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How Do Gender-Based Employment, Agricultural Machinery, and Fertilizers Influence Regional Agricultural Productivity? Panel Analyses for South and Southeast Asian Countries

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ABSTRACT: The analysis delves into key strategies for enhancing agricultural productivity in Southeast Asia and South Asia. It underscores the vital role of mechanization, sustainable input practices, and gender-inclusive policies. Customized interventions in these realms hold promise for significantly amplifying agricultural performance in the region. Fertilizer and machinery productivity are pivotal factors that correlate strongly with overall agricultural productivity, as revealed by regression analyses. Notably, male employment in agriculture and agricultural machinery exhibits positive and substantial impacts on agricultural productivity, while female employment and fertilizer consumption indicators show significant yet negative associations. The study highlights systemic issues such as unequal resource access and differing gender roles in agriculture that may impede the immediate productivity gains from increased female labor force participation. Mechanization and efficient fertilizer utilization emerge as critical drivers of enhanced agricultural output, with consistent coefficients across models. Male employment consistently demonstrates a positive influence on productivity, emphasizing the significance of labor force engagement in agriculture. Moreover, the study underscores the imperative of judicious fertilizer management to avert environmental degradation and diminishing returns. The findings affirm the efficacy of the random effects model, supported by the Hausman test, which indicates congruence in results between fixed and random effects models. This methodological choice ensures robust and reliable conclusions regarding the relationships between male and female employment, machinery, fertilizer consumption, and agricultural productivity in South and Southeast Asia.

Keywords: Gender-based employment; Machinery; Fertilizers; Agricultural productivity; Panel regression; Regional development

1. Introduction

Numerous factors significantly influence agricultural productivity in South and Southeast Asia, including land, labor, technology, and trade dynamics. Research indicates that while technical progress has historically driven productivity, recent declines in efficiency and scale raise concerns about future growth. The availability of land and labor remains crucial. Studies show that in Indonesia, agricultural production has been affected by land depletion and labor dynamics, with employment in agriculture increasing despite land constraints [1] Technological innovation is essential for enhancing productivity. Liu et al. (2020) emphasize that investment in human capital and technology is vital for sustaining agricultural growth in the region [2]. Trade liberalization and foreign direct investment, particularly from Japan, have played a pivotal role in fostering agricultural expansion in East Asia, underscoring the importance of external economic factors [3].

The relationship between agricultural machinery, fertilizer use, and productivity is well-documented, demonstrating their significant impact on agricultural output. However, despite productivity improvements, a disconnect remains between agricultural growth and rural poverty alleviation. Increased fertilizer use can lead to a 13–20% rise in GDP per capita due to higher agricultural yields. The adoption of modern agricultural machinery has also been shown to positively affect food grain production. For instance, in Pakistan, machinery and irrigation sources significantly contribute to agricultural output [4,5]. Kiresur and Melinamani (2008) found that while agricultural productivity can

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reduce rural poverty, the relationship is complex and requires substantial investment in agricultural research to yield significant benefits [6]. Similarly, Oyakhilomen and Zibah (2014) found that despite the positive influence of agricultural production on economic growth in Nigeria, poverty persists, suggesting that agricultural growth alone is insufficient for poverty alleviation. To effectively combat rural poverty, it is essential to implement government policies that enhance agricultural practices, expand wetland areas, and promote agriculture-related businesses [6,7]. While agricultural productivity is crucial for economic development, its impact on poverty reduction remains limited without comprehensive policy initiatives and investments in rural infrastructure and diversification strategies.

The interplay between gender-based employment, agricultural machinery, and fertilizer use significantly influences regional agricultural productivity in South and Southeast Asia. Research indicates that while technological advancements, such as mechanization, enhance productivity, they also have gendered implications that affect labor dynamics and agricultural output. The feminization of the rural labor force can negatively impact grain production, particularly in regions where mechanization is less prevalent. In India, mechanization has led to a greater decline in women's labor participation compared to men's, as tasks traditionally performed by women, such as weeding, are reduced [8]. Agricultural mechanization has been shown to shift labor from farm to non-farm activities, particularly for women, which can alter productivity outcomes [9]. However, the use of machinery can mitigate the negative effects of labor feminization in certain regions, enhancing overall productivity. The application of fertilizers, alongside technological innovations, is crucial for improving total factor productivity (TFP) in the region. Investment in human capital and technology, including fertilizers, is essential for sustaining agricultural growth [2]. While mechanization and fertilizers can boost productivity, they may also exacerbate gender inequalities in labor participation, highlighting the need for policies that address these disparities while promoting agricultural efficiency.

Despite extensive research on agricultural productivity in South and Southeast Asia, significant gaps remain in understanding the complex interplay between gender-based employment, mechanization, and fertilizer use in shaping agricultural outcomes. While previous studies highlight the critical role of technology and labor dynamics in boosting productivity, the gendered implications of these advancements have not been fully explored, particularly in regions experiencing labor feminization due to rural transformations. Moreover, although fertilizer application and mechanization have been recognized as essential productivity drivers, their long-term sustainability and socio-economic effects—especially on poverty alleviation and employment patterns—remain underexplored. This research bridges these gaps by offering a comprehensive analysis of agricultural employment trends, technological adoption, and input utilization, particularly in the context of sustainable development goals (SDGs). By addressing the disconnect between productivity growth and rural poverty reduction, this study provides policy-relevant insights that emphasize the need for gender-inclusive agricultural strategies, responsible input management, and targeted investments in mechanization. The findings will contribute to evidence-based policymaking, ensuring that agricultural advancements lead to both economic growth and equitable development in the region.

South and Southeast Asia were chosen for this study due to their strong dependence on agriculture, where a large share of the population relies on farming for livelihoods and economic stability. The region exhibits diverse gender employment patterns, with significant variations in male and female labor participation, making it an ideal setting to analyze their impact on agricultural productivity. Additionally, disparities in mechanization and fertilizer use across countries provide a unique opportunity to assess their role in enhancing efficiency. Policymakers in these regions are actively promoting agricultural modernization and gender-inclusive strategies, making the findings highly relevant for policy development. Lastly, the availability of comprehensive data enables a robust panel analysis, offering valuable insights into the complex interactions between gender-based employment, agricultural machinery, and fertilizers in shaping regional productivity. Moreover, other external factors affecting agriculture are excluded from the study, such as typhoons, floods, and natural hazards affecting Southeast and South Asia [10].

This study examines agricultural productivity dynamics in South and Southeast Asia, focusing on agricultural employment, machinery utilization, and fertilizer applications. The research aligns with key Sustainable Development Goals (SDGs) that are fundamental to agricultural transformation and sustainable development in these regions. SDG 8, Decent Work and Economic Growth, is particularly relevant as it promotes equitable employment opportunities and economic inclusion in agriculture, where significant wage disparities and informal work arrangements persist. This goal's emphasis on decent work directly impacts agricultural productivity by encouraging skilled labor retention and technological adoption in farming communities. SDG 11, Sustainable Cities and Communities, addresses the critical interface between urban expansion and agricultural sustainability, particularly relevant in rapidly urbanizing Asian regions. Its focus on urban-rural linkages helps maintain agricultural productivity by promoting efficient land use and protecting farming communities from urban encroachment. SDG 12, Responsible Consumption and Production,

enhances agricultural efficiency through sustainable resource management and waste reduction across the value chain. This goal's emphasis on responsible production practices directly influences how agricultural inputs—such as labor, machinery, and fertilizers—are utilized to optimize productivity while minimizing environmental impact.

These interconnected SDGs provide a comprehensive framework for understanding how various factors contribute to agricultural productivity while promoting sustainable development in South and Southeast Asia. By examining employment patterns, mechanization, and input use through this lens, this research offers valuable insights for policymakers aiming to balance productivity gains with sustainable agricultural practices.

2. Literature Review

2.1. Gender-Based Agricultural Employment and Agricultural Productivity

The study of gender dynamics in agricultural employment highlights intricate patterns of participation and productivity shaped by deeply ingrained socio-economic and cultural factors. While gender roles in agriculture have evolved, significant disparities persist, particularly in women's access to resources and recognition within the sector. Women constitute a large portion of the global agricultural workforce, accounting for 60–80% in some African regions [11]. In India, women make up 24% of cultivators and 41.1% of agricultural laborers, yet their contributions are often undervalued and inadequately reflected in economic assessments [12]. Numerous studies emphasize the barriers faced by women in agriculture, such as limited access to education, financial constraints, and legal restrictions, which hinder their economic advancement [12,13]. The connection between gender and agricultural productivity reveals notable trends. Research suggests that while male labor positively impacts agricultural output, female labor often shows insignificant short-term effects [14]. This discrepancy highlights untapped potential in female agricultural participation, underscoring the need for targeted policies that empower women in the sector [11]. Historically, women's agricultural roles have been marginalized, frequently classified as non-economic activities [15]. However, increasing global awareness of gender equality has created opportunities for greater recognition and support of women's contributions to agriculture. Addressing these historical inequities through inclusive policies and structural reforms is essential for fostering a more equitable agricultural sector. While challenges remain, ongoing advocacy for gender empowerment holds promise for transformative change, ultimately leading to a more inclusive and productive agricultural landscape.

2.2. Agricultural Machinery and Agricultural Productivity

The connection between agricultural machinery and productivity is complex, encompassing factors such as machinery structure, mechanization levels, and technological advancements. While research confirms that effective machinery use enhances productivity, it also presents challenges related to environmental sustainability. The capacity structure of agricultural machinery, particularly high-powered equipment like tractors, plays a vital role in optimizing input allocation and increasing grain production. A study in China found that the elasticity of output concerning machinery inputs is 0.03, quantifying its impact on productivity [16]. Moreover, the adoption of agricultural machinery services (AMS) has been shown to significantly boost cultivated land productivity, with productivity gains ranging from 7.6% to 12.1% among adopting farmers [17]. The most substantial benefits are observed in ploughing and harvesting, whereas its effects on management activities are comparatively modest [17]. The integration of modern technologies and process optimization has further enhanced agricultural efficiency. In India, for instance, mechanization levels currently stand at around 55%, with anticipated increases due to labor shortages and the rising demand for improved productivity. Although agricultural machinery plays a critical role in boosting productivity, the sector must address environmental concerns and sustainability challenges. Balancing productivity gains with ecological preservation will be essential for ensuring the long-term viability of agricultural practices. Moving forward, innovations in sustainable mechanization will be crucial in maximizing benefits while minimizing environmental impact.

2.3. Fertilizers and Agricultural Productivity

The link between fertilizers and agricultural productivity is crucial for improving crop yields and ensuring food security. Both customized and mineral fertilizers play a significant role in boosting agricultural output. This review consolidates research findings to highlight the importance of fertilizers in agriculture, their impact on productivity, and the need for sustainable practices. Over the past decades, fertilizer use has surged dramatically, increasing from 0.07 million tons in 1951 to over 26.5 million tons in 2018, alongside rising application rates per hectare [18]. Studies show that fertilizers contribute to over 55% of the rise in food production, reinforcing their essential role in meeting the

demands of a growing global population [18,19]. Agricultural training programs have proven highly effective in encouraging the adoption of formula fertilization techniques, leading to a 14.3% increase in crop yields among trained farmers [20]. These initiatives influence farmers' awareness and willingness to adopt innovative methods, thereby improving agricultural productivity [20]. However, heavy reliance on synthetic fertilizers poses serious environmental risks, necessitating a shift toward sustainable alternatives, such as organic fertilizers and beneficial microbes [21]. Additionally, the implementation of balanced fertilization strategies and site-specific nutrient management has been crucial in preserving soil health and preventing nutrient deficiencies [18]. Despite their importance, excessive fertilizer use can degrade the environment, emphasizing the need for sustainable agricultural practices. The integration of eco-friendly fertilization techniques and innovative technologies is vital for ensuring long-term food security while safeguarding agricultural sustainability. Future research should prioritize optimizing fertilizer efficiency while minimizing environmental harm to maintain the balance between productivity and ecological preservation.

2.3.1. Classical Theory of Employment

The Classical Theory of Employment serves as a cornerstone of economic thought, highlighting the interplay between labor, capital, and market forces. According to this theory, employment levels are dictated by the principles of supply and demand in a free market, where wage adjustments help balance labor supply with demand. A key aspect of this theory is the freedom of contract, which enables employers and employees to negotiate working conditions independently, fostering individual bargaining power [22]. Classical economists assert that labor plays a fundamental role in generating surplus value, defined as the difference between total output and input costs [23]. Additionally, the theory emphasizes that maintaining equilibrium between labor and capital is essential for achieving full employment, with interest rates serving as a crucial balancing mechanism [24]. This perspective contrasts with Keynesian economics, which argues that aggregate demand drives employment levels and advocates for government intervention to counteract unemployment [25]. While classical economists support minimal state interference, relying on market forces to self-correct, critics argue that this framework struggles to address modern economic challenges like structural unemployment and market failures. These critiques suggest that contemporary labor markets may require a more nuanced approach that integrates elements of both classical and Keynesian thought.

2.3.2. Production Function

The agricultural production function is shaped by the interplay of key inputs such as fertilizer, machinery, and employment, all of which contribute to improving crop yields and overall productivity. Fertilizers are particularly essential, with studies showing a strong correlation between their use and increased cereal production, as well as GDP growth in developing nations. Similarly, agricultural machinery plays a crucial role in boosting production capacity and efficiency, with research highlighting its positive impact on grain production, particularly for crops like rice, wheat, and corn. The availability and effective use of agricultural machinery services further enhance grain production efficiency, reinforcing the importance of modernizing agricultural practices. Employment remains a vital component of agricultural productivity. Evidence suggests that higher employment levels positively impact crop production, as labor is a fundamental factor in agricultural output. Moreover, the integration of skilled labor with modern inputs such as machinery and fertilizers amplifies production outcomes, demonstrating a synergistic relationship among these factors [4,20,26,27]. However, while these elements drive productivity gains, challenges such as environmental degradation and the sustainability of intensive farming practices must be carefully managed. Striking a balance between maximizing productivity and ensuring long-term sustainability is critical for the future of agriculture.

Conceptual Framework

Figure 1 shows the concept of the study. This section presents the study's conceptual framework, which is based on the earlier discussion of the body of current literature. This covers important factors and their relationship.

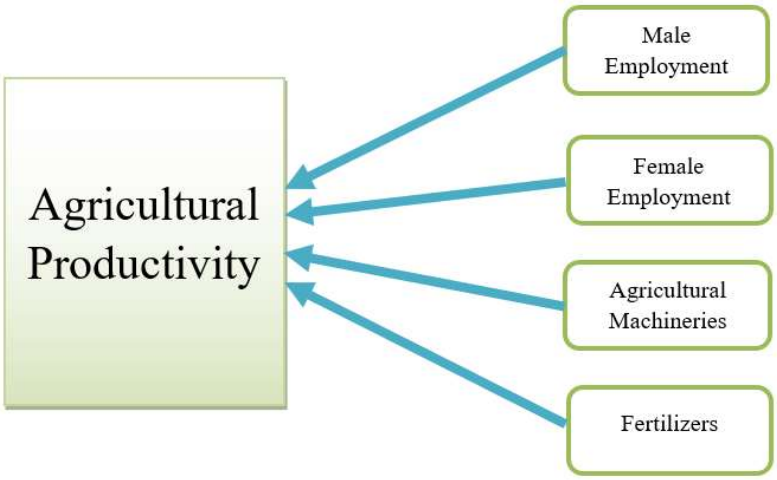

Figure 1. Conceptual framework of the study.

Figure 1 presents the complex relationships between key agricultural factors and their influence on productivity. Four independent variables—male employment, female employment, agricultural machinery usage, and fertilizer application—were examined to assess their impact on agricultural productivity, the dependent variable. The analysis uncovered intricate causal relationships among these elements, illustrating how they interact and collectively shape production outcomes. The interconnected nature of these factors suggests that changes in any single variable can trigger ripple effects throughout the agricultural system, highlighting the dynamic interplay that drives overall productivity.

3. Research Methods

3.1. Research Design

This study employs quantitative analysis using secondary data obtained from the World Bank database. The research framework examines agricultural productivity as the dependent variable, while gender-based employment, agricultural machinery, and fertilizer usage serve as independent variables. The primary objective is to analyze both correlation and causation relationships between these variables and agricultural productivity, while also identifying agricultural trends and productivity patterns across South and Southeast Asian countries. The analytical framework follows the model developed by Onsay (2024) to assess the significant impact of these factors on agricultural output [28]. For data analysis, the study implements both fixed and random effects models to determine the significance of independent variables in relation to the dependent variable. The Hausman test is employed to evaluate and determine the most appropriate model between the fixed and random effects approaches.

3.2. Data Gathering Procedure

Secondary data were gathered from the World Bank database. The data were downloaded as Excel files and carefully assessed to determine their relevance to the investigation. The researchers used R-Studio and Microsoft Excel for data preparation and analysis.

3.3. Source of Data

The research encompassed selected countries from two major Asian regions. The South Asian countries included Afghanistan, Bangladesh, Bhutan, India, Iran, Sri Lanka, Maldives, Nepal, and Pakistan. The Southeast Asian component comprised the Philippines, Indonesia, Vietnam, Thailand, Malaysia, Myanmar, Singapore, and Brunei. The study utilized panel data spanning from 1993 to 2022, with data sourced from the World Bank database, yielding a total of 1420 data entries. The World Bank, which oversees 187 member countries, serves as a prominent global development institution. Its primary mission involves providing financial assistance through loans to developing member nations, aimed at fostering economic growth and elevating living standards for their populations [29]. To process this extensive dataset effectively, the researchers employed data mining techniques to extract meaningful information for subsequent analysis.

3.4. Ethical Considerations

This study relied exclusively on secondary data available in the public domain through the World Bank database. The public nature of this data implies implicit consent for its use for research purposes. Furthermore, the data's aggregated format at the national level ensures complete anonymity, as it represents macro-level economic and agricultural indicators rather than individual responses. The researchers maintained ethical integrity by analyzing these pre-processed indicators without any attempt to identify specific participants or reveal sensitive information. This approach aligns with standard research practices for working with public, aggregate datasets while upholding principles of data privacy and ethical research conduct.

3.5. Data Analysis

Econometric Materials

The research methodology was built upon the model established by Onsay (2021), integrating both descriptive statistics and panel econometric approaches for a comprehensive analysis [30]. Panel regression analysis served as the primary analytical tool, combining cross-sectional data with time series measurements to examine the relationships between agricultural productivity and its various determinants—including employment patterns, machinery utilization, and fertilizer application—across South and Southeast Asian nations. To ensure methodological rigor, the study incorporated two crucial statistical tests. First, the Hausman test was employed to make an informed choice between fixed and random effects models. The fixed effects model proved particularly valuable as it accounts for country-specific unobserved heterogeneity—those time-invariant factors that might simultaneously influence both dependent and independent variables. The random effects model, which operates under the assumption that these factors remain uncorrelated with independent variables, was deemed potentially less appropriate for this particular analysis. Additionally, the study utilized the Variance Inflation Factor (VIF) to assess and quantify multicollinearity among independent variables. The VIF analysis provided crucial insights into how each independent variable's behavior might be influenced by its correlations with other variables, allowing for necessary model adjustments and ultimately strengthening the statistical significance of the findings. This comprehensive methodological approach ensured robust analysis of the complex relationships between agricultural productivity and its various determinants. Table 1 lists the variables and their respective sources utilized in our study.

Panel model basis [30]:

$$d = \beta_0 + \beta_{1i} + \sum_{m=1}^{m} \delta_m r_m$$

Study's model:

$$APMT = ß_1 + \alpha_i + ß_2 EAGMA_{it} + ß_3 EAGFE_{it} + ß_4 AMTPHS_{it} + ß_5 FCKPH_{it} + \varepsilon_{it}$$

where:
α_i (i = 1…*n*) = is the unknown intercept for each sample (*n* entity-specific intercepts).
Y_{it} = is the dependent variable (DV) where i = entity and t = time.
X_{it} = represents one independent variable (IV),
$ß_1$ = is the coefficient for that IV,
$Ɛ_{it}$ = is the error term
List of Variables
Dependent Variables:
APMT = Agricultural Productivity (Metric Tons)
Independent Variables:
EAGMA = Employment in Agriculture, Male (% of male employment)
EAGFE = Employment in Agriculture, Female (% of female employment
AMTPHS = Agricultural Machinery (Tractors per 100 sq. km of arable land)
FCKPH = Fertilizers Consumption (Kilograms per hectare of arable land).

Table 1. List of Variable Descriptions and Sources.

Variables		VAR	Description	Apriori Ex
Dependent Variables	Agricultural Productivity	*AMPT*	Agricultural productivity is measured by calculating the relationship between agricultural outputs and the inputs required to generate them. While the yield or weight of individual crops provides a straightforward measurement for specific products, calculating overall agricultural output presents a greater challenge due to the diverse range of agricultural goods produced [31–33].	
Independent Variables	Male Employment on Agriculture	*EAGMA*	Male agricultural employment, as calculated by the International Labor Organization (ILO), represents the percentage of the male workforce engaged in or actively seeking work in the agricultural sector. This metric captures both currently employed men and those seeking agricultural employment [31–33].	Positive (+)
	Female Employment on Agriculture	*EAGFE*	Female agricultural employment, as measured by the International Labor Organization (ILO), represents the percentage of the female workforce either actively working in or seeking employment within the agricultural sector. This metric encompasses both currently employed women and those actively pursuing agricultural work opportunities [31–33].	Negative (−)
	Agricultural Machinery	*AMTPHS*	Agricultural machinery usage is measured by the density of tractors per 100 square kilometers of arable land, providing an indicator of mechanical farming capacity in a given area [31–33].	Positive (+)
	Fertilizers	*FCKPH*	Agricultural fertilizers are measured in kilograms per hectare of arable land [31–33].	Negative (−)

WORLD BANK Database (1993–2002).

4. Result and Discussions

4.1. Empirical Analysis in South Asia

Figure 2 illustrates the trends in male employment in agriculture across South Asian countries from 1993 to 2002. The data indicates a general decline in the percentage of males working in agriculture, suggesting a gradual shift toward other economic sectors such as industry and services. Among the countries observed, Nepal consistently exhibits the highest percentage of male agricultural employment, maintaining levels between 70% and 75%, although showing a slight downward trend. Similarly, Bhutan maintains over 60% employment in agriculture, though it also follows a gradual decline. India, Bangladesh, and Iran display moderate levels of male agricultural employment. India starts with over 60% in 1993 but experiences a steady decline, reaching approximately 50% by 2002, indicating the effects of industrialization and urbanization. Bangladesh exhibits a more noticeable decrease, dropping below India by the end of the period, while Iran follows a similar trend. In contrast, Pakistan and Sri Lanka maintain fluctuating but generally declining patterns, with employment percentages ranging between 30% and 40%. Afghanistan remains relatively low, at approximately 20–25%, with a slight decline, whereas the Maldives consistently has the lowest male agricultural employment, reflecting its economic reliance on tourism, fishing, and other non-agricultural sectors. These trends highlight the broader economic transformation occurring in South Asia during this period. The declining agricultural employment in India and Bangladesh suggests increasing mechanization and a shift to urban-based economies. Meanwhile, Nepal and Bhutan's persistently high agricultural employment indicate a slower transition, possibly due to economic dependency on farming. The patterns in Sri Lanka and Pakistan suggest a mixed transition, where agriculture remains a significant employment source despite gradual diversification. Finally, the data underscores the evolving economic landscape in South Asia, where agriculture continues to play a crucial role but is steadily declining as other sectors expand [34–37].

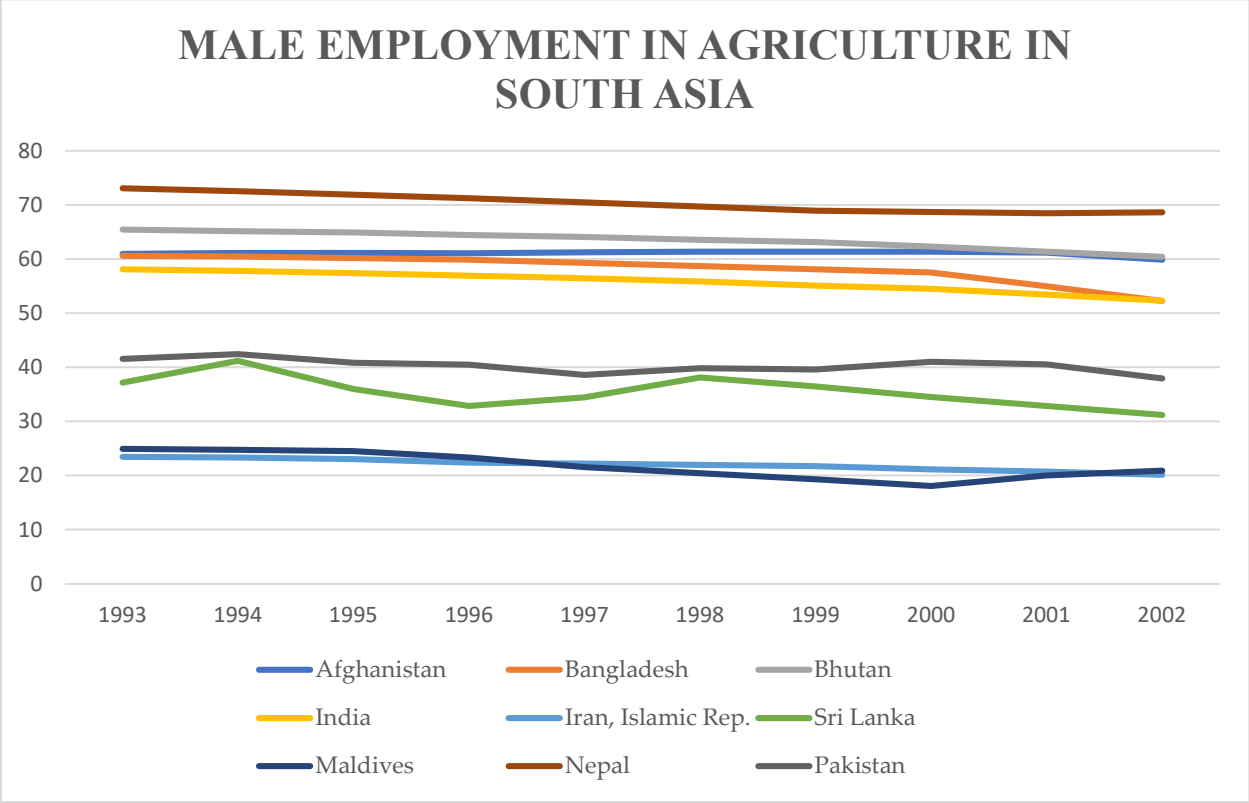

Figure 2. Male employment in agriculture in South Asia.

Figure 3 presents data on female employment in agriculture across South Asian countries from 1993 to 2002. The data indicates that women play a significant role in the agricultural workforce, with the majority of countries showing consistently high female employment in this sector. Nepal and Bhutan have the highest levels, maintaining approximately 85–90% of female employment in agriculture throughout the period. India and Bangladesh also show high levels, with over 70% of women engaged in agriculture, though there is a gradual decline in later years. Afghanistan and Pakistan exhibit relatively lower female participation in agriculture, with employment rates between 30% and 50%, but Afghanistan demonstrates an increasing trend over time. Iran, on the other hand, maintains a significantly lower percentage, with fewer than 30% of women working in agriculture, suggesting a more diversified economy or cultural and policy-driven employment constraints. Sri Lanka and the Maldives consistently have the lowest female employment in agriculture, indicating a reliance on other industries such as services, trade, and tourism. The overall trend suggests that, while agriculture remains a primary employment sector for women in South Asia, some countries are experiencing a gradual shift away from traditional farming roles. This could be attributed to increasing urbanization, economic diversification, and shifts in labor dynamics. However, in countries like Nepal and Bhutan, the persistently high percentage of women in agriculture may reflect limited economic opportunities outside the agricultural sector. The data highlights the gendered nature of agricultural labor in the region and suggests that policies aimed at economic development should consider the role of women in transitioning to alternative forms of employment [38,39].

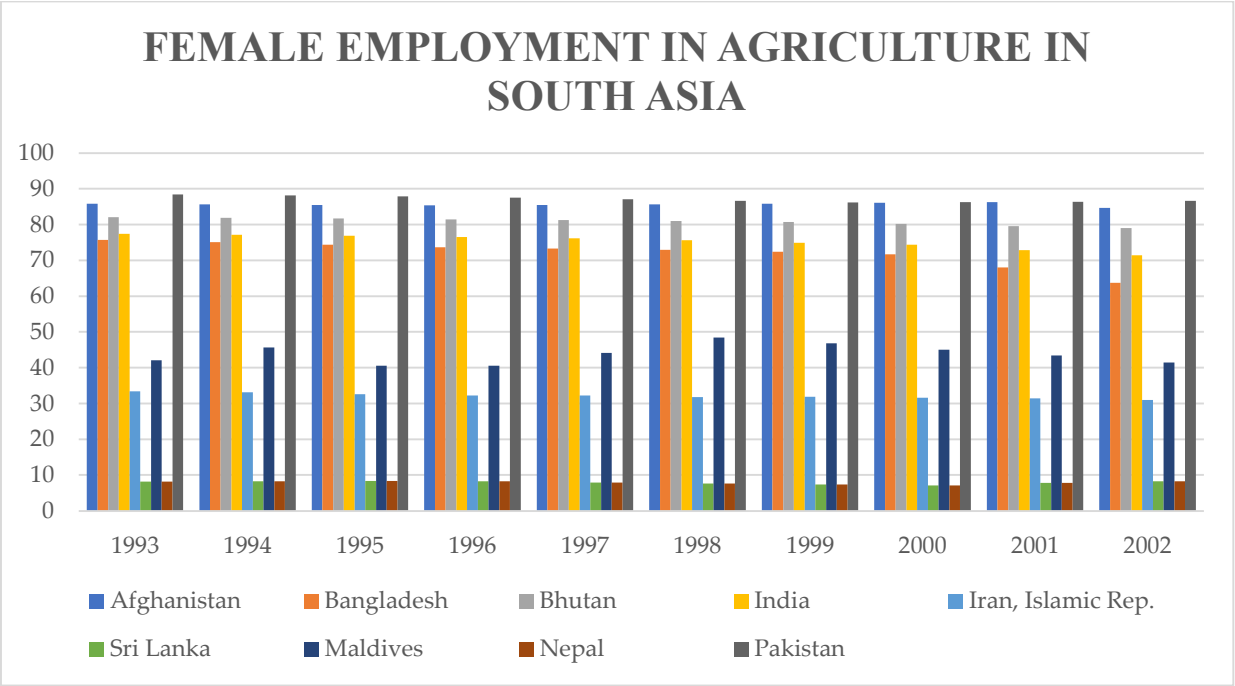

Figure 3. Female employment in agriculture in South Asia.

Figure 4 illustrates the usage of agricultural machinery in arable land across South Asian countries from 1993 to 2002. The data shows a clear dominance of India in agricultural mechanization, with the number of machines steadily increasing each year, surpassing 2.5 million by 2002. In contrast, Pakistan and Iran (Islamic Republic) maintain moderate levels of machinery usage, with only slight fluctuations over the years. Meanwhile, other South Asian countries, including Afghanistan, Bangladesh, Bhutan, Sri Lanka, Maldives, and Nepal, exhibit minimal mechanization, with little to no growth in the number of machines used. The trend suggests that India has undergone significant agricultural modernization during this period, while other countries in the region still rely heavily on traditional farming methods. The steady increase in mechanization in India indicates advancements in agricultural infrastructure, potentially leading to higher productivity. In contrast, the stagnation in other countries might reflect economic constraints, limited access to technology, or continued dependence on manual labor. The moderate levels in Pakistan and Iran suggest some degree of industrialization, but not at the scale seen in India. This disparity highlights the varying levels of agricultural development across South Asia during the given time frame. The bars that are not shown represent very minimal or insignificant performance relative to other countries on the list. This does not mean zero, as it is impossible for a country to perform in agriculture without the necessary inputs for production [40,41].

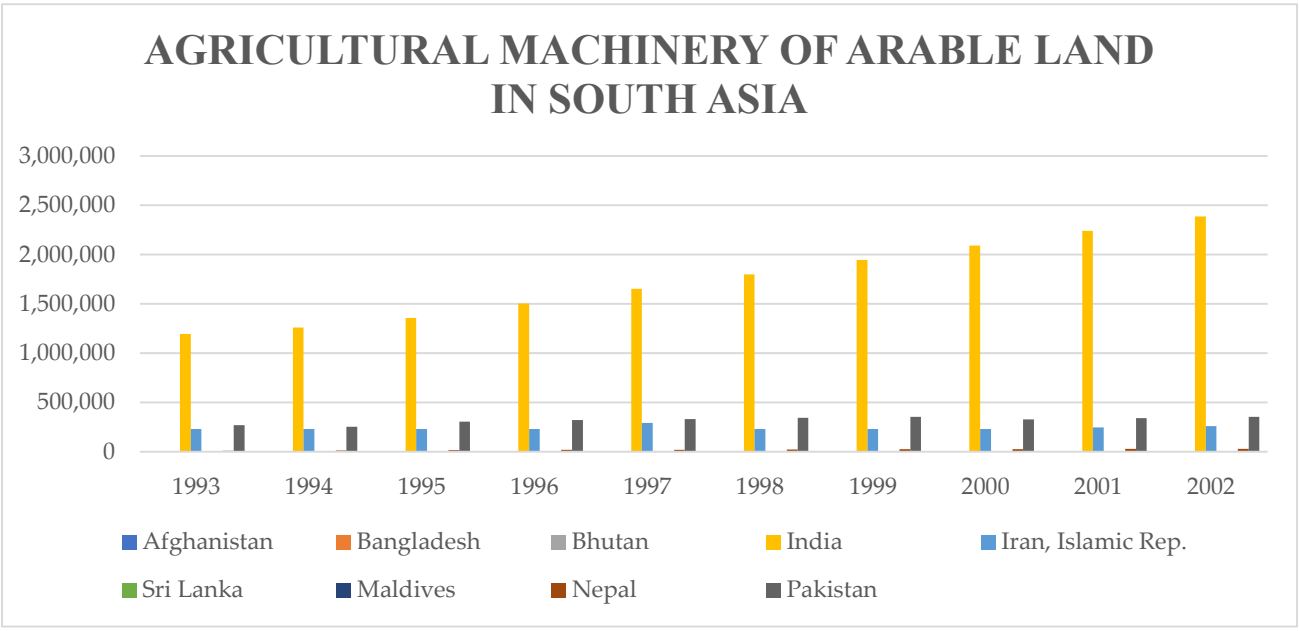

Figure 4. Agricultural Machinery Tractors Per 100 sq. km of Arable Land in South Asia.

Figure 5 illustrates fertilizer consumption on arable land across South Asian countries from 1993 to 2002. Bangladesh consistently exhibits the highest fertilizer usage, significantly surpassing other nations throughout the period. The country's fertilizer consumption fluctuates but remains above 2000 units per year, peaking in 1994 and 1999, which suggests a strong reliance on chemical fertilizers to enhance agricultural productivity. In contrast, all other countries demonstrate significantly lower levels of fertilizer consumption. India, Pakistan, and Iran show moderate but relatively stable fertilizer use, with minor variations across the years. Bhutan, Nepal, Sri Lanka, and the Maldives report minimal fertilizer consumption, which may indicate a lower level of agricultural intensification, a preference for organic farming practices, or economic constraints in accessing chemical fertilizers. The contrast in fertilizer consumption among South Asian countries suggests varying degrees of agricultural modernization and dependency on chemical inputs. Bangladesh's high fertilizer usage aligns with its densely populated agricultural sector and intensive farming practices. Meanwhile, countries with lower consumption may rely more on traditional or subsistence farming methods. The data underscores the need to examine sustainable agricultural practices and the environmental impact of fertilizer dependency in the region [42,43].

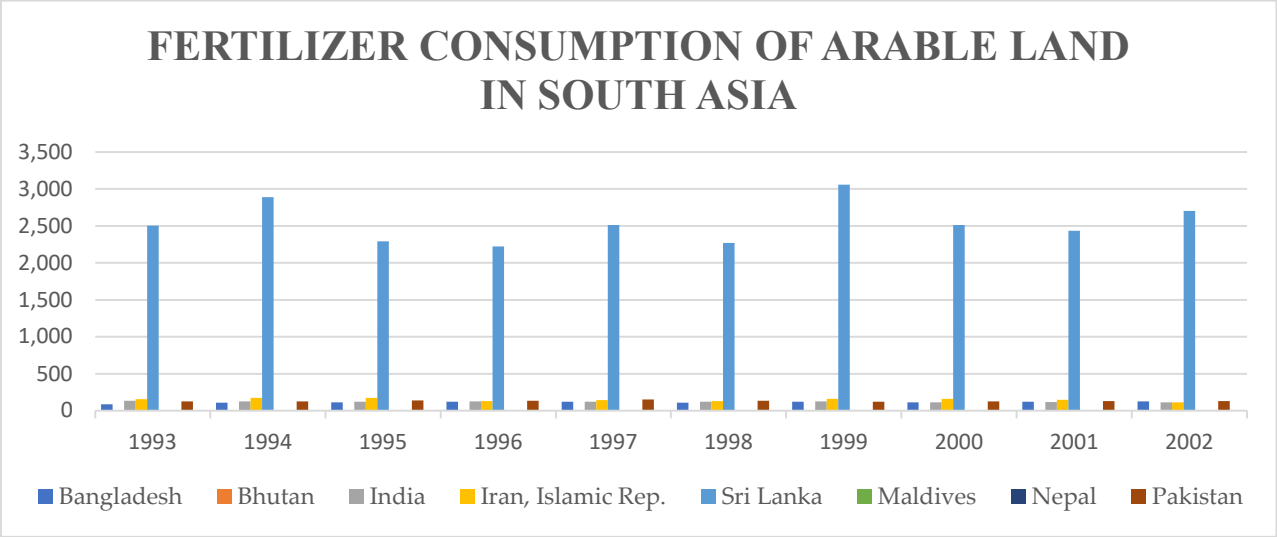

Figure 5. Fertilizer Consumption Kilograms Per Hectare of Arable Land in South Asia.

Figure 6 represents agricultural productivity in South Asia from 1993 to 2002. India exhibits the highest agricultural productivity throughout the period, significantly surpassing all other South Asian countries. Its agricultural output remains relatively stable, with minor fluctuations, indicating a consistent level of productivity driven by large-scale farming, irrigation systems, and the extensive use of fertilizers and modern agricultural techniques. Bangladesh and Pakistan follow India, though their agricultural productivity is much lower in comparison. Both countries show a gradual increase over time, reflecting improvements in agricultural practices, technological advancements, and policy interventions. Iran also demonstrates a moderate level of productivity, maintaining a steady trend similar to Bangladesh and Pakistan. Other South Asian nations, including Afghanistan, Bhutan, Sri Lanka, Nepal, and the Maldives, show considerably lower agricultural productivity, indicating limited agricultural output due to factors such as smaller land areas, lesser mechanization, reliance on traditional farming methods, or geographical constraints. The Maldives, in particular, records the lowest agricultural productivity, likely due to its limited arable land and dependence on imports for food production. Overall, significant disparities in agricultural productivity across South Asia are observed, with India dominating the sector. The data suggests a correlation between high agricultural productivity and factors such as land availability, technological adoption, and investment in the agricultural sector [2,44].

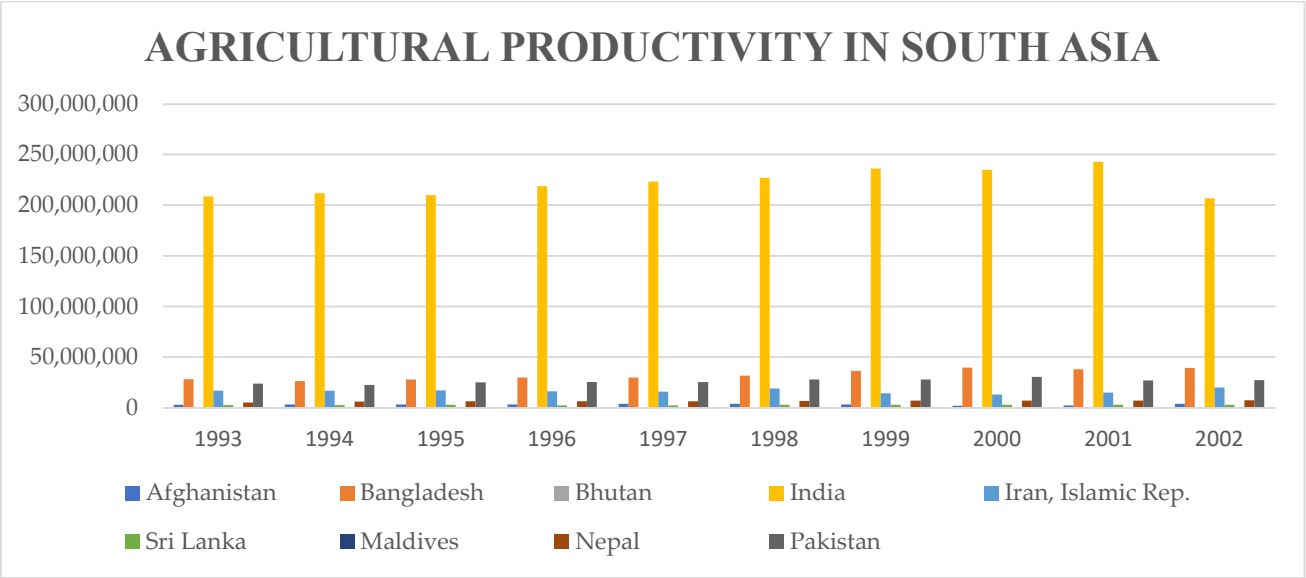

Figure 6. Agricultural Productivity, Metric Tons in South Asia.

4.2. Empirical Analysis in Southeast Asia

Figure 7 illustrates male employment in agriculture across Southeast Asian countries from 1993 to 2002. Myanmar consistently had the highest proportion of male employment in agriculture, maintaining a level above 65%, though it showed a slight decline over time. Similarly, Vietnam also had a high percentage of male employment in agriculture, but it experienced a gradual decrease, reflecting shifts toward industrial and service sectors. Thailand and the Philippines displayed mid-range male agricultural employment levels, with figures fluctuating between 40% and 55%. While Thailand showed a slight increase in the mid-1990s before stabilizing, the Philippines exhibited a consistent downward trend, indicating an ongoing transition away from agricultural labor. Indonesia maintained a relatively stable male employment rate in agriculture, hovering around 45–50%, suggesting a slower pace of structural transformation compared to some other nations. Malaysia, on the other hand, had a much lower share, consistently staying around 20%, which aligns with its rapid industrialization and economic diversification. Singapore and Brunei Darussalam had the lowest male employment in agriculture, remaining close to zero throughout the period, reflecting their urbanized economies with minimal reliance on agriculture. Overall, the data reveals a general decline in male employment in agriculture across Southeast Asia, particularly in countries experiencing industrialization and urbanization. However, some nations, like Indonesia and Thailand, exhibited a more gradual transition compared to others like Vietnam and the Philippines [45–47].

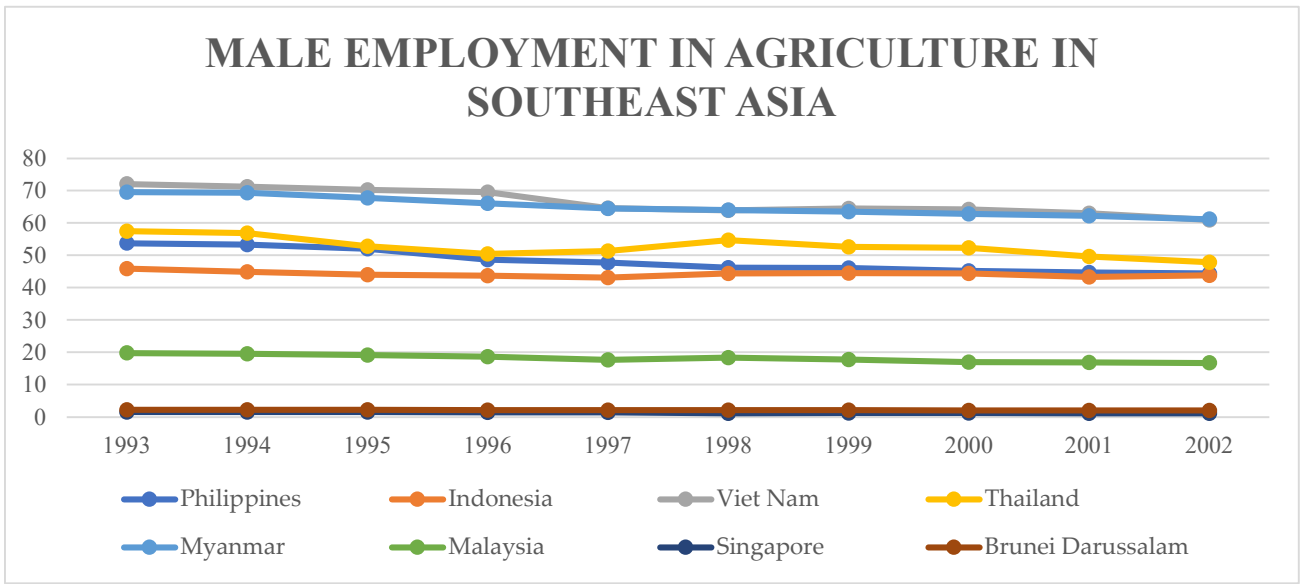

Figure 7. Male employment in agriculture in Southeast Asia.

Figure 8 illustrates female employment in agriculture across Southeast Asian countries from 1993 to 2002. A significant upward trend is evident in Thailand, where female employment in agriculture increased steadily, surpassing all other countries by 2002. Vietnam also experienced consistent growth in female agricultural employment, though at a slower rate compared to Thailand. Myanmar exhibited high levels of female employment in agriculture at the beginning of the period, with figures surpassing 300 in 1993 and increasing further to nearly 500 by 1995. However, after this point, data for Myanmar is not available, making it unclear if the upward trend continued. The Philippines showed a steady but moderate increase in female agricultural employment, maintaining a consistent trajectory without sharp rises or declines. Similarly, Indonesia followed a gradual upward trend but at a much lower scale than Thailand and Vietnam. Malaysia, Singapore, and Brunei Darussalam remained at the lowest levels of female agricultural employment throughout the period, reflecting their urbanized economies and reduced dependence on agricultural labor. These countries showed no significant fluctuations, indicating a stable labor structure in their agricultural sectors. Overall, the data suggests that female participation in agriculture varied widely across Southeast Asia, with Thailand and Vietnam experiencing rapid increases, while other nations maintained more gradual or stable trends [45–47].

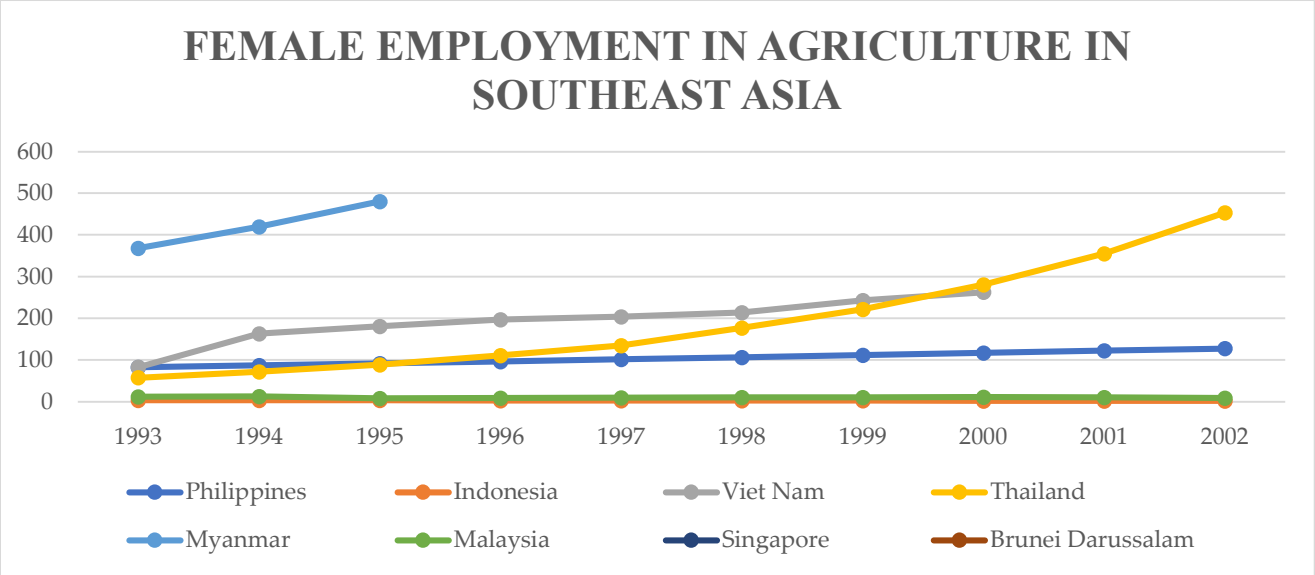

Figure 8. Female employment in agriculture in Southeast Asia.

Figure 9 illustrates the usage of agricultural machinery in Southeast Asia from 1993 to 2002, revealing significant disparities among the countries. The Philippines consistently exhibits the highest level of agricultural machinery usage, peaking in 1993 and experiencing fluctuations in the following years. Despite occasional declines, it remains the dominant country in terms of mechanization. Myanmar follows as the second-largest user, though its levels are considerably lower than the Philippines, with a gradual decline after 1996. Meanwhile, Indonesia, Vietnam, and Thailand show relatively low but stable machinery usage, with slight increases over the years, indicating moderate growth in mechanization. On the other hand, Malaysia, Singapore, and Brunei Darussalam demonstrate minimal reliance on agricultural machinery, likely reflecting their more industrialized economies with less dependence on mechanized farming. Overall, the data highlights an uneven pattern of agricultural mechanization across Southeast Asia, with the Philippines leading by a substantial margin while other nations show only moderate or minimal growth in machinery adoption [48,49].

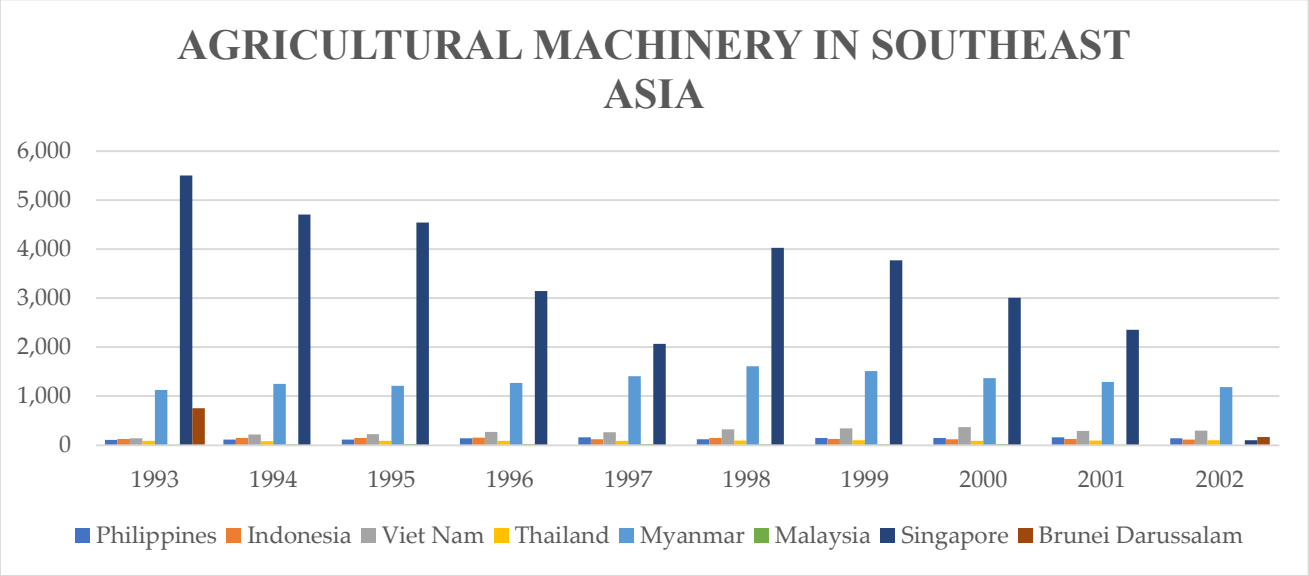

Figure 9. Agricultural Machinery Tractors Per 100 sq. km Of Arable Land in Southeast Asia.

Figure 10 illustrates fertilizer consumption trends in Southeast Asia from 1993 to 2002, highlighting varying levels of agricultural input usage among the countries. Indonesia consistently records the highest fertilizer consumption, surpassing 60 million units at its peak, with a generally increasing trend despite minor fluctuations. Vietnam and Thailand follow, demonstrating steady growth in fertilizer use, suggesting increased agricultural intensification. The Philippines and Myanmar maintain moderate levels of consumption, with gradual increases over the years. Meanwhile, Malaysia, Singapore, and Brunei Darussalam exhibit minimal fertilizer usage, likely reflecting their smaller agricultural sectors or alternative farming practices. The overall trend indicates a gradual rise in fertilizer application across most Southeast Asian countries, reinforcing the growing demand for agricultural productivity enhancements in the region. The increasing fertilizer consumption across most Southeast Asian countries suggests a shift toward more intensive agricultural practices to meet rising food demand. This trend may enhance crop yields but also raises concerns about environmental sustainability, such as soil degradation and water pollution. Countries with lower fertilizer use, like Malaysia and Brunei Darussalam, may rely on alternative agricultural methods or have less dependency on large-scale farming. Policymakers should balance agricultural productivity with sustainable practices to mitigate potential ecological impacts [50,51].

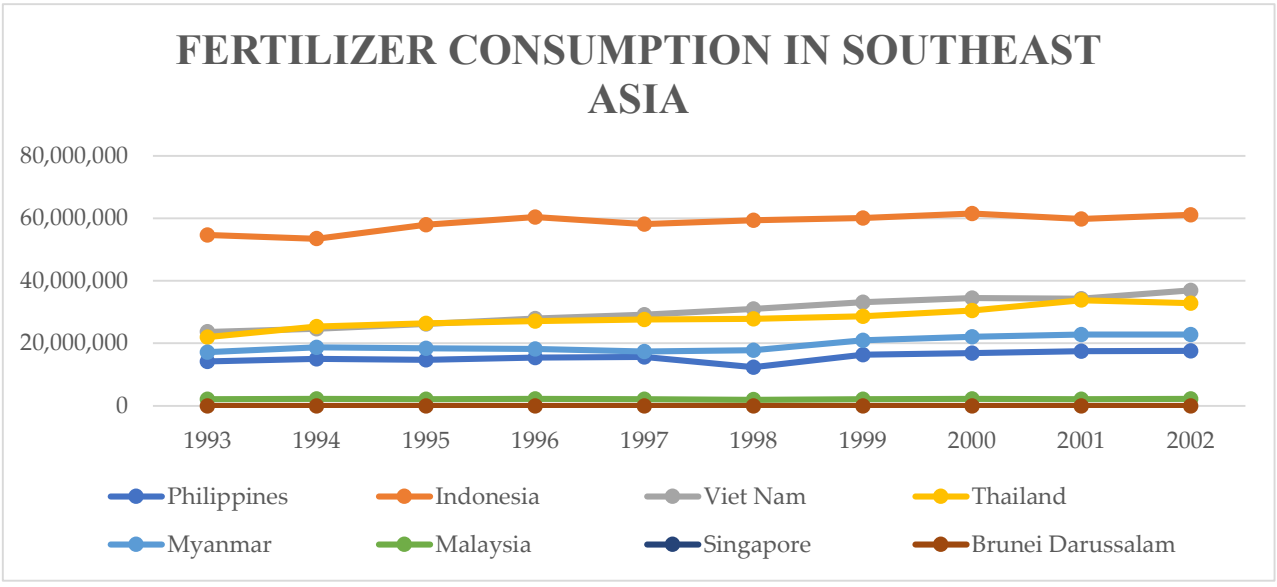

Figure 10. Fertilizer Consumption Kilograms Per Hectare of Arable Land in Southeast Asia.

Figure 11 shows the agricultural productivity in Southeast Asia highlighting Indonesia's dominance in the sector, consistently outperforming other countries. Thailand and Viet Nam also show significant agricultural output, indicating strong farming economies with continuous improvements in agricultural practices, infrastructure, and resource utilization. The steady

growth across most nations suggests advancements in farming techniques and policy support. However, countries such as Malaysia and Brunei Darussalam, which show lower agricultural productivity, may be more focused on industrial and service sectors rather than agriculture. This economic diversification can lead to a reduced reliance on farming but also raises concerns about food security and import dependency. Indonesia's high productivity suggests effective agricultural policies, technological advancements, and extensive arable land, but challenges such as climate change and land degradation must be addressed to sustain growth. Meanwhile, Thailand and Viet Nam's increasing productivity may reflect significant investments in export-oriented agriculture, which can boost economic growth but may also affect local food security. The lower agricultural output in Malaysia and Brunei Darussalam underscores their economic transition away from farming, necessitating strong food import policies and sustainable agricultural strategies. Rising productivity across the region also raises sustainability concerns, including deforestation, excessive fertilizer use, and water resource depletion. Moving forward, governments should balance agricultural expansion with sustainable practices, promote technological innovation, and support smallholder farmers to ensure inclusive and resilient growth in the sector [2,44,51,52].

Table 2 shows the results of random effects panel regression providing insights into the relationship between male and female employment in agriculture, agricultural machinery, and fertilizer consumption on agricultural productivity. The coefficient for male employment in agriculture is positive and statistically significant (coef. = 987,220.70, $p < 0.01$), indicating that an increase in male employment is associated with higher agricultural productivity. This suggests that male agricultural labor plays a crucial role in enhancing productivity, possibly due to their involvement in labor-intensive farming activities or mechanized agricultural operations. Conversely, female employment in agriculture has a negative and significant effect on agricultural productivity (coef. = −400,296.30, $p < 0.01$). This finding may reflect structural challenges, such as lower access to resources, mechanization, or land ownership for female agricultural workers, which could limit their overall contribution to productivity. It may also suggest that female labor is more concentrated in subsistence farming rather than large-scale commercial agriculture. Agricultural machinery positively impacts productivity (coef. = 107.81, $p < 0.01$), highlighting the importance of mechanization in boosting efficiency and output. This underscores the need for continued investment in modern farming equipment to enhance agricultural performance. However, fertilizer consumption has a negative and significant effect on agricultural productivity (coef. = −39,794.92, $p < 0.01$), suggesting that excessive or inefficient fertilizer use might be detrimental. This could indicate issues such as soil degradation, diminishing marginal returns, or improper fertilizer application techniques. The constant term (_cons) is statistically insignificant, indicating that other unobserved factors may influence agricultural productivity. Overall, the results emphasize the crucial role of mechanization and male labor while highlighting the need for policies that enhance women's agricultural contributions and optimize fertilizer usage for sustainable productivity growth [4–6,53,54].

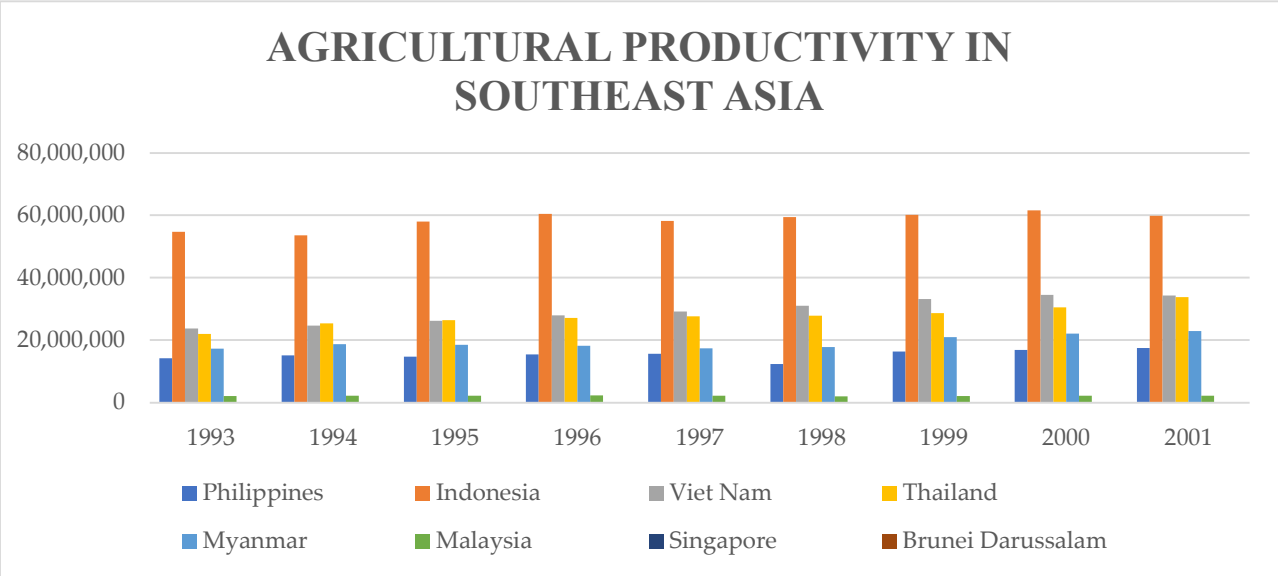

Figure 11. Agricultural Productivity, Metric Tons in Southeast Asia.

Table 2. Panel Regression result on the relationship between male and female employment, agricultural machinery, fertilizers on the agricultural machinery.

AGRICULTURAL PRODUCTIVITY	Coef.	Std. Err. *	*z*	*p* > *z*	[95% Conf. Interval]	
MALEEMPLOYMENT IN AGRICULTURE	987,220.70	161,073.40	6.13	0.00	671,522.60	1,302,919.00
FEMALEEMPLOYMENT IN AGRICULTURE	−400,296.30	121,889.00	−3.28	0.00	−639,194.40	−161,398.10
AGRICULTURALMACHINERY	107.81	4.06	26.54	0.00	99.85	115.77
FERTILIZER CONSUMPTION	−39,794.92	13,576.50	−2.93	0.00	−66,404.37	−13,185.46
cons	2,284,490.00	8,100,517.00	0.28	0.78	−13,600,000.00	18,200,000.00

* Robust standard errors were employed to ensure consistency and reliability of the estimated coefficients by addressing potential heteroskedasticity and within-panel correlation.

4.3. Panel Regression Analysis

Table 3 reveals the results of fixed-effects panel regression providing further insights into the causation between agricultural productivity and its key determinants: male and female employment in agriculture, agricultural machinery, and fertilizer consumption. The coefficient for male employment in agriculture remains positive and highly significant (coef. = 975,875.2, $p < 0.01$), reaffirming that an increase in male employment contributes positively to agricultural productivity. This suggests that male labor plays a critical role in driving productivity, possibly due to their involvement in mechanized farming and physically demanding agricultural activities. In contrast, female employment in agriculture continues to have a negative and significant impact on productivity (coef. = −410,290.6, $p < 0.01$). This result may reflect systemic barriers such as limited access to technology, land, and financial resources for female agricultural workers, potentially constraining their ability to enhance productivity. It also aligns with broader trends where female labor is more concentrated in subsistence farming rather than high-yield commercial agriculture. The impact of agricultural machinery remains strongly positive (coef. = 108.32, $p < 0.01$), emphasizing the critical role of mechanization in increasing efficiency and output. This finding underscores the necessity of continued investment in modern farming technologies to improve productivity. On the other hand, fertilizer consumption again shows a negative and significant relationship with agricultural productivity (coef. = −42,315.8, $p < 0.01$). This suggests that excessive or inefficient fertilizer use may lead to diminishing returns, soil degradation, or improper application techniques that reduce rather than enhance productivity. Optimizing fertilizer use through improved management practices and sustainable agricultural techniques could be essential to reversing this trend. The constant term (_cons) is statistically insignificant, suggesting that unobserved factors beyond those included in the model may also influence productivity. Overall, these results highlight the critical role of mechanization and male labor while pointing to potential inefficiencies in female labor utilization and fertilizer application. These insights emphasize the need for gender-responsive agricultural policies and sustainable input management strategies to improve productivity in the sector. [8–15,53,54].

Table 3. Panel regression result on the causation of male and female employment, agricultural machinery, fertilizers on the agricultural productivity using fixed effects.

AGRICULTURAL PRODUCTIVITY	Coef.	Std. Err. *	*t*	*p* > *t*	[95% Conf. Interval]	
MALEEMPLOYMENT IN AGRICULTURE	975,875.2	168,507.3	5.79	0.0000	640,837.6	1,310,913
FEMALEEMPLOYMENT IN AGRICULTURE	−410,290.6	127,383.9	−3.22	0.0020	−663,563.9	−157,017.3
AGRICULTURALMACHINERY	108.3234	4.263551	25.41	0.0000	99.84628	116.8004
FERTILIZER CONSUMPTION	−42,315.8	14,397.67	−2.94	0.0040	−70,942.22	−13,689.38
_cons	3,678,878	8,551,007	0.43	0.6680	-1.33×10^7	2.07×10^7

* Robust standard errors were employed to ensure consistency and reliability of the estimated coefficients by addressing potential heteroskedasticity and within-panel correlation.

Table 4 shows the Hausman test that evaluates whether a fixed-effects (FE) or random-effects (RE) model is more appropriate for analyzing the relationship between agricultural productivity and key factors such as male and female employment in agriculture, agricultural machinery, and fertilizer consumption. The results show that the coefficients for male employment in agriculture are relatively similar between the FE and RE models, with a minor difference of −11,345.48 and a standard error of 49,498, suggesting that both models yield consistent estimates for this variable. However, a significant discrepancy is observed in the case of female employment in agriculture, where the FE model estimates a coefficient of −810,586.9, compared to only −9994.34 in the RE model. This large difference indicates that the RE model likely underestimates the negative impact of female employment on agricultural productivity, making the FE model the more reliable choice. Similarly, for fertilizer consumption, the FE estimate (−82,110.72) is notably larger in absolute value than the RE estimate (−2520.88), suggesting that unobserved factors significantly influence the

relationship between fertilizer use and productivity. On the other hand, agricultural machinery shows nearly identical coefficients in both models (108.32 *vs*. 107.81), indicating robustness in its positive contribution to productivity regardless of the chosen model. Given these findings, the significant differences between FE and RE estimates, particularly for female employment in agriculture and fertilizer consumption, suggest that unobserved heterogeneity affects these variables. Therefore, the fixed-effects model is the preferred approach for this analysis, as it accounts for such unobserved factors and provides more reliable causal estimates. These results highlight the importance of gender-sensitive agricultural policies and efficient fertilizer management while confirming the role of mechanization in enhancing productivity [4–6,31–33,53,54].

Table 4. Hausman tests on the causation of male and female employment, agricultural machinery, fertilizers on the agricultural productivity.

Hausman Test Results	Coefficients			
	(b)	(B)	(b−B)	Sqrt(diag(V_b V_B))
	fe	re	Difference	S.E.
MALEEMPLOYMENT IN AGRICULTURE	975,875.2	987,220.7	−11,345.48	49,498
FEMALEEMPLOYMENT IN AGRICULTURE	−810,586.9		−9994.337	37,010
AGRICULTURALMACHINERY	108.3234	107.8094	0.5139573	1.2941
FERTILIZER CONSUMPTION	−82,110.72		−2520.88	4792.9

5. Conclusions

Male employment is positively correlated with agricultural productivity, whereas female employment is negatively correlated. This could be because structural constraints disadvantage women in agriculture, including limited land ownership and limited access to vital resources. Women tend to pursue subsistence farming instead of large-scale, mechanized farming, which might be the reason for the lower productivity of female labor. In addition, cultural practices influence labor segmentation in ways that can restrict women's participation and perpetuate prevailing inequalities. Gendered patterns of employment in developing economies also imply that male labor, which is more mechanized and capital-intensive, has a greater impact on productivity. These results emphasize the importance of gender-sensitive agricultural policies that enhance women's access to mechanization, land, and credit, and thereby enhance their capacity to contribute to agricultural productivity. Our work validates the positive and significant contribution of farm machinery to productivity, affirming the position of mechanization in promoting efficiency and production. Mechanization minimizes dependence on labor-based practices, enabling increased productivity and resource utilization. This is consistent with studies highlighting how technology uptake improves agricultural performance, especially in developing economies where conventional farming practices are prevalent. Investment in new farming technologies is critical to closing productivity gaps and promoting economic growth. With these observations, policies that enhance access to mechanization—particularly for smallholder farmers—are critical to maintaining long-term agricultural expansion and minimizing inefficiencies in the industry. Our paper shows that overuse of fertilizer adversely affects farm productivity, probably through misuse, soil deterioration, or returns to scale. This concurs with research citing the danger of over-reliance on chemicals without corresponding management measures, tending towards environmental and economic risks. Ineffective use of fertilizer not only diminishes productivity but also enhances soil erosion and contamination. Highlighting precision farming practices and sustainable soil management is critical to maximizing fertilizer efficiency while reducing negative impacts. These findings indicate that fertilizer policy must transition towards efficiency-based approaches, encouraging prudent application and incorporating sustainable farming practices to secure long-term productivity benefits. We prefer the fixed-effects model since it is more effective in controlling for unobserved heterogeneity, especially in female labor and fertilizer use. This resonates with literature that highlights gender-specific employment behavior and input efficiency as being highly context-specific, requiring models to capture unobserved factors. Furthermore, the choice of the right econometric model is also important in accurately analyzing agricultural productivity and guiding policy. From our results, some of the key implications are: First, structural gender-sensitive agricultural policy responses are necessary to overcome structural constraints on women's labor contribution. Second, increased investment in mechanization is necessary to support productivity growth. Third, ensuring sustainable fertilizer management practices is necessary to avoid long-term soil degradation and inefficiencies. Last but not least, application of strong econometric methods, including fixed effects, is necessary to confirm correct policy prescriptions that adequately capture the richness of agricultural productivity.

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Author Contributions

A.C.P.: Conceptualization, Formal analysis, Investigation, Resources, Data Curation, Writing—Original Draft, Writing—Review and Editing, Visualization; B.L.B.: Conceptualization, Formal analysis, Investigation, Resources, Data Curation, Writing—Original Draft, Writing—Review and Editing, Visualization; E.A.O.: Conceptualization, Methodology, Software, Visualization, Project administration.

Ethics Statement

The study received approval from the Partido State University College of Business and Management and the Partido Institute of Economics under the PARSU-CBM-PIE-ECON7-2024-3 research project. Data analysis and procedures were conducted voluntarily and independently, without any laboratory experimentation. The human data utilized in this study are strictly socioeconomic in nature, ensuring that no laboratory experiments were involved, thereby negating the need for ethical clearances. Additionally, the research does not include animal testing, direct human participation, or data collection from social media platforms.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data utilized in this work is publicly available via World Bank Open Data https://data.worldbank.org/ (accessed on 20 October 2024).

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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