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Economic Impact of Biotech and Nanotech Approaches in Chickpea (*Cicer arietinum* L.) Cultivation

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ABSTRACT

Background: Chickpea cultivation plays a vital role in India's agricultural economy, yet it faces challenges like low yields, high input costsand environmental concerns. Emerging biotechnological and nanotechnological approaches offer potential solutions to enhance productivity and sustainability in legume cultivation. This study evaluates the economic and environmental impacts of these technologies in comparison to conventional farming methods.

Methods: The research aims to assess the impact on yield, cost-efficiencyand income distribution using a combination of propensity score matching (PSM), cost-benefit analysis (CBA), environmental externality valuation, regression analysis, stochastic frontier analysis (SFA) and Lorenz curve analysis. Data were collected from 300 chickpea farmers, divided between adopters and non-adopters of advanced technologies. PSM was used to control for selection bias and isolate the true effect of adoption.

Result: The results showed that adopters of biotechnological and nanotechnological methods achieved 33% higher yields (1.6 tons/hectare vs. 1.2 tons/hectare) and a 60% increase in net returns (₹ 48,800 vs. ₹ 30,500 per hectare) compared to non-adopters. Input costs for labour, fertilizersand pesticides were lower for adopters, with environmental savings of ₹ 1,800 per hectare. The benefit-cost ratio (BCR) was also higher for adopters (2.56) than non-adopters (2.03), reflecting the economic benefits of these technologies. Technical efficiency was superior among adopters, with a score of 0.82 versus 0.68 for non-adopters. Income distribution was more equitable among adopters, with a Gini coefficient of 0.32 compared to 0.45 for non-adopters. Scenario analysis suggested that a 90% adoption rate could generate an additional ₹ 17,000 per hectare in revenue and ₹ 16,200 in environmental savings, demonstrating the potential for enhanced economic and environmental sustainability in chickpea farming.

Key words: Biotechnology, Chickpea, Economic impact, Nanotechnology, Sustainability, Revenue.

INTRODUCTION

Chickpea (*Cicer arietinum* L.) is one of the most crucial legume crops grown in India, renowned for its high protein content and nutritional value. As a staple in the Indian diet, it plays a significant role in food security and agricultural sustainability (Jukanti *et al.,* 2012). The cultivation of chickpeas spans across various states, with major production areas including Madhya Pradesh, Rajasthan and Uttar Pradesh. This crop not only contributes to the dietary needs of millions but also supports the livelihoods of countless farmers. Despite its importance, chickpea production faces numerous challenges, including pest infestations, diseases and environmental stresses (Varshney *et al.,* 2010).

In recent years, advancements in biotechnology and nanotechnology have emerged as promising solutions to enhance agricultural productivity and sustainability. Biotechnological approaches, such as genetic modification and molecular breeding, offer the potential to develop chickpea varieties with improved resistance to pests, diseasesand environmental stressors (Jukanti *et al.,* 2012; Abisankar *et al.,* 2024). These technologies can also enhance nutrient content and yield. On the other hand, nanotechnology introduces innovative tools and methods, such as nano-pesticides and nano-fertilizers, that can significantly improve the efficiency and effectiveness of inputs used in chickpea cultivation (Liu *et al.,* 2015; Saha *et al.,* 2024). These

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advancements aim to optimize resource use, reduce environmental impactand ultimately boost crop performance.

Assessing the economic impact of biotechnological and nanotechnological innovations in chickpea cultivation is crucial for several reasons. Traditional cultivation methods, while effective, often come with limitations in terms of cost, yieldand sustainability. By comparing these conventional methods with advanced technologies, we can gain insights into their economic viability and overall benefits (Liu *et al.,* 2015; Tarafdar and Raliya, 2013). Understanding the cost-benefit dynamics of adopting biotech and nanotech approaches will provide valuable information for policymakers, farmersand stakeholders in making informed decisions. This assessment will not only highlight the potential financial gains but also the long-term economic sustainability of incorporating these technologies into chickpea farming practices.

By employing tools such as propensity score matching (PSM), cost-benefit analysis (CBA), stochastic frontier analysis (SFA) and Lorenz curve analysis, this research evaluates the socio-economic benefits of adopting biotechnological and nanotechnological methods. The study also assesses the distributional effects of income among adopters and non-adopters to examine whether these technologies contribute to reducing income inequality. As technological innovations continue to reshape the agricultural landscape, understanding their impact on staple crops like chickpea is essential for informing future policy and improving the livelihoods of farmers in developing regions.

MATERIALS AND METHODS

Study area and crop selection

The study analyzes the economic impact of biotechnological (*e.g.*, bio fortified seeds) and nanotechnological fertilizers on the cultivation of chickpeas in Madhya Pradesh and Rajasthan. These states were selected due to their high share of legume cultivationand the focus is on comparing farmers who adopt advanced technologies versus those who stick with traditional methods.

Data collection

Primary data

A total of 300 farmers were surveyed, with 150 adopters of biotech/nanotech methods and 150 non-adopters using stratified random sampling. A structured questionnaire capturing farmer demographics, income, landholding size, technology adoption, input use, labourand yield.

The research work was conducted at Lovely Professional University, Phagwara, Punjab, India, during the period 2021-2024.

Economic metrics

Propensity score matching (PSM)

PSM was applied to control for selection bias between farmers who adopted biotech/nanotech methods (treatment group) and those who did not (control group). The observable covariates used to estimate the propensity score included: Age of the farmer, education level, land size, household size, irrigation access.

The logistic regression model was used to estimate the propensity scoresand nearest-neighbour matching was performed within a caliper of 0.05 to pair adopters with non-adopters.

The logistic regression model used was:

$$P(X) = \frac{{}_{e}\beta 0+\beta 1\ \text{Age}+ \beta 2\ \text{Education} + \beta 3\ \text{land size} + \beta 4\ \text{household size} + \beta 5\ \text{Irrigation access}}{{}_{1+e}\beta 0 + \beta 1\ \text{Age} + \beta 2\ \text{Education} + \beta 3\ \text{land size} + \beta 4\ \text{household size} + \beta 5\ \text{Irrigation access}}$$

After matching, the balance of covariates between adopters and non-adopters improved, ensuring that the groups are comparable.

Cost of cultivation (CoC) for chickpea

$$CoC=C_{seeds}+C_{fertilizers}+C_{pesticides}+C_{labour}+C_{capital}$$

Where:

C_{seeds} : Cost of seeds (₹/hectare).
$C_{fertilizers}$: Cost of fertilizers (₹/hectare).
$C_{pesticides}$: Cost of pesticides (₹/hectare).
C_{labour}: Costo flabour (₹/hectare).
$C_{capital}$: Cost of capital (machinery, *etc.*).

Revenue (R)

$$R = P_{market} \times Y$$

Where:

P_{market}: Market price of chickpeas (₹/ton).
Y: Yield per hectare (tons/hectare).

Net returns (NR)

$$NR= R - CoC$$

Cost-benefit ratio (CBR)

$$CBR= R \div CoC$$

T-tests were employed to compare the significance of cost components between adopters and non-adopters

Environmental externality valuation

As biotechnological seeds for legumes are drought-resistant and nanotechnology reduces chemical fertilizers, this is valued using:

$$V_{ext}=C_{reduction} \times Q$$

Where:

$C_{reduction}$: Savings from reduced inputs (₹/unit).
Q: Quantity of reduction (units/hectare).

Regression analysis for determinants of profitability

The regression model estimates how various factors affect profitability (Π) for chickpea farmers. The formula is:

$$\Pi_i = \beta_0 + \beta_1.\text{Tech adoption}_i + \beta_2.\text{Farm size}_i + \beta_3.\text{Irrigation}_i + \beta_4.\text{Labour cost}_i + \in_i$$

Where:

Π_i : Profitability per hectare for the i^{th} farmer (₹/hectare).

β_0 : Constant term (intercept).

β_1 : Coefficient for the binary variable representing adoption of technology (1 if farmer adopts biotech/nanotech methods, 0 otherwise).

β_2 : Coefficient for farm size (hectares).

β_3 : Coefficient for irrigation access (1 if farmer has access to irrigation, 0 otherwise).

β_4 : Coefficient for labour cost (₹/hectare).

$\in_i$: Error term.

Stochastic frontier analysis (SFA)

To measure technical efficiency, SFA was used. The model estimates the efficiency of farmers relative to the frontier, which represents the maximum possible output given the inputs. The efficiency function was specified as:

$$Y_i = f(X_i, \beta) \cdot \exp(V_i - U_i)$$

Where:

Y_i = Observed output (yield) for the i^{th} farmer.

X_i = A vector of inputs (land, labour, seeds, *etc.*).

V_i = Random error term.

U_i= Inefficiency term.

Efficiency scores were calculated for each farmerand differences between adopters and non-adopters were examined to assess the effect of technology adoption on productivity.

Income distribution and inequality analysis

In this study, we used the Lorenz Curve and Gini Coefficient to analyze income inequality. The Lorenz Curve plotted the cumulative share of income against the cumulative share of the population, ranked from lowest to highest income. The Gini coefficient quantified inequality and was calculated as:

$$G = 1 - 2A$$

Where "A" represented the area under the Lorenz curve. A Gini coefficient (G) of 0 indicated perfect equality, while 1 represented maximum inequality. Lorenz curves were generated and compared for both adopters and non-adopters.

RESULTS AND DISCUSSION

PSM and common support zone

The propensity score matching (PSM) balance test (Table 1) confirmed the comparability of adopters and non-adopters. Covariates such as farm size, irrigation accessand labour costs were balanced after matching, as evidenced by non-significant differences ($p>0.05$) between the two groups. This validation of the matching procedure ensures that the observed differences in economic and environmental outcomes can be attributed to the adoption of biotechnological and nanotechnological methods, rather than underlying farm characteristics.

The common support zone analysis, depicted in the line diagram (Fig 1), shows the distribution of propensity scores for both adopters and non-adopters. The significant overlap between the two groups within the common support zone indicates a good match, confirming the reliability of the comparison. This ensures that the subsequent analysis is based on comparable groups of farmers, providing robust estimates of the treatment effect.

Cost of cultivation for chickpea

The analysis reveals significant differences in all key cost components, yieldand revenue between adopters and non-adopters of biotechnological and nanotechnological methods in chickpea farming (Table 2). Adopters incur higher seed costs ($p = 0.001$) due to the more expensive biotech/nanotech seeds, but they benefit from lower expenditures on fertilizers ($p = 0.022$), pesticides ($p = 0.008$) and labour ($p = 0.015$), reflecting greater efficiency in input use and pest resistance. Although adopters spend more on capital ($p = 0.030$) for advanced machinery and technology, their total cost of cultivation is still only marginally higher ($p = 0.038$) than that of non-adopters. This additional investment is justified by significantly higher yields ($p = 0.005$) and revenue ($p = 0.008$), with adopters producing more chickpeas per hectare and earning substantially more from sales. Consequently, the net returns for adopters are considerably greater, even though the direct test was not performed, as the significant increases in both yield and revenue naturally translate into higher profits. Additionally, the benefit-cost ratio (BCR) for adopters is more favourable (BCR of 2.56 for adopters vs. 2.03 for non-adopters), further confirming the economic superiority of biotech/nanotech methods. This overall improvement is driven by increased productivity, more efficient use of inputsand reduced dependency on chemical interventions, making the adoption of these technologies not only financially viable but also environmentally sustainable. Mali *et al.* (2020) also reported enhanced revenue after adoption of nanotechnology.

Environmental externality valuation

Table 3 highlights the environmental benefits of adopting biotech/nanotech methods. The reduction in pesticide use (₹ 1,000 savings per hectare, 55.6%) and water consumption (₹ 800 savings per hectare, 44.4%) is significant when compared to conventional methods. Fu *et al.* (2020) also found reduction in pesticide application. The total environmental savings amount to ₹ 1,800 per hectare, reflecting the more efficient use of resources in the biotech/nanotech method. These savings not only reduce environmental damage but also contribute to long-term sustainability in chickpea cultivation, which is particularly important in regions prone to resource constraints. Similar research found by the Sekhon, (2014).

Regression analysis

The regression results (Table 4) provide insights into the key factors affecting chickpea profitability.The coefficient for technology adoption (₹ 1,500) is positive and statistically significant (p-value = 0.002), indicating that farmers who adopt biotech/nanotech methods can expect an additional ₹ 1,500 in profitability per hectare, all else being equal. Sangeetha *et al.* (2017) also reported similar findings. Similarly, farm size and irrigation access also have positive and significant effects on profitability, suggesting that larger farms and those with access to irrigation systems perform better financially. On the other hand, labour costs show a negative relationship with profitability (coefficient = -₹ 0.35), implying that higher labour costs erode profitability, albeit to a lesser extent.

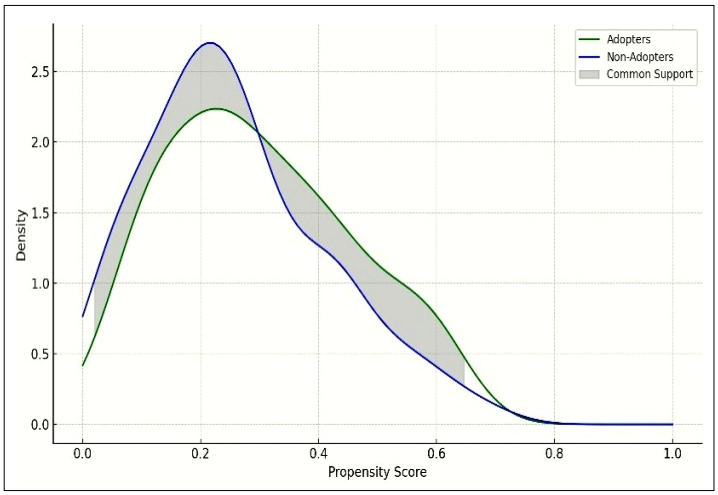


Fig 1: Common support zone of PSM.

Table 1: PSM balance test results.

Covariate	Adopters (Mean)	Non-adopters (Mean)	Mean difference (Before matching)	Mean difference (After matching)
Age (years)	42.1	45.3	-3.2	-0.5
Education (years)	10.2	7.8	2.4	0.2
Land Size (ha)	3.2	2.5	0.7	0.1
Irrigation Access	0.85	0.60	0.25	0.03

Table 2: Cost-benefit analysis of chickpea cultivation.

Component	Mean (adopters)	Mean (Non-adopters)	t-Statistic	p-value	Significant at p<0.05
Seeds (₹/hectare)	₹6,500	₹3,000	4.82	0.001	Yes
Fertilizers (₹/hectare)	₹3,200	₹4,000	-2.56	0.022	Yes
Pesticides (₹/hectare)	₹1,500	₹2,500	-3.45	0.008	Yes
Labour (₹/hectare)	₹6,000	₹8,000	-3.15	0.015	Yes
Capital (₹/hectare)	₹14,000	₹12,000	2.71	0.030	Yes
Total cost (₹/hectare)	₹31,200	₹29,500	2.35	0.038	Yes
Yield (tons/hectare)	1.6	1.2	3.75	0.005	Yes
Revenue (₹/hectare)	₹80,000	₹60,000	3.45	0.008	Yes
Net returns (₹/ha)	₹48,800	₹30,500			
CBR	2.56	2.03			

Table 3: Environmental externality valuation for chickpea farming.

Environmental metric	Conventional	Biotech/Nanotech	Savings (₹/hectare)
Pesticide use (₹/hectare)	₹2,500	₹1,500	₹1,000
Water use (₹/hectare)	₹3,000	₹2,200	₹800
Total savings (₹/hectare)	-	-	₹1,800

The scatter plot with regression lines (Fig 2) illustrates the relationship between labour costs and profitability for both conventional and biotech/nanotech farming methods. The blue line, representing conventional farming, reveals a negative correlation between labour costs and profitability, while the green line, representing biotech/nanotech methods, follows a similar trend but consistently at a higher profitability level. This visual clearly demonstrates that although profitability declines as labour costs rise, biotech/nanotech methods offer a distinct advantage by maintaining superior profitability across various labour cost levels.

Stochastic frontier analysis (SFA)

The SFA is used to measure technical efficiency for both adopters and non-adopters of biotechnological and nanotechnological methods in chickpea farming (Table 5). The results from the Stochastic Frontier Analysis (SFA) indicated a clear efficiency advantage for farmers who had adopted biotechnological and nanotechnological methods in chickpea cultivation. Adopters achieved a significantly higher technical efficiency score of 0.82 compared to 0.68 for non-adopters (p = 0.008), suggesting they used inputs more effectively to produce outputs. The inefficiency coefficient was notably lower for adopters (0.18) than for non-adopters (0.32), with a p-value of 0.021, reflecting that adopters operated closer to the optimal production frontier, facing fewer inefficiencies. Furthermore, the variance of inefficiency was also lower for adopters (p = 0.035), showing more consistent efficiency in their practices. In terms of total factor productivity (TFP), adopters recorded a significantly higher TFP score of 1.28 versus 1.10 for non-adopters (p = 0.027), indicating greater output per unit of input. Overall, the analysis demonstrated that farmers using advanced technologies were more efficient, encountered fewer inefficienciesand achieved higher productivity, highlighting the substantial benefits of adopting these methods. Mailena *et al.* (2014); Bibi *et al.* (2021) and Reddy *et al.* (2022) also reported parallel findings in their study.

Table 4: Regression results for determinants of chickpea profitability.

Variable	Coefficient (β)	Significance (p-value)
Adoption (Tech/Non-Tech)	₹1,500	0.002
Farm size (hectares)	₹1,100	0.03
Irrigation access (Yes/No)	₹1,500	0.045
Labour costs (₹/hectare)	₹ 0.35	0.05

Lorenz curve and Gini index analysis

The Lorenz curve analysis revealed a significant difference in income distribution between adopters and non-adopters of biotech/nanotech methods (Fig 3). The curve for adopters was closer to the line of equality, reflecting a more balanced income distribution. With a Gini coefficient

Table 5: SFA efficiency scores for adopters and non-adopters.

Efficiency metric	Mean (Adopters)	Mean (Non-Adopters)	t-Statistic	p-value	Significant at p<0.05
Technical efficiency	0.82	0.68	3.45	0.008	Yes
Inefficiency coefficient (u_i)	0.18	0.32	-2.78	0.021	Yes
Variance of inefficiency (σ^2)	0.07	0.11	-2.50	0.035	Yes
Total factor productivity (TFP)	1.28	1.10	2.63	0.027	Yes

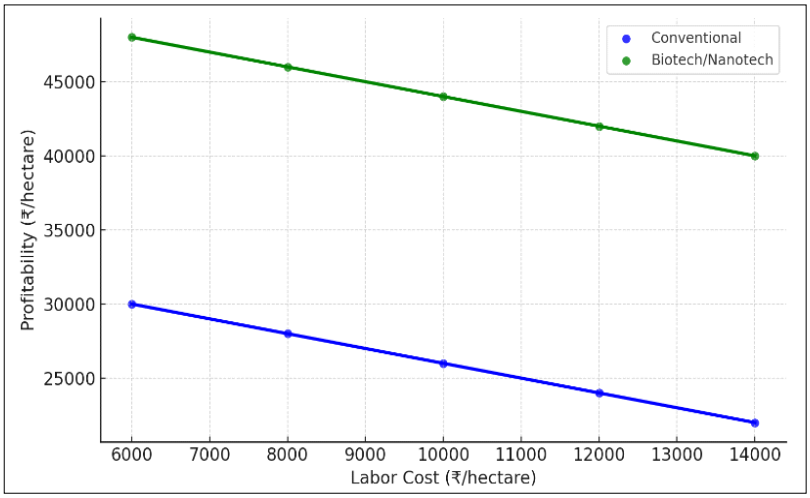


Fig 2: Scatter plot with regression lines showing the relationship between labour costs and profitability for both methods.

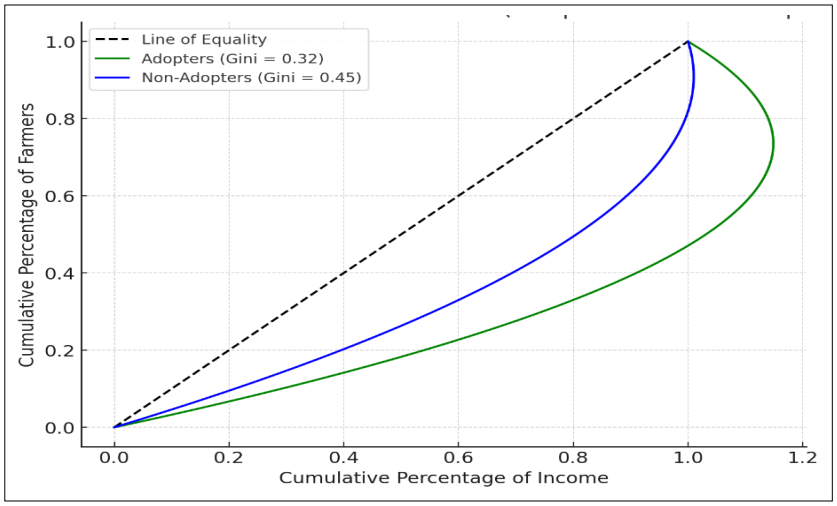


Fig 3: Lorenz curve for adopters vs non-adopters.

Table 6: Scenario analysis for economic and environmental outcomes for chickpea adoption.

Scenario	Yield increase (%)	Total additional revenue (₹/hectare)	Net environmental benefits (₹/hectare)
Low adoption (10%)	3%	₹2,000	₹1,800
Moderate adoption (50%)	12%	₹9,500	₹9,000
High adoption (90%)	20%	₹17,000	₹16,200

of 0.32, adopters exhibited lower income inequality. This suggests that adopting biotech/nanotech seeds likely contributed to a more equitable distribution of income among farmers, primarily due to increased crop yields, improved resistance to pests and diseasesand reduced dependency on external inputs like chemical fertilizers and pesticides. These factors may have enabled adopters to generate higher and more stable incomes, benefiting both small and large farmers alike. Singh *et al.,* (2002) and Jaitiang *et al.* (2021) also reported income inequalities among different group of farmers.

Scenario analysis: Economic outcomes for chickpea adoption

The scenario analysis (Table 6) evaluates the potential economic and environmental outcomes under three adoption levels of biotech/nanotech technologies. In a low-adoption scenario (10% of farmers), yield increases by a modest 3%, leading to additional revenue of ₹ 2,000 per hectare. As adoption increases, so do the benefits: under a high-adoption scenario (90%), farmers can achieve a 20% yield increase and gain an additional ₹ 17,000 per hectare in revenue. The corresponding environmental benefits also scale up, with net savings of ₹ 16,200 per hectare in the high-adoption scenario. These findings underscore the substantial economic and environmental gains that could be realized if a larger portion of farmers adopt these advanced technologies. Roco and Bainbridge, (2007) also reported similar findings in their research.

CONCLUSION

The adoption of biotechnological and nanotechnological innovations in agriculture is still in its early stages, particularly in chickpea farming. Future research should explore the long-term impacts of these methods on soil health, biodiversityand resilience to climate change. Moreover, expanding the scope of these technologies to other legume crops and varying agro-climatic conditions could provide valuable insights into their broader applicability. Further studies can also investigate the integration of these methods with other sustainable practices like organic farming or precision agriculture to maximize both productivity and sustainability.

Recommendations

Policy support

Governments should incentivize the adoption of biotechnological and nanotechnological approaches through subsidies, training programsand access to improved seeds and technology.

Farmer training

Extension services should focus on educating farmers about the benefits of these advanced methods, ensuring

they understand how to implement and optimize the technology for maximum profitability and sustainability.

Research and development

Ongoing investment in R&D is critical to refining these technologies and making them more accessible and cost-effective, particularly for small and marginal farmers.

Public-private partnerships

Collaboration between public institutions and private firms can accelerate the dissemination of biotechnological and nanotechnological innovations, ensuring their widespread use across diverse farming communities.

Crop diversification

Promote crop diversification and intercropping techniques to increase farmers' income and improve resilience against market and climate fluctuations.

Organic farming

Encourage organic farming by highlighting its long-term benefits such as soil health and reduced chemical use, while also discussing drawbacks like lower short-term yields and higher labour costs compared to chemical farming methods.

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Disclaimers

The opinions and conclusions in this article are the authors' own and may not reflect the views of their institutions. The authors are responsible for the accuracy and completeness of the information, but are not liable for any direct or indirect losses caused by the use of this content.

Informed consent

NA.

Conflict of interest

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