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CASE STUDY

Assessment of Mechanization Indices: Insights from Rice-Growing Region of the Southern Asia–Pacific Region

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Abstract Agricultural mechanization and farm power availability are pivotal for sustainable production, especially in developing countries where small land holder farmers lack access to necessary machinery. This study aims to evaluate the degree of agricultural mechanization across small, medium, and large-scale farms in the South Asia–Pacific coastal regions, characterized by tropical monsoon climates, where rice cultivation is predominant. The investigation focuses on the period leading up to 2021–2022, employing Pareto analysis, descriptive statistics, and agglomerative hierarchical clustering techniques. Data collection encompassed diverse sources of farm power, cultivated areas dedicated to major crops, and the principal inputs utilized in cultivation, quantified in cost per unit area. The analysis indicated that, despite mechanical and electrical sources contributing to 79.55% of farm power, the overall average mechanization index based on the cost of machinery usage stood at only 11.54%. The density of tractors and power tillers, significant contributors to the overall available farm power, were identified at 44 and 32 units per 1000 hectares, respectively. Additionally, the crop-wise mechanization index was utilized to quantify the extent of mechanization for different major crops, reflecting the level of technology adoption. The mechanization index varied from the highest value of 22.70% in rice to the lowest value of 5.02% in groundnut. The findings shed light on the challenges and opportunities for enhancing agricultural productivity through targeted mechanization interventions. If enacted, these findings could yield substantial social and economic impacts on the livelihoods of farmers inhabiting coastal plains reliant on rice cropping systems, while simultaneously enhancing productivity.

Keywords Agricultural mechanization · Mechanisation index · Paddy · Small-scale farms · Agglomerative hierarchical cluster

Introduction

An important factor in the Asia–Pacific region's economic growth, which is fuelled by rice farming, is the agriculture sector. Macroeconomic statistics show that the agricultural sector plays a substantial role in the GDP of South Asia–Pacific countries. In Afghanistan, this sector constitutes 25.8%, in Sri Lanka 7.4%, Bangladesh 12.7%, Bhutan 15.8%, India 16%, Pakistan 22%, and Nepal 24.3%. India ranks first in absolute value-added at US$ 459,461 million, with Pakistan following at US$ 61,324 million, Bangladesh at US$ 38,367 million, and Nepal at US$ 7,432 million. Furthermore, the agricultural sector of the region also makes a significant contribution through exports, generating foreign exchange earnings (Source: World Bank Development Indicators). Research highlighted positive outcomes of agricultural mechanization and automation like, enhanced worker efficiency, increased productivity, lowered production costs, precision and commercialization while reducing physical strain. Modern mechanization, utilizing mobile hydraulics and electronic control systems, guided by GPS sensors, enhances efficiency, minimizes crop damage, and improves resource management, reducing ecological impact [1–11]. Automation also reduces greenhouse gas emissions,

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mitigating climate change and aiding adaptation to extreme weather events. The judicious use of inputs decreases the emission of greenhouse gases in vegetable production [12]. Additionally, in the scenario of Indian agriculture, the engagement of women in the workforce is highly valuable. Thus, the development of labour-saving technologies that are gender-friendly and enhance the efficiency of women in farm operations is equally crucial [13, 14]. Therefore, to enhance food security, income of agricultural households and to alleviate poverty, the adoption of farm mechanisation is inevitable, thereby supporting the Sustainable Development Goals (SDGs) [15].

Among the countries discussed, India stands out as a leader in farm mechanization, with considerable attention given to machinery utilization and production [16–19]. Despite significant advancements over the past decade, India's level of farm mechanization remains at 45%, notably lower than that of the China (57%), Brazil (75%), and United States (95%) [20, 21]. This percentage reflects the mechanization level in Indian agriculture; however, small and marginal farmers still encounter challenges due to limited access to farm machinery [22]. Moreover, the variations in mechanization patterns across India are influenced by factors such as land size and topography [8]. Reports suggest that certain Indian states face obstacles in implementing farm mechanization due to the small size of agricultural holdings, with the average land area per holding being less than one hectare, particularly impacting small-scale farmers with limited resources [23–25]. The reduction in average landholding size across all social classes, attributed to urbanization and land conversion for non-agricultural purposes, exacerbates this issue. Mehta [26] reported mechanization levels for various crops in India, with wheat, rice, maize, pulses, oilseeds, sorghum, cotton, and sugarcane standing at 63, 45, 40, 34, 34, 26, 26, and 24%, respectively [26]. Enhancing the current level of average farm power availability is crucial for facilitating diverse agricultural activities [27]. Singh and De [28] and Nowacki [29] conducted comprehensive evaluations to quantify mechanization indicators within the framework of macro-level planning [28, 29]. Similarly, the Sub-Mission on Agricultural Mechanisation (SMAM) calculated farm power by determining the average farm power availability for districts and states of India [30]. Tractors are predominantly utilized in northern regions like Punjab, Uttar Pradesh, and Haryana, indicating a higher level of mechanization. Conversely, in southern and eastern parts of India where small-scale farming is prevalent, power tillers are more common [20], particularly in regions known for its significant rice cultivation.

Based on the preceding information, Odisha, a prominent rice-producing state in eastern coastal plains of India, serves as the study point (Fig. 1). In Odisha, out of the total cultivated land covering 61.80 lakh hectares, 47% consists of high land, 28% medium land, and 25% low land. Approximately 65% of this cultivated area receives irrigation during the Kharif season [31]. Regarding operational holdings, 45% are held by marginal farmers (< 1 ha), 30% by small farmers (1–2 ha), 17% by semi-medium farmers (2–4 ha), 6% by medium farmers (4–10 ha), and 2% by large farmers (> 10 ha) [25]. Rice is the primary crop, yet also benefits from cultivating non-paddy crops like pulses and groundnuts, contributing to financial stability and food security. Strategic capacity building and the dissemination of technical expertise can enhance profitability and cost-effectiveness in production [32]. The state has experienced significant growth in farm mechanization, with agricultural machinery sales surpassing Rs 805 crores in the fiscal year 2022–2023, aiming for Rs 1000 crores by 2023–2024 [33]. The above facts highlight the Odisha's selection as a study area stem from its substantial involvement in rice cultivation, small holding farms, and coastal plains.

Materials and Methods

The thorough evaluation of mechanization encompassed an extensive analysis that goes beyond isolated components. It scrutinized the overall availability of farm power, including specialized mechanical farm power components, exploring the intricate dynamics of agricultural machinery and power resources. This evaluative process considered the interaction of various factors, including human labour contributions, the impact of animal power, and the utilization of mechanical powers, which included, tractor, power tiller, combine harvester, and diesel engines. The quantification of these parameters, specifically to determine the total farm power availability, was outlined as follows:

$$\mathrm{F}_{Py} = \frac{\left[0.05N_{HLy} + 0.38N_{Ay} + 3.7N_{EMy} + 5.6\left(N_{PTy} + N_{DEy}\right) + 26.1N_{Ty} + 45N_{CHy}\right]}{A_y} \tag{1}$$

$$\mathrm{F}_{MPy} = \frac{\left[5.6\left(N_{PTy} + N_{DEy}\right) + 26.1N_{Ty} + 45N_{CHy}\right]}{A_y} \tag{2}$$

where: F_{Py} is total farm power availability in kW/ha and F_{MPy} is mechanical farm power in y^{th} year; N_{HLy} is number of human labours in agriculture in y^{th} year; N_{Ay} is number of draught animals in y^{th} year; N_{Ty} is number of tractors in y^{th} year; N_{PTy} is number of power tiller in y^{th} year; N_{CHy} is number of combine harvester in y^{th} year; N_{DEy} is number of diesel engines in y^{th} year; N_{EMy} is number of electric motors in y^{th} year; and A_y is net sown area in ha in y^{th} year.

When considering economic factors, the development of a Mechanization Index (MI) incorporating both animate and mechanical energy inputs emerged as a valuable tool, enhancing the accuracy and relevance of mechanization

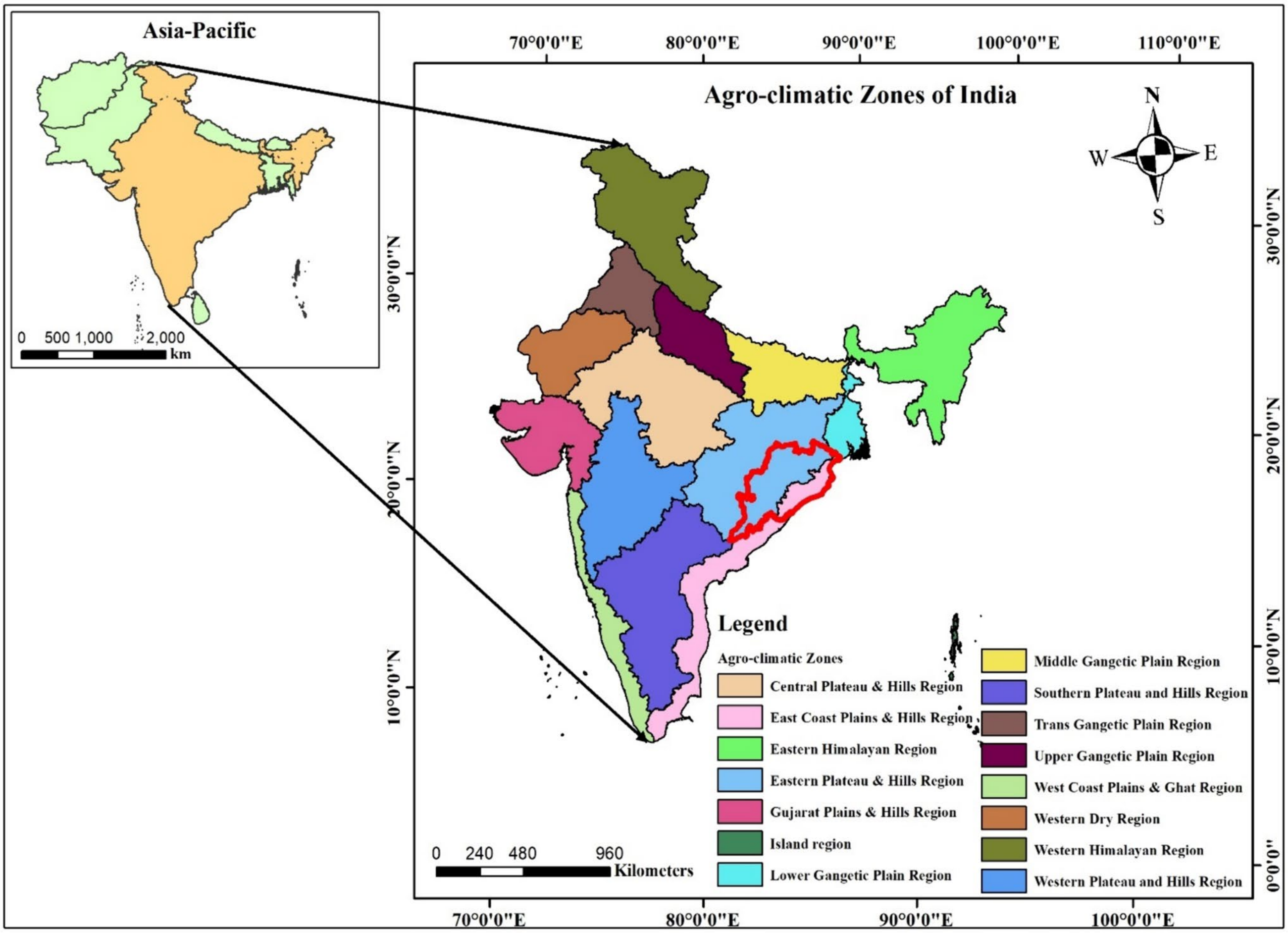

Fig. 1 Map depicting the study area. *Note* The purpose of this map is to highlight the location of the study area, Odisha, encompassing two prominent rice-producing agroclimatic zones in India—the Eastern Plateau and the East Coast Plains

evaluations. By incorporating cost considerations, a MI based on the matrix of animate and mechanical energy input usage was formulated as:

$$\mathrm{MI}_x = \frac{C_{Mx}}{C_{HLx} + C_{Ax} + C_{Mx}} \quad (3)$$

where: MI_x represents the mechanisation index of the x^{th} crop; C_{Mx} represents the machinery usage cost for the x^{th} crop; C_{HLx} represents the human labour usage cost for the x^{th} crop; and C_{Ax} represents the draught animal usage cost for the x^{th} crop.

The empirical basis of this study relied on data sourced from the 'Cost of Cultivation of Principal Crops in India' and the 'Five Decades of Odisha Agriculture Statistics' [34, 35]. Data collection followed a rigorous three-stage stratified random sample approach, ensuring comprehensive coverage of crop and state-specific factors. These sources provided an information on production and economic aspects, which were subsequently utilized for analysis. Direct expenses, including depreciation, material input costs (such as seed, irrigation, fertilizer, manure, and pesticides expenses), hired labour (human, animal, and machinery), maintenance, and indirect costs such as land rent or revenue from leased land, were considered. The mean cultivation cost for key crops was computed in Indian Rupees per hectare (INR/ha), incorporating a thorough assessment of cultivation costs associated with each crop.

Result and Discussion

Trend in Farm Power Utilization and its Effect on Productivity of Food Grain

In the study area, the minimal utilization of animate power was observed, but while it may be considered an alternative, it did not ensure timeliness. Consequently, the adoption of mechanical and electrical power in agriculture has outpaced other agricultural power sources such as draught animals and agricultural workers. Analyses conducted by Singh and De [28] and Alam and Singh [36] confirmed the transition of farmers from conventional to scientific agriculture, coupled with an increase in cropping intensity, resulted in a greater utilization of electric motors, diesel engines, tractors, and associated equipment [28, 36]. Farm power availability was assessed by considering multiple factors, as outlined in Eqs. 1 and 2. The resulting values were compiled and presented in Table 1. Additionally, the table offered an overview of the growth patterns observed in various farm power sources from 1996–1997 to 2021–2022. Notably, there was a significant increase in agricultural power availability, rising from 0.52 kW/ha in 1996–1997 to 2.00 kW/ha in 2021–2022. The proportion of mechanical power within the overall farm power experienced a substantial surge, climbing from 8 to 79% over the specified timeframe. Similarly, there was an increase in the proportion of tractors and power tillers, rising from 8 to 60% between 1996–1997 and 2021–2022. Conversely, the proportion of human labour and draught animal power declined from 91% in fiscal year 1996–1997 to 20% in fiscal year 2021–2022, collectively.

Descriptive statistic for total available mechanical power, which was considered as a variable, is provided in Table 2. According to the information presented, the average total mechanical power per hectare was roughly 1.76 kW/ha. However, the comparatively large standard deviation of 1.46 kW/ha indicated a significant degree of variability around this mean, indicating that power levels varied significantly from one district to the next. A leptokurtosis of 11.89 in the context of total available mechanical power per hectare showed that there are few districts with very high-power values, contributing to a fatter tail and a sharper peak. These extreme values represented specific districts where the mechanical farm power availability is exceptionally high, like in districts of Cuttack, Khordha, and Puri, compared to the majority of districts, within the study area. Again, the distribution is positively skewed, with a skewness of 3.13, showing that the data was skewed towards higher mechanical power availability, indicating the presence of a tail of significantly higher readings. The dataset contained a wide range of values, ranging from roughly 0.75 kW/ha in Nuapada district to approximately 8.05 kW/ha in Cuttack district. Overall, the data highlighted the heterogeneous nature of overall available mechanical power levels in this context, with some districts having more mechanical farm power than others. Comparable findings were noted in other studies, attributable to factors such as small land holdings and diverse topography [8, 23–25].

Table 2 Descriptive statistics of total available mechanical power sources of districts of study area

Total power (kW/ha)			
Mean	1.76	Kurtosis	11.89
Standard error	0.26	Skewness	3.13
Median	1.24	Range	7.29
Mode	–	Minimum	0.74
Standard deviation	1.45	Maximum	8.04

Pareto analysis of tractors, power tiller, combine harvester and diesel engines as power source across all districts of the study region are given in Figs. 2, 3, 4 and 5. The graphs indicated a non-uniform mechanisation situation, which could be attributed to the presence of agro-ecological diversities, varying population densities, and socio-economic differences within the region. The distribution of tractors as power source across thirty districts is illustrated Fig. 2. The average density of tractor per thousand hectares of net sown area when examined at the district level is 44.00. Moving from left to right along the districts, there was a noticeable decline in the contribution of each district to the total tractor power. The top contributing districts in terms of tractor power are Cuttack, Khordha, Bargarh, Jagatsingpur, Puri and Balasore with a cumulative percentage of around 50% of the total

Table 1 Share of different power sources in total farm power

Power source	Farm power (kW/ha (% share to the total farm power)					
	1996–1997	2001–2002	2006–2007	2011–2012	2016–2017	2021–2022
Human power	0.021(4.01)[a]	0.079(12.82)[b]	0.082(11.43)[b]	0.102(9.84)[c]	0.096(6.91)[c]	0.100(5.00)[d]
Animal power	0.456(87.18)[a]	0.459(74.51)[a]	0.474(66.10)[a]	0.316(30.50)[b]	0.296(21.31)[b]	0.309(15.45)[b]
Tractor	0.042(7.70)[a]	0.070(11.36)[a]	0.144(20.08)[b]	0.487(47.00)[c]	0.669(48.16)[d]	1.048(52.4)[e]
Power tiller	0.001(0.19)[a]	0.005(0.81)[a]	0.013(1.81)[b]	0.060(5.79)[c]	0.120(8.63)[d]	0.155(7.75)[e]
Combine harvester	0.000(0.00)[a]	0.000(0.00)[a]	0.000(0.00)[a]	0.003(0.28)[b]	0.017(1.22)[c]	0.062(3.10)[d]
Diesel engines	0.000(0.00)[a]	0.0001(0.01)[a]	0.0004(0.05)[a]	0.068(6.56)[b]	0.188(13.53)[c]	0.307(15.35)[d]
Electric power	0.003(0.57)[a]	0.003(0.48)[a]	0.003(0.41)[a]	0.004(0.38)[b]	0.007(0.503)[c]	0.020(1.00)[d]
Total farm power	0.523[a]	0.616[b]	0.717[c]	1.036[d]	1.389[e]	2.000[f]

DBT, 2022 Schemes for farm implements; TMA, 2022; Census of India, 2011; Odisha Livestock Census—III, 2012 [37–40];Values in same row categorized with different alphabets has significant difference according the Tukey HSD test at $p = 0.05$

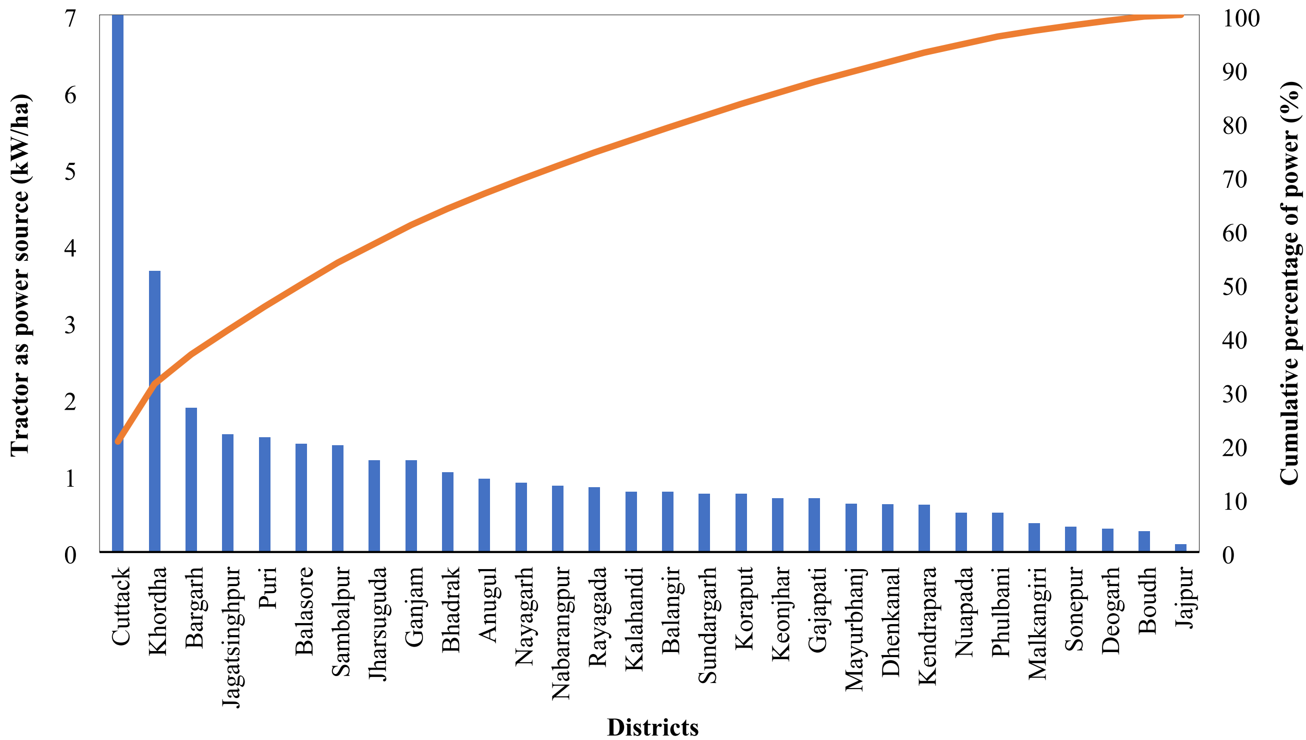

Fig. 2 Pareto graph for tractor as power source across districts of study area

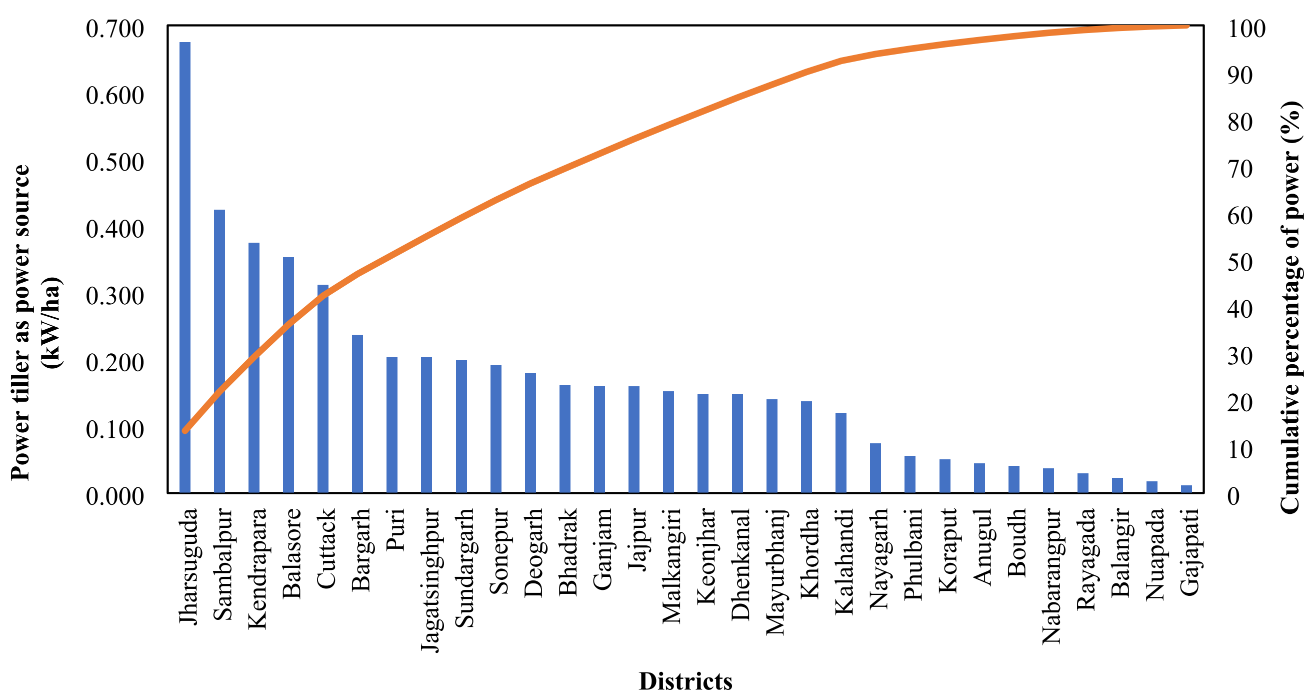

Fig. 3 Pareto graph for power tiller as power source across districts of study area

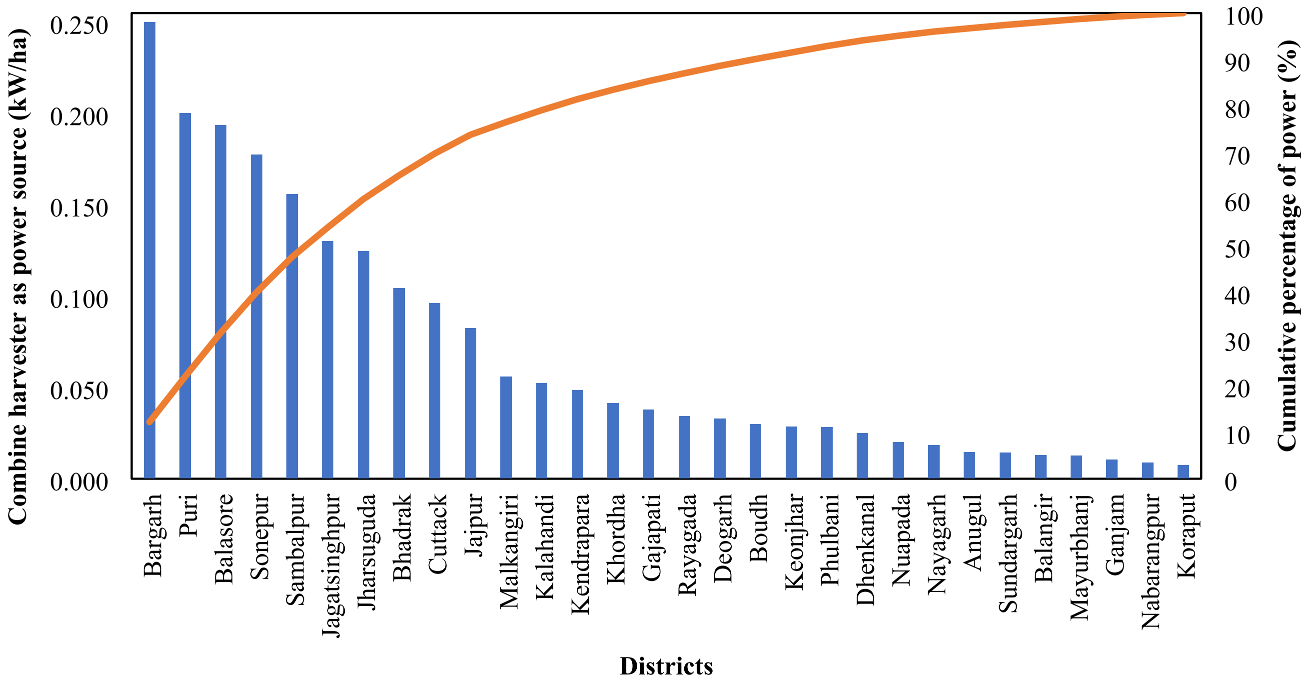

Fig. 4 Pareto graph for combine harvester as power source across districts of study area

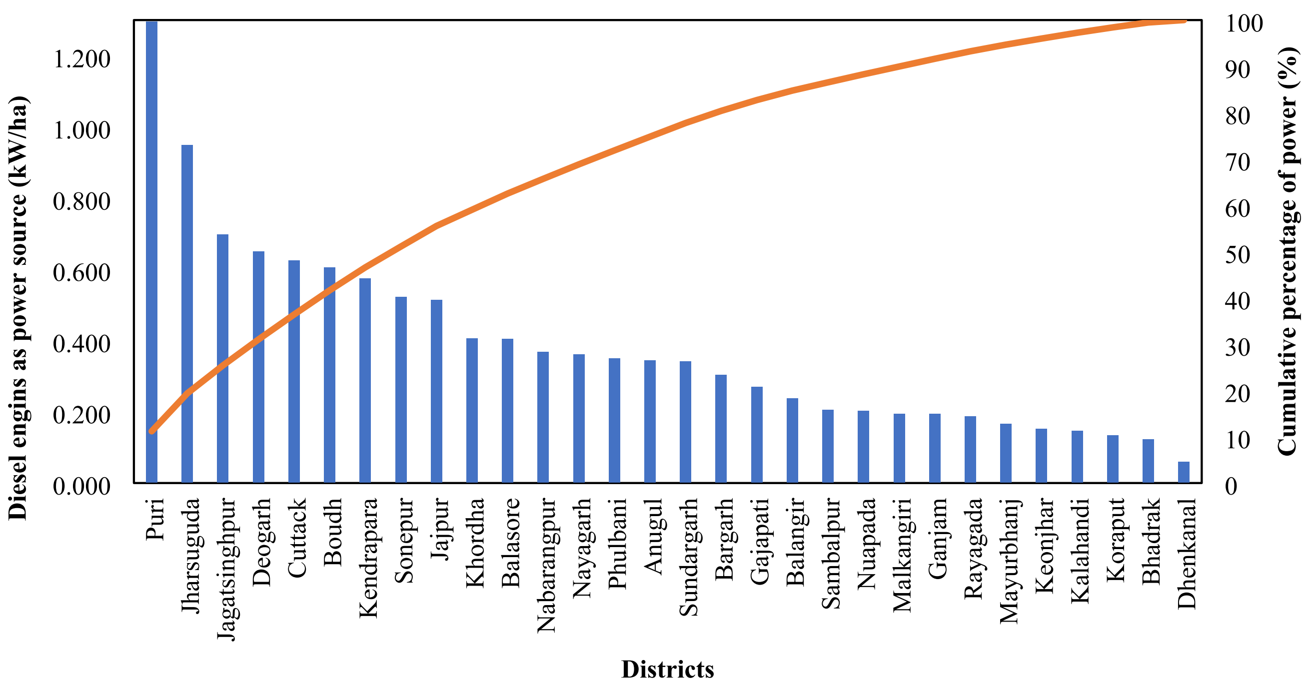

Fig. 5 Pareto graph for diesel engine as power source across districts of study area

tractor power. It was evident that approximately 80% of the tractor power is generated by 50% of the districts. Similar trends were observed in case of power tiller, combine harvester and diesel engine as power sources in the districts. It can be observed from Fig. 3 that, the districts of Jharsuguda, Sambalpur, Kendrapada, Balasore, Cuttack, Puri and Bargarh collectively accounted for 50% of the total power contributed by power tiller, with an average power tiller density per thousand hectares at the district level being 32.42. Also, it was evident from Figs. 2 and 3 that, the intensity of adoption of tractor and power tiller, which were major mechanical farm power sources, was not uniform in different districts. In case of combine harvester, the top contributing districts were Bargarh, Puri, Balasore, Sonepur, Sambalpur, and Jagatsinghpur with a cumulative percentage of 54% of the total combine harvester power (Fig. 4), and Puri, Jharsuguda, Jagatsinghpur, Deogarh, Cuttack, Boudh, Kendrapara, and Sonepur contributed half of the total diesel engine power (Fig. 5). It was observed that the irrigated command area of western and coastal districts like Cuttack, Jagatsinghpur, Puri, and Balasore had a higher concentration of all the four category of mechanical power sources than other regions. Due to the relatively smaller size of farms and restricted access to financial resources, small and marginal farmers encountered limitations in utilising machinery throughout the state.

The agglomerative hierarchical analysis of 30 districts considered their combined tractor and power tiller power and productivity. The analysis employed group average clustering algorithms and was depicted in the dendrogram (Fig. 6). In this analysis, Euclidean distance is used to measure the similarity or dissimilarity between data points or clusters. Greater distances between clusters indicate more dissimilarity. At a Euclidean distance of around 1.2, the analysis yielded two distinct clusters. Cuttack formed a cluster on its own at a distance of approximately 6.3, whereas the other districts grouped together at around a distance of 1.2. This significant dissimilarity in Euclidean distance indicates that Cuttack alone comprised a distinct cluster characterized by its high tractor and power tiller farm power of 7.15 kW/ha and high productivity of 1.68 t/ha. At a Euclidean distance of 1, the analysis yielded four distinct clusters. Like Cuttack, Jharsuguda alone constituted a separate cluster. The remaining districts formed two clusters distinguished by total tractor and power tiller farm power and productivity attributes. Jharsuguda, despite having a comparatively high power of 1.23 kW/ha, exhibited lower productivity of 0.45 t/ha compared to other districts with high power. This could be attributed by the factors like lateritic soil type and high industrialization in the district. Balasore, Bargarh, Mayurbhanj, Koraput, Khordha, Puri, Ganjam, Jagatsingpur, Keonjhar, and Sambalpur collectively formed one cluster. This grouping was based on similar tractor and power tiller farm power (ranging from 1.88 kW/ha in Bargarh to 1.20 kW/ha in Ganjam) and respective productivity (ranging from 2.45 t/ha in Balasore to 0.98 t/ha in Sambalpur). The higher productivity in these areas could be attributed to factors such as Bargarh district being in a major irrigation command areas and districts like Balasore being in coastal locations. The remaining 18 districts formed the fourth cluster. These districts were characterized by comparatively low farm power, ranging from 1.04 kW/ha in Bhadrak to 0.10 kW/ha in Jajpur.

Developing nations that depend on equipment powered by human and animal labour could attain economic productivity provided they had access to sufficient irrigation, high-quality crops, and soil nutrients [41]. Productivity and farm power relationship in the study area exhibited an exponential trend during the financial years spanning from 1971–1972

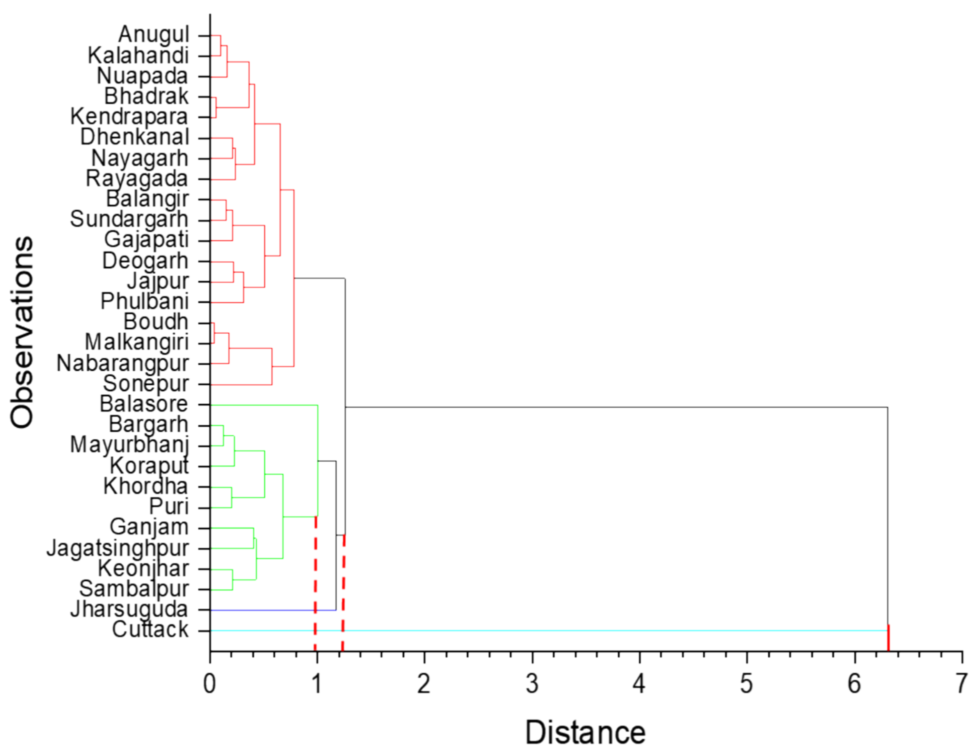

Fig. 6 Dendrogram of data through group average clustering

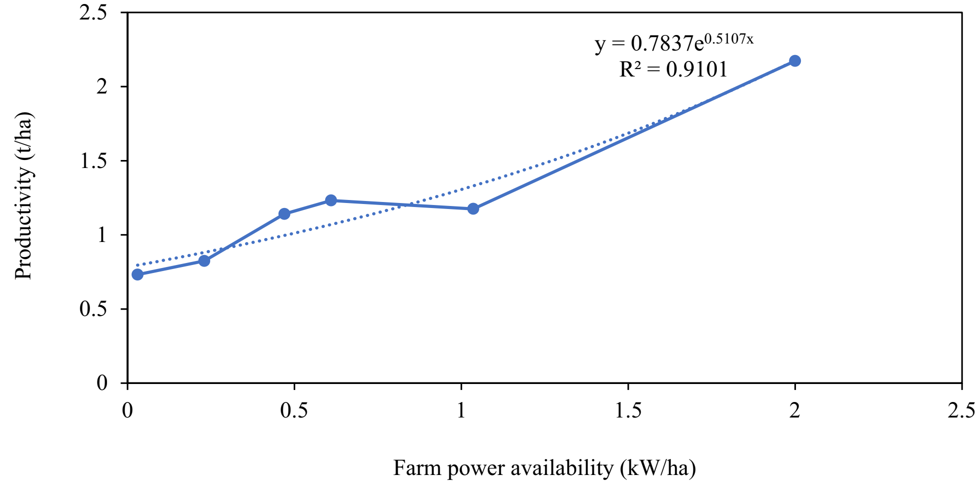

Fig. 7 Trends of farm power and agricultural productivity from 1971 to 2021

to 2021–2022, as depicted in Fig. 7. The observed phenomenon could be attributed to technological advancements in agriculture in recent decades, including mechanization, enhanced irrigation systems, genetically modified crops, and precision farming techniques. These innovations had increased farm power, efficiency, and productivity. Moreover, increased government investment in agriculture through subsidies and training on modern equipment to farmers has likely contributed to more efficient farm power utilization and productivity gains. However, Tiwari et.al. [27] found a linear trend between food grain productivity and power availability prediction during the period 1960–1961 to 2032–2033 for Indian agriculture scenario [27]. The relationship between the availability of farm power and productivity during the time span could be represented in the following equation:

$$Y = 0.7837\, e_{P}^{0.5107\,F} \tag{4}$$

where, Y is productivity in tonnes/ha and F_P represents available farm power in kW/ha.

It was a fact that productivity was affected directly by quality and quantity of agricultural input. Nevertheless, there was solid validation indicating higher farm productivity was positively correlated with farm power availability. Farmers using high-capacity self-propelled machinery in wheat growing areas of India have higher productivity as well as higher farm power availability [42].

Machinery Shares in the Total Cultivation Cost and MI

Agricultural inputs fall into two main categories: durable inputs, exemplified by farm machinery providing extended services, and consumable inputs like seeds, fertilizers, agrochemicals, oils, and lubricants with single-use services. Skilful management of these factors holds significant potential to substantially increase productivity [43, 44]. One of the primary objectives of mechanization was to reduce the costs associated with agricultural operations. However, in regions where 92% of land holdings were categorized as semi-medium, small, and marginal (≤ 4 ha), this objective was not always realized. This could be attributed to factors such as small and fragmented land holdings, which were not conducive to achieving economies of scale. Similar findings were also supported by research [45]. Additionally, in areas where farm mechanization is in its early stages, many farm machines were not utilized to their full capacity, resulting in low annual usage and high ownership costs. Nevertheless, farm mechanization is gaining importance due to labour shortages during peak times and the need for timely operations, indicating a growing adoption of mechanization practices. While farmers may not have yet found suitable farm machinery for their landholding sizes, they had begun using farm equipment, leading to a reduction in the use of animate power inputs in crop cultivation. This trend was expected to ultimately reduce cultivation costs through mechanization.

Consequently, the mean cultivation cost for key crops and the corresponding MI values, calculated as per Eq. 3, were provided in Table 3. The data showed the proportion of human labour costs in the overall cultivation expenses ranged from 39.48% for paddy to 54.61% for ragi. Additionally, the contribution of draught animal power to the total costs varied from 2.79% for maize to 16.09% for sesamum. The cost of machinery share differed from 3.28% (groundnut) to 12.62% (paddy). Paddy (12.62%), green gram (9.70%), and maize (8.94%) recorded comparatively higher machinery shares, pointing higher usage of machinery in these crops. The machinery shares in other crops like groundnut (3.28%), black gram (3.57%), sesamum (5.45%), and Cotton (6.17%) were comparatively low.

Moreover, it was evident that the average MI of crops was at 11.54%, despite the fact that mechanical and electrical power sources accounted for 79.55% of the overall farm power. Once again, it could be noted that not all crops are

Table 3 Share of mechanisation input in total operational cost in major crops of study area (2021–22)

Crop	Average cost of cultivation, INR/ha	Cost of cultivation, INR/ha (% share of the total cost)			Mechanization Index (MI), %
		Human labour	Animal	Machinery	
Paddy	75,629.40	29,857.21 (39.48)[ade]	2659.71 (3.52)[a]	9546.77 (12.62)[a]	22.70[a]
Maize	60,233.85	30,752.09 (51.05)[bcd]	1679.52 (2.79)[a]	5387.25 (8.94)[b]	14.24[b]
Ragi	31,756.54	17,342.24 (54.61)[c]	3299.22 (10.39)[b]	2706.67 (8.52)[b]	11.59[c]
Green gram	28,306.41	12,659.57 (44.72)[de]	1421.31 (5.02)[c]	2746.54 (9.70)[b]	16.32[d]
Black gram	29,320.90	14,327.75 (48.87)[bcde]	1034.17 (3.53)[a]	1045.96 (3.57)[c]	6.37[e]
Groundnut	70,356.30	38,337.63 (54.49)[bc]	5305.63 (7.54)[d]	2306.3 (3.28)[c]	5.02[e]
Sesamum	23,490.52	10,207.98 (43.46)[e]	3778.59 (16.09)[e]	1279.92 (5.45)[e]	8.38[fg]
Niger	20,283.33	10,910.16 (53.79)[bc]	2701.4 (13.32)[f]	1326.09 (6.54)[e]	8.88[g]
Cotton	80,960.54	40,856.74 (50.47)[bcde]	2332.56 (2.88)[a]	4991.58 (6.17)[e]	10.36[cg]
Average	48,366.18	22,805.708 (48.27)	2690.234 (7.17)	3481.90 (6.97)	11.54

Cost of cultivation of principal crops in India, Directorate of Economics and Statistics Ministry of Agriculture, New Delhi [34]; Values in same column categorized with different alphabets has significant difference according the Tukey HSD test at $p = 0.05$

subject to consistent mechanisation. Crop-wise values of MI varied from the highest value of 22.70% in paddy to the lowest value of 5.02% in groundnut. The largest area under cultivation was occupied by paddy, around 4.4 million ha. Due to increased usage of machinery in this crop in field preparation and harvesting, it exhibited an MI of 22.70%. However, the labour intensive and tedious process of transplantation of paddy was still performed manually. Several districts were undergoing a pilot introduction of mechanical transplanters. The crops other than paddy had hardly mechanized and therefore showed low MI. However, during recent year machines were slowly being introduced in these crops for seed bed preparations, sowing and threshing in selected areas.

MI in paddy cultivation was comparatively higher than that of other crops in rice dominated nations. Trends in operational cost and different input cost of paddy crop for the period from 2003–2004 to 2021–2022 are shown in Fig. 8. According to Singh and Chandra [46], rising input and operating costs resulted in higher crop production costs for the majority of crops [46]. The cost of human labour had increased at a pace of 27.21%, despite the fact that labour input utilisation was dropping at a rate of 4.67% owing to wage hikes throughout the years (Fig. 8). Similarly, despite a decrease rate of 18.27% in the share of draught animal energy input annually, the share of cost of draught animal energy input had increased at a rate of 7.28% due to similar reasons. The imperative for timely completion of farm tasks, alongside the availability of modern machinery, had diminished reliance on traditional draught animals. Urbanization had precipitated a migration of labour to urban centres, diminishing the pool of skilled animal caretakers. Economic considerations, encompassing the costs of maintaining draught animals, outweighed

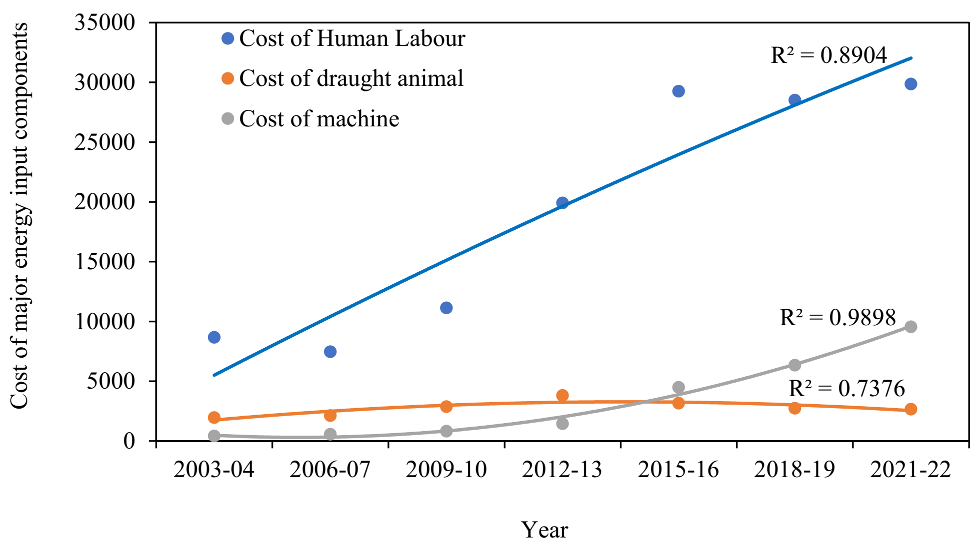

Fig. 8 Trends in the cost of major energy input in paddy cultivation in INR/ha

the benefits for certain farmers. Furthermore, in this particular study area, the loss of livestock due to a severe cyclone in October 1999 had contributed to the decline in draught animal utilization, demise of approximately 4.45 lakh livestock. [47]. Moreover, the substitution of animal power with power tillers by farmers was evident from the proportion of power tillers in total farm power (Table 1). The machinery cost component had shown a significant annual average growth rate of 76.60% between 2003–2004 and 2021–2022, despite a 35% increase in the utilization of machinery inputs during this period. This annual growth rate in the machinery usage cost indicated positive response and adaptiveness of farm machinery by farmers in paddy cultivation.

The mean cultivation cost of paddy crop in 2021–2022 was recorded as Rs. 75,630/ha. The comprehensive cost of cultivation encompassed fixed costs such as depreciation on implements and farm structures, capital interest, taxes, land revenue, cesses, the rental value of owned land, and rent paid for leased-in property (Fig. 9). The cost of cultivating rice crop was comprised of the collective proportion of expenses related to human labour, draught animal, and machinery, which accounted for 59% of the total cost. Despite the high degree of mechanisation for rice cultivation, the cost of human labour remained the primary factor contributing to the overall cost of cultivation. This was attributed by the fact that operations like sowing and weeding were still done manually.

Effect of the MI on Cultivation Cost, Yields, and Deployment of Human Labour and Draught Animal

Relation between MI and yield of paddy crop was studied by employing year-wise variation in the MI, cost of cultivation (C_{OC}) and paddy yield (Y) from the year 2003–2004 to 2021–2022 and is shown in Fig. 10. It was observed that Y and MI were positively correlated ($r = 0.63$) and it increased exponentially with increase in MI ($R^2 = 0.57$). All these mechanical interventions had contributed in boosting the yield from 1496 kg/ha in 2003–2004 to 2654 kg/ha in 2021–2022. The cultivation cost in mechanised agriculture was always more than that for conventional agriculture. Though adoption of agricultural mechanization needed higher initial investment than conventional agricultural practices, the use of appropriate mechanisation technology led to higher land and human labour productivity, resulting in higher yield and reduced cultivation cost per unit crop yield. Also, the cultivation cost had increased linearly with increase in MI ($r = 0.96$ and $R^2 = 0.91$) (Fig. 10). The initial stages of mechanization had hindered by the unavailability of suitable machinery for small-scale farm operations, leading to heightened cultivation costs for paddy production and

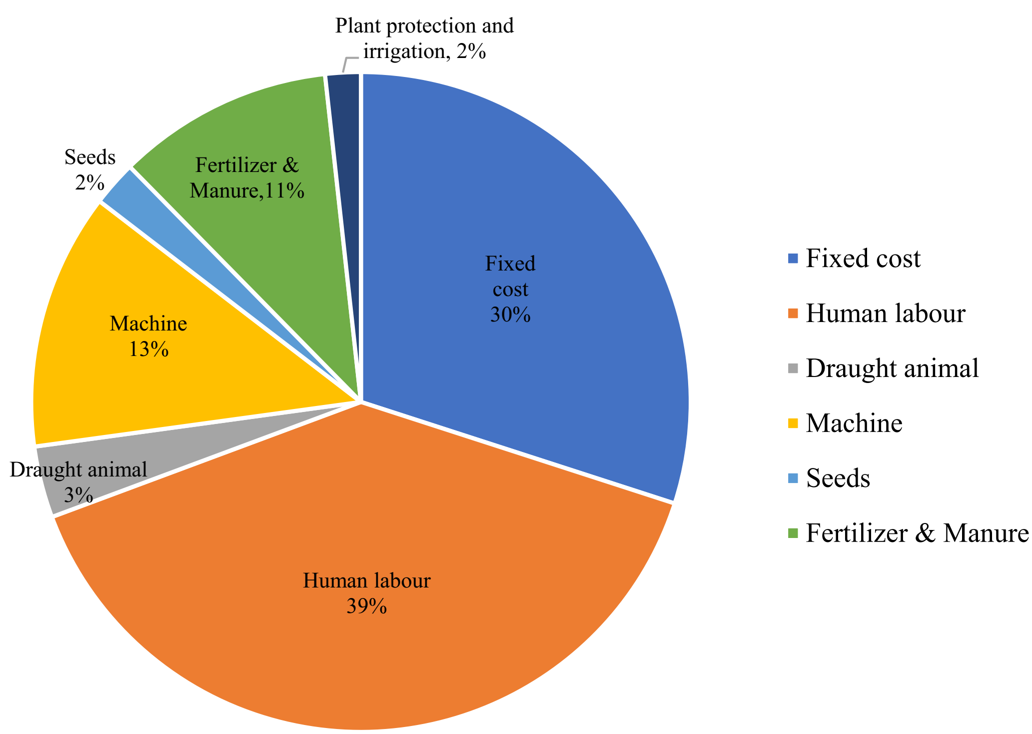

Fig. 9 Share of different inputs in the total cost of cultivation, in INR /ha of paddy crop in study area (2021–2022)

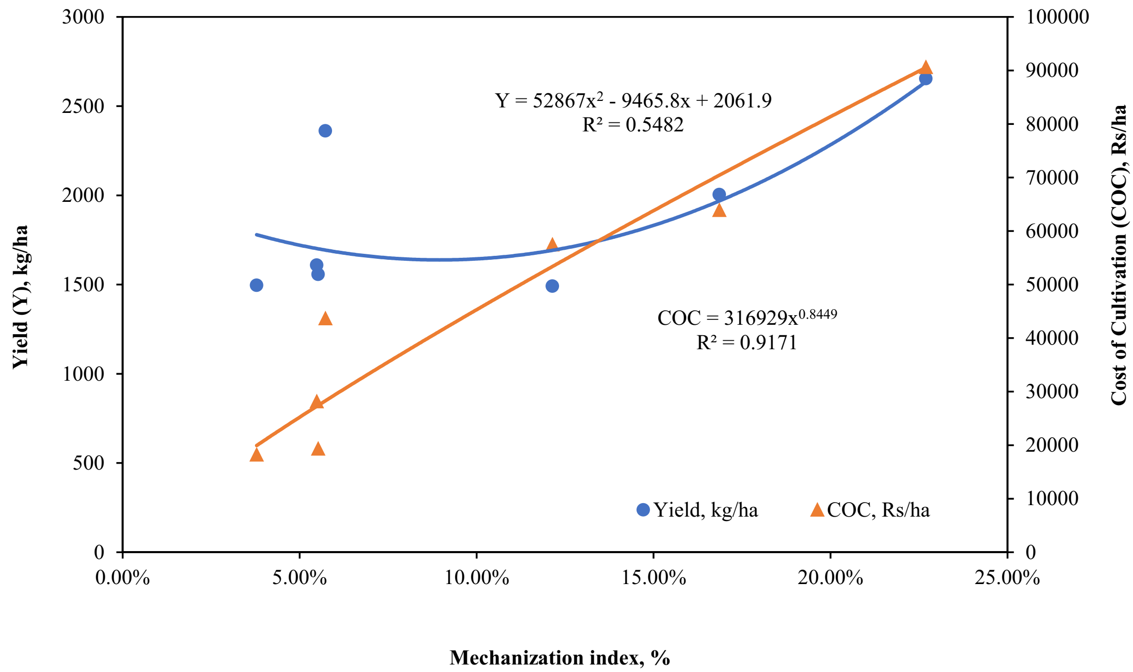

Fig. 10 Trends in yield Y in kg/ha and cost of cultivation COC in INR/ha as influenced by mechanization index MI (2021–2022)

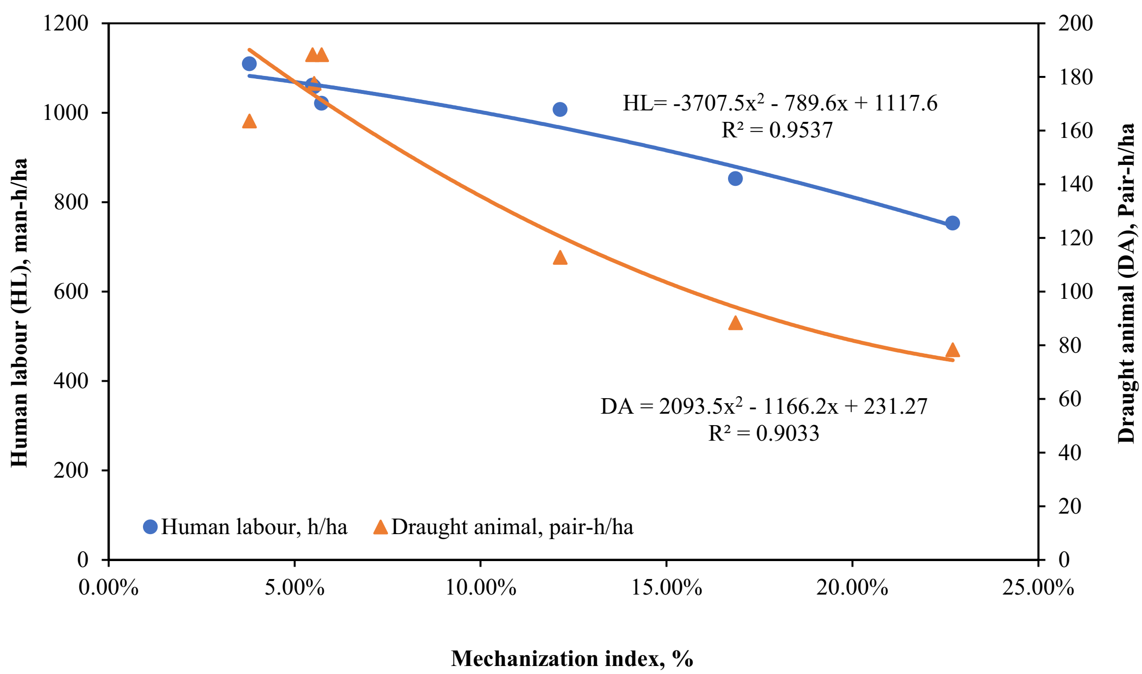

Fig. 11 Trends in deployment of human labour (HI) in man-hours/ha and draught animal (AI) in pair-hours/ha as influenced by MI in paddy cultivation

increased efficiency with mechanization. Furthermore, even though the human input in terms of man-hours per hectare had decreased (Fig. 11), the hike in wages over time did not allow the expected profit for farmers with increased MI. As a result, the cost of cultivation did not reduce at the expected pace. This trend is anticipated to abate with the attainment of a higher level of appropriate mechanization. Therefore, leveraging high-powered machinery through custom hiring for various farming tasks, along with establishing customized manufacturing hubs, was recommended. Research by Mehta in [45] and [26], and Singh in [42], supported these findings.

$$Y = 17628\, e^{0.0821MI} \tag{5}$$

MI and utilisation of human labour and draught animal in paddy cultivation were analysed for the duration from 2003–2004 to 2021–2022 (Fig. 11). The substitution of human work was commonly viewed as a detrimental consequence of farm mechanisation, particularly in developing nations. The data clearly demonstrated a strong negative correlation between manual labour and the usage of draught animals with MI as indicated by correlation coefficients of − 0.97 and − 0.96, respectively. Human labour in cultivation of paddy had experienced a slight decrease from 1094 to 793-man h/ha, decreasing at an average rate of 4.67% annually. In other words, it could be inferred that mechanisation did not have a significant impact on reducing human labour. However, as Eq. 6 was in quadratic form, there could have been a greater chance of higher human labour recession with an increase in MI in the near future. This was also corroborated by Meena and Jhamtani [48] and Gyanendra Singh [42]. The use of draught animals, in contrast, experienced a substantial decline from 171 to 78 pairs per hectare, exhibiting an annual reduction rate of 18.27%. The rising expenses associated with maintaining draught animals in comparison to mechanical power prompted farmers to increasingly rely on power tillers and tractors, particularly through custom hire arrangements, for operations like tillage, sowing, and threshing. Equations 6 and 7 were utilised to depict the impact of MI on the utilisation of human labour (HI) and draught animals (AI) in deployment scenarios.

$$H_I = 1117.596 - 789.598\, MI - 3707.52\, MI^2 \tag{6}$$

$$A_I = 222.32 - 1025.5\, MI + 1629\, MI^2 \tag{7}$$

Conclusion

Investigating farm power sources, mechanization indices, and the distribution patterns of farm power inputs within agricultural landscapes dominated by rice cultivation in developing nations offered valuable insights into the evolving dynamics of mechanization and its impact on productivity. These regions typically exhibited a tropical monsoon climate characterized by high humidity and significant rainfall during the monsoon season, providing favourable conditions for a diverse range of crops including rice, pulses, oilseeds, fruits, and vegetables. This analysis held particular significance considering that more than 50% of agricultural land was classified as low to medium land, and over 70% of land holdings were categorized as marginal or small in size. Over the observed period from 1996–1997 to 2021–2022, the transformation in utilisation of farm power sources was remarkable. With a four-fold increase in available farm power to 2 kW/ha, the dominance of mechanical power surged from 8 to 79%. Notably, the contribution of mechanical tractive power, encompassing tractors and power tillers, rose substantially from 8 to 60%, reshaping the traditional reliance on human labour and draught animals for motive power. Variations in the densities of tractors and power tillers at the district level highlighted the unequal adoption of mechanization across regions. Spatial analysis revealed a concentrated presence of tractors in districts such as Cuttack, Bargarh, and Khordha, whereas Jajpur, Koraput, and Boudh exhibited lower levels of adoption. Similarly, Jharsuguda, Kandhamal, and Sambalpur showed higher densities of power tillers, while Gajapati, Mayurbhanj, Bolangir, Nayagarh, and Rayagada experienced limited adoption. These disparities were primarily attributed to variations in topography, as well as reduced net sown area resulting from land conversion for urbanization and industrialization purposes to drive economic growth. The relationship between productivity and power availability exhibited an exponential trend, reflecting the intricate interplay of mechanization, agricultural practices on production fluctuations. However, the analysis exposed complexities in the expected cost reduction due to mechanization. Despite the significant transition, the reduction in manual labour deployment remained marginal, possibly due to the continued prevalence of labour-intensive tasks like transplanting and weeding. The shift from draught animals to tractors was more pronounced, driven by cost considerations and operational efficiency. While the mechanization index remained relatively low at 11.54%, the variability among crops was evident. Paddy with a relatively high MI of 22.70%, needed further targeted interventions, especially in labour-intensive operations. This analysis underscored the necessity for a nuanced approach to mechanization strategies, recognizing both technological advancements and the specific challenges inherent in regional agricultural landscapes. In the pursuit of sustainable agricultural development, the findings emphasized the importance of tailored mechanization policies that accounted for diverse crop requirements, regional disparities, and the imperative to enhance productivity while promoting equitable benefits. The increased adoption of agricultural mechanization extended beyond merely substituting human and animal labour; it also entailed optimizing efficiency, conserving resources, and fostering balanced rural development. Analogous outcomes are anticipated in comparable rice-growing regions across the Asia–Pacific, where power tillers are being embraced at a faster rate than tractors. This trend was influenced by various factors including fragmented land holdings, limited average land area, socio-economic circumstances of farmers, and the early stages of mechanization presenting challenges to realizing expected cost-saving benefits.

Author Contributions All authors contributed to the final version of the manuscript. Dr. P.L. Pradhan had the idea for the article. I. Rath performed the survey and collection of data and A. Behera, Dr. M. Mahapatra, Dr. R.C. Dash, Dr. P. K. Sahoo and Dr. D. Behera helped in analysis and interpretation of results. Kumudini Verma contributed in draft manuscript preparation. All authors reviewed the results and approved the final manuscript.

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Data Availability The datasets generated during and/or analysed during the current study are available in these repositories: Tractor and Mechanization Association, https://www.tmaindia.in/; DBT Schemes for farm implements, https://odishafarmmachinery.nic.in/; Cost of cultivation of principal crops in India, https://eands.dacnet.nic.in/Cost_of_Cultivation.htm; Five Decades of Odisha Agriculture Statistics, https://agri.odisha.gov.in/sites/default/files/2021-06/Five%20Decades%20of%20Odisha%20Agriculture%20Statisticss%20%282%29.pdf; World Bank Development Indicators, https://wdi.worldbank.org/

Declarations

Conflict of interest The authors have no relevant financial or non-financial interest to disclose.

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