agricultural training curricula. Given regional disparities in adoption and benefits, interventions should be tailored to local conditions. In regions with high poverty and food insecurity, combining GHF promotion with social protection schemes (e.g., input vouchers or public works programs) could generate stronger impacts.

In addition, the positive impacts of GHF are contingent on farmers' access to reliable markets. Without strong market linkages, the food security benefits of GHF are muted. Policies should therefore prioritize connecting farmers to produce markets and expanding access to market information, which can be facilitated through digital platforms, extension services, and farmer-based organizations. Targeted support in these areas would enhance adoption and maximize the food security benefits of GHF. Establishing structured market systems—such as contract farming arrangements with supermarkets, school feeding programs, and agro-processing firms—would reduce uncertainty about post-harvest sales. Governments can also support digital platforms that provide real-time price and demand information.

While this study advances understanding of the role of GHF in improving food and nutrition security, several areas warrant further investigation. First, longitudinal studies could examine the long-term impacts of GHF on household welfare, including income stability and resilience to climatic and economic shocks. Second, future research should explore the gender dimensions of GHF adoption, particularly given the observed differences between male and female farmers. Third, more work is needed to assess the cost-effectiveness and scalability of GHF relative to other climate-smart agricultural practices. Finally, examining the environmental outcomes of GHF adoption—such as water use efficiency and carbon footprint—would provide a more comprehensive understanding of its contribution to sustainable agricultural development.

This study is subject to some limitations. First, the analysis relies on cross-sectional data, which limits the ability to capture dynamic or long-term effects of GHF adoption. Second, the sample is geographically constrained, which may limit the generalizability of the findings to other regions or countries with different institutional settings. Finally, while the study highlights adoption outcomes, it does not fully assess environmental trade-offs, such as water use or energy intensity, which are important for evaluating the sustainability of GHF.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author, [Enoch Owusu-Sekyere].

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** fes370137-sup-0001-Supinfo.docx.