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Design and development of a cost-efficient, user-centric leaf plate moulding machine for decentralized tribal and rural applications

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ABSTRACT

Single-use plastic tableware is a persistent source of environmental pollution in India, and the ban on identified single-use plastic items that came into force in July 2022 has intensified the search for affordable biodegradable substitutes. In the forest-fringe districts of *Odisha*, leaves of Sal and Siali have long been stitched into disposable plates and bowls, and this trade supports many tribal households. Most of that production is still done by hand, which is slow, physically tiring and yields plates of uneven quality, resulting in low incomes. Machines that could raise output are either too costly, too power-hungry or demand too much operator skill to be adopted in tribal settings. This study reports the design, development and prototype evaluation of a compact, low-cost leaf plate moulding machine intended for decentralised use by rural self-help groups. Requirements were established from a structured bilingual survey of 74 stakeholders drawn from six districts along the *Odisha* leaf plate value chain, and the responses were analysed using descriptive statistics and a Pareto ranking of reported problems. Respondents ranked low machine cost, operational safety and ease of operation as the three most important attributes, and the six most frequently reported complaints accounted for about four-fifths of the total complaint burden. These findings were translated into quantified engineering targets, which guided the selection of a crank and connecting rod pressing mechanism driven by a small single-phase motor, an electrically heated aluminium die set held between 100 and 150 degrees Celsius, guide-pillar ram guidance and an interlocked safety enclosure. A half-scale prototype was fabricated and tested. It produced plates of consistent shape and finish, held die temperature within five degrees of the set point, drew well below the target power ceiling, and its safety features functioned reliably throughout the trials. Extrapolated to full scale, the machine is projected to meet the output preferred by most respondents, at a fabrication cost within the range they could afford. Automatic leaf feeding, digital temperature control and solar operation are identified as the next steps.

Keywords: Leaf plate moulding machine, Biodegradable tableware, Voice of customer, Tribal livelihood, Rural mechanisation

1. Introduction

Single-use plastic tableware persists in soil and water for decades and breaks down into fragments that enter the food chain, which is why it has become one of the most visible targets of waste policy in India. Of the plastic that the country produces, roughly two-fifths is never recycled and ends up in landfills or waterways (Datta *et al.*, 2022) [1]. Acting on this, the Ministry of Environment, Forest and Climate Change notified the Plastic Waste Management (Amendment) Rules in 2021 [2] and banned a list of single-use plastic items, including plates, cups and cutlery, with effect from 1 July 2022 (Ministry of Environment *et al.*, 2021) [2]. The ban has created a regulatory pull for biodegradable substitutes that the market has not yet fully met. Comparative assessments of disposable tableware report that plant-based items generally carry a lower environmental burden than their plastic equivalents, although the margin depends on the material and on the end-of-life route available to the user (Pantovic *et al.*, 2025; Liu *et al.*, 2020) [3, 4].

In the deciduous forest belts of eastern India, that substitute already exists. Leaves of Sal (*Shorea robusta*) and Siali (*Bauhinia vahlii*) have been stitched into plates and bowls for generations; they compost within weeks and leave no toxic residue. *Odisha* holds a large share of India's Sal forest, and leaf collection, stitching and trade support several lakh tribal households in the state (Ministry of Tribal Affairs, 2022; Sheetal *et al.*, 2024) [5, 6]. The trade is nonetheless a poor one. Collectors earn only a few thousand rupees a season, because hand stitching is slow and the plates it yields are uneven in shape and finish and therefore fetch low prices. Value addition to minor forest produce, as pursued under the Van Dhan Vikas Karyakram, has been shown to raise tribal household incomes appreciably (TRIFED, 2018) [7], which is precisely the opportunity that mechanised moulding represents.

Mechanisation, however, has not reached these households. Commercial semi-automatic hydraulic presses turn out more than a thousand plates an hour with good consistency, but they cost several lakh rupees, draw

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three to five horsepower from a three-phase supply and need a trained operator (Table 1). Recent work has begun to probe lower-power alternatives: a semi-automatic moulder driven by a small direct-current motor with electrically heated dies has been reported, though it forms plates from crushed leaf powder and binder rather than from whole stitched leaves (Sudarshan Rao *et al.*, 2023) [8]. Each of those three requirements is difficult to satisfy in a forest-fringe village. The prior art is thin. The earliest relevant Indian Patent, 1998 [9], describes a Sal leaf plate apparatus heated by a biomass furnace and pressed by a manual lever, delivering roughly 140 plates an hour with no temperature regulation (Indian Patent, 1998) [9]; a later patent introduced continuous rotary casting with cam-driven dies, electrically heated punches and closed-loop temperature control, but presupposes industrial infrastructure (Chakravarthi *et al.*, 2007) [10]. Between these two poles sit a small number of intermediate machines. A grassroots motorised design supported by the National Innovation Foundation reaches roughly a thousand plates an hour on a half-horsepower motor, but has no safety enclosure and heats its dies inconsistently [11]; a biomass-fired portable machine developed for West Bengal tribal clusters works off-grid but exposes women operators to combustion fumes and controls temperature poorly [12]. Work on the neighbouring areca leaf-sheath trade is instructive: an energy-efficient plate-making machine has been designed for that material (Kalita *et al.*, 2008) [13], and mechanical characterisation has shown that palm leaf sheath tolerates very large forming strains, so that plates can be pressed in a single step, with hydration and alkali pre-treatment raising formability further (Mohanty *et al.*, 2021; Mohanty *et al.*, 2022) [14, 15]. Automation of areca plate production is now being actively pursued for institutional and export markets (Chandrasekar *et al.*, 2023) [16], a commercial momentum that has not yet reached the Sal and Siali belt. What is missing is a machine designed around the people who would actually use it: one that a self-help group can buy, run on a single-phase village supply, operate without training and use safely. Rather than assume those requirements, we elicited them. The voice of the customer approach offers a structured way to convert stated user needs into quantified engineering specifications (Griffin *et al.*, 1993) [17], and design for manufacturability principles keep the resulting design fabricable in a district workshop at low cost (Ulrich *et al.*, 2016; Boothroyd *et al.*, 2011) [18, 19]. This study therefore sets out to establish design requirements from a field survey of the Odisha leaf plate value chain, to translate those requirements into engineering targets, and to design, fabricate and evaluate a prototype machine against them.

2. Materials and Methods

2.1 Design process

The work followed four sequential phases. In the first, a prior art search covering Indian patent databases, institutional prototypes, commercial catalogues and peer-reviewed literature was used to characterise the existing technology landscape [9, 10, 11, 12]. In the second, the machines so identified were scored against the operational requirements of a tribal self-help group to expose the gaps between them. In the third, those gaps were tested against the stated needs of users through a field survey. In the fourth, the machine was modelled in Autodesk Fusion 360, a half-scale prototype was fabricated according to design-for-manufacturability principles (Ulrich *et al.*, 2016) [18], and its performance was measured against the targets the survey had produced. Benchmarking preceded design synthesis, so the proposed machine does not appear in the benchmarking comparison; it is compared against the derived targets in the Results.

2.2 Field survey and voice of customer analysis

A structured questionnaire in English and regional language Odia was shared with 120 stakeholders across Mayurbhanj, Sundargarh, Keonjhar, Sambalpur, Rayagada and Koraput, the principal Sal and Siali leaf-producing districts of Odisha. Seventy-four (74) valid re-

sponses were returned, a response rate of 61.7%. Respondents included self-help group members and leaf plate makers, farmers and agricultural labourers, forest officials and livelihood programme workers, and traders, so that the whole value chain was represented. The instrument had four parts: respondent profile and current practice; problems with existing machines; expected machine specifications; and importance ratings for eight design attributes. It was pre-tested on eight respondents who were excluded from the main sample, and ambiguous items were reworded before full administration.

Attribute importance was rated on a five-point Likert scale, where 1 denotes 'not important' and 5 'extremely important' (Likert, 1932) [20]. For each attribute the arithmetic mean, standard deviation, median, mode and Fisher's coefficient of skewness were computed (Walpole *et al.*, 2012) [21]:

$$\bar{x} = (1/n) \sum x_i \text{ (Datta et al., 2022) [1]}$$

$$SD = \sqrt{[(1/(n-1)) \sum (x_i - \bar{x})^2]} \text{ (Ministry of Environment et al., 2021) [2]} \text{ (Ministry of Environment et al., 2021) [2]}$$

$$\gamma_1 = [n / ((n-1)(n-2))] \sum [(x_i - \bar{x}) / SD]^3 \text{ (Pantovic et al., 2025) [3]} \text{ (Pantovic et al., 2025) [3]}$$

where x_i is the score given by respondent i and $n = 74$. A negative skewness coefficient indicates a left-skewed distribution, that is, that most respondents assigned high importance scores rather than that a minority did so. Problem-frequency data were ranked by a Pareto analysis (Juran *et al.*, 1999) [22] to separate the few complaints that account for the bulk of the complaint burden from the many that do not. Because respondents could report more than one problem, the denominator for the cumulative percentage is the total number of complaints recorded (297), not the number of respondents. Analysis was carried out in Python 3.11 using NumPy, SciPy, pandas, and Seaborn (Harris *et al.*, 2020) [23].

2.3 Translation of survey outcomes into engineering targets

Attributes combining a high mean importance with a low standard deviation were treated as non-negotiable, on the reasoning that they were both highly valued and widely agreed upon; the uniformly negative skewness confirmed that this agreement extended across the sample. The vital few problems isolated by the Pareto ranking were each mapped to a specific engineering response, and the modal specification preferences reported by respondents were adopted directly as the quantified target set. The targets that emerged from this exercise are reported in the Results, and the prototype was subsequently evaluated against them.

2.4 Statistical analysis of prototype trial performance

Worker-level performance trials were conducted to characterise the variability in production rate and plate quality attributable to operator experience, gender and age. For each participant the total number of plates produced during an 8-hour session was recorded and converted to an hourly production rate (plates per hour), and the percentage of plates passing a combined visual and manual flexural quality inspection was taken as the plate accuracy score.

Descriptive statistics, that is, arithmetic mean ($\bar{x}$), standard deviation (SD) and variance (s^2), were computed for hourly production rate and plate accuracy across the full sample and within each sub-group, using Equations (Datta *et al.*, 2022) [1] - (Pantovic *et al.*, 2025) [3] defined above (Walpole *et al.*, 2012) [21].

A one-way analysis of variance (ANOVA) was applied to test whether mean hourly production rate differed significantly across the three experience levels (skilled, semi-skilled and unskilled) (Field, 2018) [24]. The ANOVA F -statistic is:

$$F = MS_b / MS_e \text{ (Liu et al., 2020) [4]}$$

where MS_b is the mean square between groups (variance explained by experience level) and MS_e is the mean square within groups (residual variance). A significance threshold of $\alpha = 0.05$ was applied throughout.

The association between hourly production rate and plate accuracy was quantified using the Pearson product-moment correlation coefficient r (Cohen, 1988) [25]:

$$r = \Sigma[(x_i - \bar{x})(y_i - \bar{y})] / [(n-1) \cdot SD_x \cdot SD_y] \text{ (Ministry of Tribal Affairs, 2022) [5]}$$

where x_i and y_i are the hourly production rate and plate accuracy of participant i , $\bar{x}$ and $\bar{y}$ are the respective sample means, and SD_x and SD_y are the respective sample standard deviations. Values of $|r| \geq 0.7$ were taken as indicating a strong association (Cohen, 1988) [25].

3. Results

3.1 Existing technology and the gaps it leaves

The prior art search returned a sparse field: only two patents of direct relevance, both filed before 2010, and neither addressing the constraint set that defines the tribal context, namely single-phase power, capital cost below one lakh rupees, and usability by a non-technical woman operator. Four families of machine were identified and are compared in Table 1.

Table 1. Benchmarking of existing leaf plate machine technologies

Technology	Power source	Cost	Output (plates/h)	Principal limitation	Rural suitability
Manual lever press (IIT Kharagpur)	Manual / biomass	₹20,000–25,000	100–150	Very low output; operator fatigue; no thermal control	Subsistence only
Biomass-heated moulding machine (CSIR CFTRI)	Biomass	₹15,000–35,000	150–200	Poor temperature control; combustion fumes; no safety features	Off-grid gain offset by health risk
Motorised crank based machine (Grassroots innovator NIF-India)	Electric, 0.5 HP (373 W) motor + 750 W heater; single-phase; total connected load 1,123 W	₹30,000–60,000	800–1,200	Inconsistent die heating; heavy; no safety enclosure	Safety and heat optimization issue
Semi-automatic hydraulic press (Commercially available)	Electric, 3–5 HP, three-phase	₹3–5 lakh	> 1,000	High capital cost; three-phase supply; skilled operator	Out of reach economically and technically

Scoring these four families against eight design dimensions on a five-point scale exposed a consistent shortfall (Table 2 and Figure 1). No existing machine clears the minimum acceptable threshold on more than four of the eight dimensions simultaneously. The gaps that matter most are affordability, energy efficiency on a single-phase supply,

ease of operation without training, portability, operational safety, production rate, local maintainability, and regulated die temperature. Together these eight define the design agenda for the present machine.

Table 2. Gap analysis of existing technologies across eight design dimensions

Design dimension	Manual lever	Biomass machine	Motorised crank based machine	Commercial hydraulic	Gap severity
Affordability	Low (₹20,000–25,000)	Low–Medium (₹15,000–35,000)	Medium (₹30,000–60,000)	₹3–5 lakh	Critical
Energy efficiency (≤ 500 W, single-phase)	Manual	Biomass only	Partial	3–5 HP, three-phase	High
Ease of operation (no training)	Skill needed	Skill needed	Simple	Skilled operator	High
Portability (movable by 1–2 persons)	Very portable	Portable	Heavy	Fixed installation	Medium
Operational safety (enclosure, e-stop)	Absent	Absent	Absent	Partial	Critical
Production rate (≥ 500 plates/h)	100–150	150–200	800–1,200	> 1,000	High
Local maintainability	High	High	Moderate	Low (imported spares)	High
Temperature control (100–150 °C)	None	Uncontrolled	Basic	Good	High

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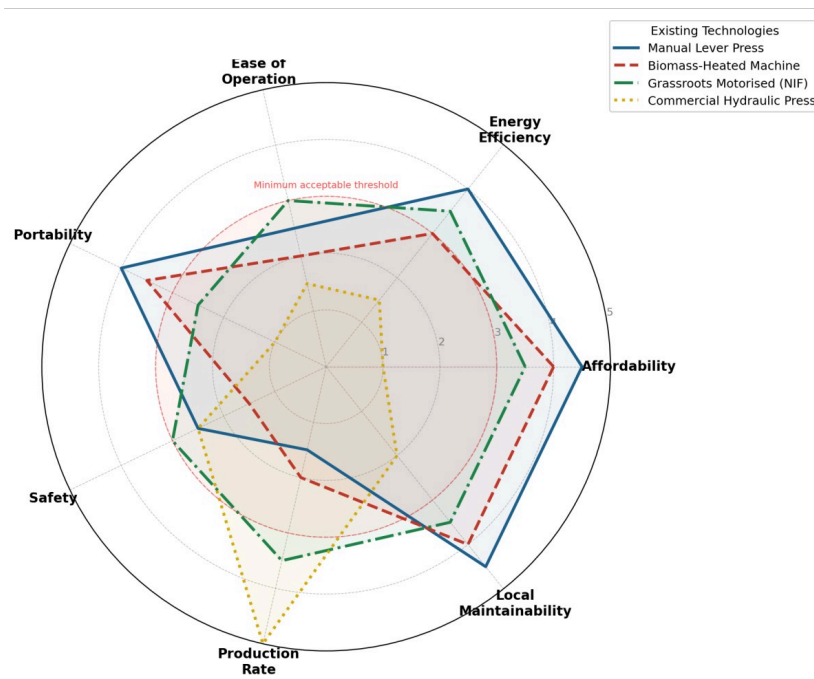


Figure 1. Performance of the four existing leaf plate machine categories across eight design dimensions (score 1–5; dashed circle denotes the minimum acceptable threshold of 3).

3.2 Survey respondents and reported problems

The respondent profile is set out in Table 3 and summarised graphically in Figure 2. Women made up 59.5% of the sample, which is consistent with the women-led composition of self-help groups in the

Odisha leaf plate trade (Ministry of Tribal Affairs, 2022) [5]. Leaf plate makers and self-help group members accounted for 60.8% of respondents ($n = 45$), and more than half the sample (54.1%) still stitches plates by hand, which is the clearest single indication of unmet need of mechanisation.

Table 3. Respondent profile and current production practice ($n = 74$)

Parameter	Response option	Count	%
Occupation	Leaf plate makers / SHG members	45	60.8
	Farmers / agricultural labourers	15	20.3
	Forest officials / NGO workers	9	12.2
	Traders / others	5	6.8
Current production method	Manual stitching	40	54.1
	Manual lever press	21	28.4
	Electric / hydraulic machine	13	17.6
Average daily production	Below 500 plates	29	39.2
	500–1,000 plates	32	43.2
	Above 1,000 plates	13	17.6

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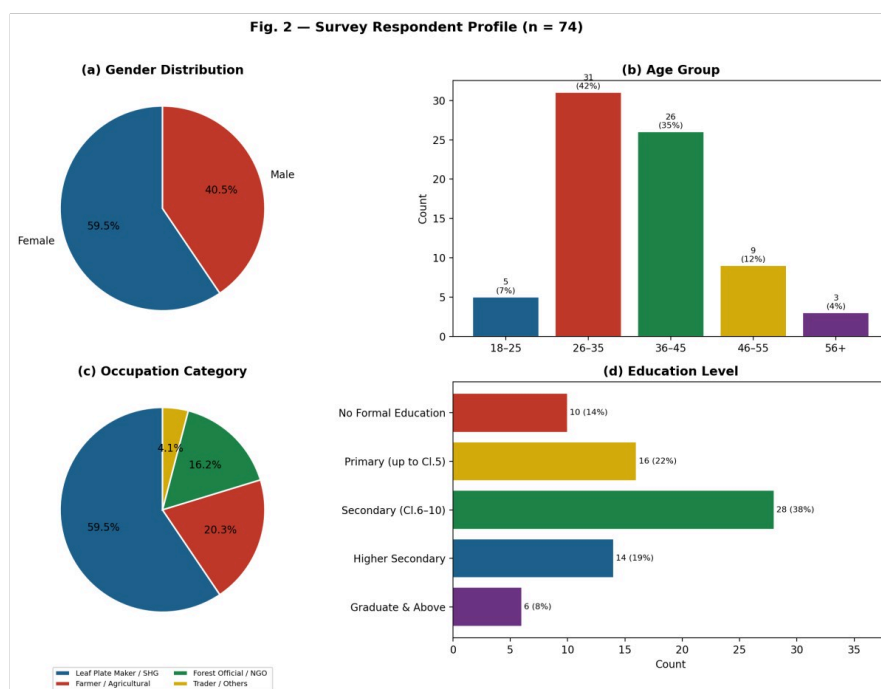


Figure 2. Respondent demographic profile (n = 74): (a) gender; (b) age group; (c) occupation; (d) education level.

The problems respondents reported with existing machines are given in Table 4 and ranked in Figure 3. High machine cost was the most widespread complaint (75.7%, $n = 56$), followed by high electricity consumption (58.1%, $n = 43$) and machine weight (54.1%, $n = 40$). Across the sample, 297 individual complaints were recorded. The cumulative share crosses the Pareto 80% threshold at the sixth problem:

machine cost, electricity consumption, portability, production rate, safety and maintenance together account for 81.5% of all complaints (Juran *et al.*, 1999) [22]. The five most frequent problems alone account for 70.0%. These six complaints, rather than the full list of eight, therefore set the engineering priorities.

Table 4. Problems reported with existing leaf plate machines ($n = 74$; 297 complaints recorded)

Problem reported	Count	% of respondents	Cumulative % of complaints	Engineering response
High machine cost	56	75.7	18.9	Fabrication cost target ₹50,000–₹1,00,000
High electricity consumption	43	58.1	33.3	Total connected load 723 W (373 W motor + 350 W heater); within 1 HP (746 W) ceiling; single-phase
Machine too heavy / not portable	40	54.1	46.8	Compact H-frame; weight below 60 kg
Low production rate	35	47.3	58.6	Target 500–700 plates/h; 60 strokes/min
Safety concerns during operation	34	45.9	70.0	Interlocked enclosure; emergency stop; belt guard
Maintenance and breakdown	34	45.9	81.5	Modular design; standard fasteners; local spares
Heating / temperature control	30	40.5	91.6	Thermostat-regulated dies at 100–150 °C
Difficult to operate	25	33.8	100.0	Push-button controls; dial thermostat

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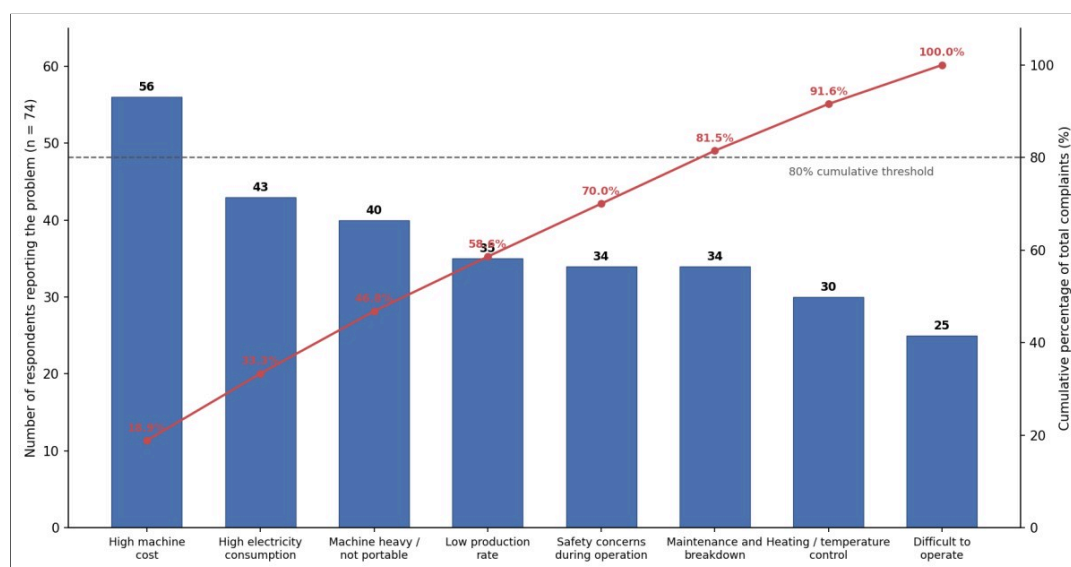


Figure 3. Pareto ranking of problems reported with existing leaf plate machines. Bars give the number of respondents reporting each problem; the line gives the cumulative percentage of the 297 complaints recorded. The 80% threshold is crossed at the sixth problem.

3.3 Specification preferences and attribute importance

Respondent preferences for machine specifications are summarised in Table 5 and Figure 4. A total connected load between 500 W and 1 HP (746 W), covering both the drive motor and the die-heating elements, was preferred by 70.3% ($n = 52$). This supports the selection of a 0.5 HP (373 W) motor combined with a 350 W tubular heater, giving a full-scale connected load of 723 W, which falls within the

preferred ceiling of 746 W. An output of 500–700 plates per hour was preferred by 58.1% ($n = 43$), a price between ₹50,000 and ₹1,00,000 was acceptable to 58.1%, and a medium, single-operator machine was preferred by 67.6% ($n = 50$).

Only the leading options selected by respondents are tabulated; remaining respondents chose other options within each parameter; so counts within a parameter do not sum to 74.

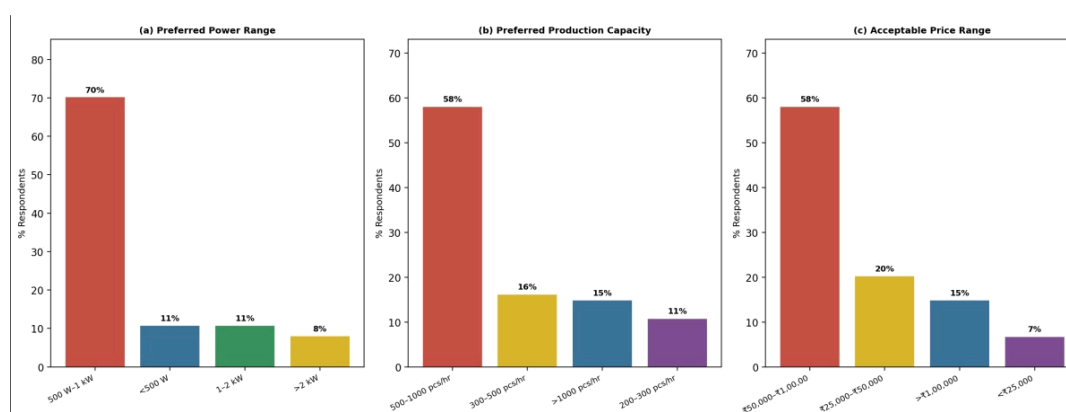


Figure 4. Respondent preferences for machine specifications ($n = 74$): (a) drive power; (b) production capacity; (c) price range.

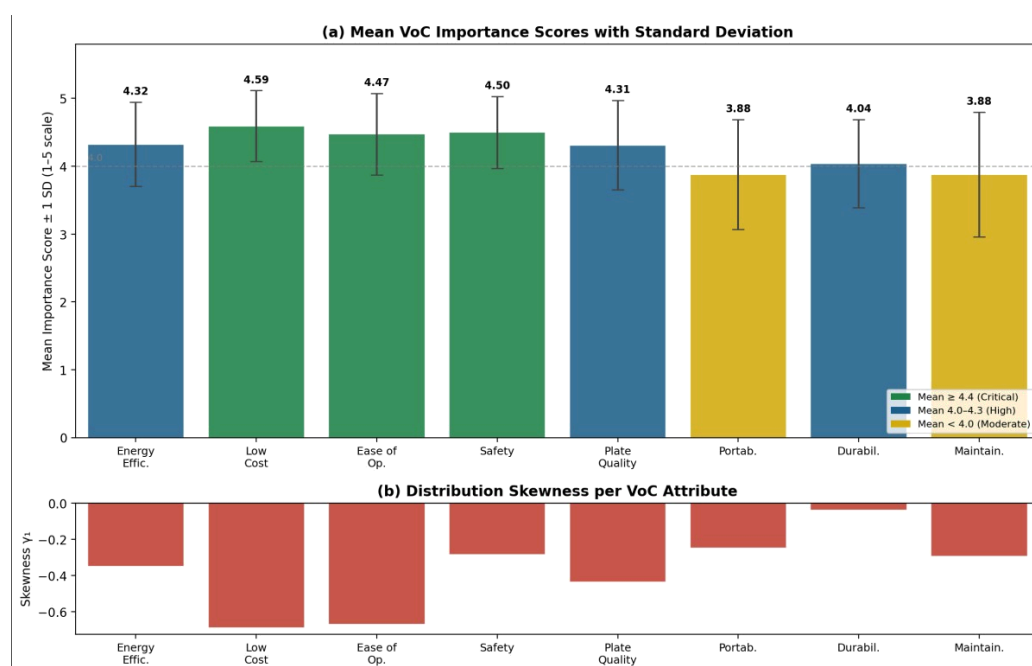
Descriptive statistics for the eight design attributes are given in Table 6 and plotted in Figure 5. Low machine cost drew the highest mean rating (4.59, SD = 0.52), followed by operational safety (4.50, SD = 0.53) and ease of operation (4.47, SD = 0.60). Every attribute returned a negative skewness coefficient, between -0.039 and -0.690 , meaning that ratings clustered toward the top of the scale in each

case. The three highest-ranked attributes also had the tightest spread (SD 0.52–0.60), which indicates that respondents agreed with one another as well as rating these attributes highly. Portability and maintainability drew wider spreads (SD 0.81 and 0.92), most plausibly because respondents differed in how much prior experience of machines they had.

Table 5. Machine specifications preferred by respondents ($n = 74$)

Parameter	Preferred option	Count	%	Specification adopted
Drive power	Total load 500 W – 1 HP (746 W)	52	70.3	Total connected load 723 W (373 W motor + 350 W heater); within 1 HP (746 W) ceiling preferred by respondents
Production capacity	< 500 W	8	10.8	Secondary efficiency target
	500–700 plates/h	43	58.1	Design target at full scale
	300–500 plates/h	12	16.2	Acceptable for smaller units
	> 700 plates/h	11	14.9	Future multi-die design
Machine size	Medium (1 operator)	50	67.6	Single-operator compact frame
	Portable (1-person carry)	19	25.7	Weight below 60 kg
Price range	₹50,000–₹1,00,000	43	58.1	Fabrication cost target
	₹25,000–₹50,000	15	20.3	Noted for future optimisation

Ratings on a five-point Likert scale (1 = not important, 5 = extremely important). Skewness computed from Eq. (Pantovic et al., 2025) [3].

**Figure 5.** Attribute importance ratings ($n = 74$): (a) mean $\pm$ 1 SD per attribute; (b) skewness coefficient per attribute.

Taken together, the Pareto ranking, the specification preferences and the attribute statistics converge on a single target set: a total connected load (motor plus heater) within 1 HP (746 W) on a single-phase supply, met by 373 W motor and 350 W heater giving 723 W; an output of 500–700 plates per hour at full scale; a fabrication cost

between ₹50,000 and ₹1,00,000; thermostat-regulated dies at 100–150 °C; push-button operation with under thirty minutes of training; a mandatory safety package of interlocked enclosure, emergency stop and belt guard; and a machine weighing under 60 kg.

Table 6. Descriptive statistics of attribute importance ratings ($n = 74$)

Attribute	Mean	SD	Median	Mode	Min	Max	Skewness (γ_1)
Low machine cost	4.59	0.52	5	5	3	5	-0.690
Operational safety	4.50	0.53	5	5	3	5	-0.284
Ease of operation	4.47	0.60	5	5	3	5	-0.669
Energy efficiency	4.32	0.62	4	4	3	5	-0.350
Consistent plate quality	4.31	0.66	4	4	3	5	-0.436
Durability	4.04	0.65	4	4	3	5	-0.039
Portability	3.88	0.81	4	4	2	5	-0.249
Maintainability	3.88	0.92	4	4	2	5	-0.294

3.4 Machine design

Table 7. Design considerations and engineering solutions adopted

Table 7. sets out the principal design considerations identified from the gap analysis and VoC findings, and the engineering solution adopted for each. The paragraphs that follow describe each sub-system in detail.

Design Consideration	Constraint / Requirement	Engineering Solution Adopted
Pressing mechanism	Low maintenance; adjustable speed; operable by small single-phase motor; proven in grassroots use	Crank and connecting rod; 160 mm stroke; speed adjusted via pulley ratio without mechanical modification
Frame and structure	Weight below 60 kg; deflection below 0.2 mm at 2 kN peak pressing load; locally repairable	Welded H-geometry in 40 × 40 × 3 mm square hollow section mild steel; two 25 mm guide pillars; four return springs
Die material and heating	Rapid uniform heating; 100–150 °C; total heater load within 746 W total-load ceiling	Aluminium alloy die halves; 350 W tubular resistance heaters in bored channels; bimetallic thermostat (prototype) / PID controller (production)
Drive power	Total connected load (motor + heater) within 1 HP (746 W); single-phase village supply	0.5 HP (373 W) motor + 350 W heater = 723 W (full scale); 200 W DC motor + 350 W heater = 550 W (prototype)
Safety system	45.9% of respondents cited safety concerns; access to moving die and belt must be prevented	Interlocked sheet-metal enclosure; large toggle emergency stop; belt guard; MCB overcurrent protection
Controls and operation	Training time below 30 min; operable by non-literate women operators; no oil circuit	Push-button start/stop; dial thermostat; PWM speed control (prototype); no hydraulics
Fabrication and maintainability	Cost below ₹1,00,000; serviceable at block-level workshop; locally available spare parts	Standard SHS sections; standard fasteners; modular sub-assemblies; SMAW welding throughout

A crank and connecting rod mechanism was chosen over hydraulic and toggle-clamp alternatives for four reasons: it is mechanically simple and cheap to maintain; it works with a low-power single-phase motor; its stroke speed can be altered through the pulley ratio without mechanical modification; and it has already proved reliable in grass-roots motorised designs^[11]. A crank stroke of 160 mm gives sufficient die closure for plates up to 300 mm in diameter.

The frame is a welded H-geometry assembly in $40 \times 40 \times 3$ mm square hollow mild steel section, which provides a symmetric load path from the pressing mechanism to the die table while keeping material use, and therefore cost, low (Ulrich *et al.*, 2016) [18]. Frame analysis indicated deflection below 0.2 mm at the estimated 2 kN peak pressing load. Two precision-ground hardened steel guide pillars of 25 mm diameter constrain the ram to vertical travel and so prevent lateral die misalignment, and four return compression springs, matched to the 8 kg ram mass and the 160 mm stroke, reset the punch after each cycle.

Both die halves were prepared by die casting and machined from aluminium alloy, chosen for its high thermal conductivity, which promotes rapid and even heating. Tubular resistance elements set into bored channels in each half hold the dies between 100 and 150 °C. This window was established empirically in the present trials as the range within which Sal and Siali fibres set permanently without charring, and is consistent with the reported thermoformability of palm-family leaf materials (Mohanty *et al.*, 2021; Mohanty *et al.*, 2022) [14, 15]. Temperature is held by a bimetallic dial thermostat in the prototype; a digital proportional-integral-derivative controller is intended for the production version (Astrom *et al.*, 1995) [26]. A die-to-punch clearance of 0.5–1.0 mm accommodates the compressed leaf stack. The electrical circuit comprises a single-phase supply, a miniature circuit breaker, motor start and stop buttons, a large toggle emergency stop, the thermostat and two heating elements. The complete machine occupies an envelope of roughly $700 \times 500 \times 1,200$ mm (Figure 6).



Figure 6. Computer-aided design model of the machine: (a) front view; (b) isometric view.

3.5 Prototype

A half-scale prototype was built to validate the mechanism and the moulding performance before fabricating an actual full scale model. Motor power was reduced from 373 W to 200 W, and a switched-mode-supply direct-current motor with pulse-width-modulated speed control was used for the said purpose. The prototype comprised three subassemblies: the mould assembly (aluminium die block, punch, two guide pillars, four return springs); the drive assembly (motor, pulleys, crankshaft, connecting rod, ram); and the body (square hollow section

H-frame, worktable, motor mounting plate, sheet-metal enclosure, electrical panel). Cutting, machining, shielded metal arc welding, drilling, grinding and fitting operations were performed on general workshop machinery, consistent with the intent that the machine be fabricable locally (Ulrich *et al.*, 2016; Boothroyd *et al.*, 2011) [18, 19]. The assembled prototype is shown in Figure 7.

The prototype used a 200 W direct-current motor and a 350 W tubular resistance heater. The total connected electrical load of the prototype was therefore 200 (motor drive) + 350 (heating element) = 550 W.



Figure 7. Assembled prototype: (a) front view; (b) isometric view.

3.6 Trial runs

Cleaned and dried Sal and Siali leaf sheets were placed between the heated die halves, with the thermostat set to 130 °C and allowed to stabilise before each run. Plates were then inspected for shape accuracy, edge finish, surface uniformity and structural integrity under manual flexural loading. Across repeated trials the reciprocating motion remained smooth, punch and die stayed aligned, and plates formed reliably without significant defects. Die temperature held within ± 5 °C of the 130 °C set point throughout continuous running, and the belt guard, emergency stop and interlocked enclosure functioned as designed in every session.

Measured performance is set against the survey-derived targets in Table 9. At half scale and 200 W the machine achieved 450–750 forming strokes per hour; scaled to the full 373 W design, it is projected to meet the 500–700 plates per hour that 58.1% of respondents preferred. Steady-state draw of 350–400 W (motor running continu-

ously at 200 W plus the thermostat-cycled heater contributing ~150–200 W), against a total connected load of 550 W (200 W motor + 350 W tubular heater), well within the 1 HP (746 W) total-load ceiling preferred by 70.3%, and the prototype was fabricated for approximately ₹32,000, inside the price band 58.1% of respondents said they could accept.

To characterise operator-dependent variability in production rate and plate quality, the prototype was operated by 24 participants of the target user population: five age groups (18–25, 26–35, 36–45, 46–55 and 56+), both genders (15 women, 9 men) and three experience levels (9 skilled, 9 semi-skilled and 6 unskilled), each completing a full 8-hour trial session. The total plates produced over 8 hours was recorded and converted to an hourly production rate; the percentage of plates passing a combined visual and manual flexural quality check was taken as the plate accuracy score. Descriptive statistics, one-way ANOVA and Pearson correlation were applied as described in Section 2.4.

Table 8. Worker performance trial ($n = 24$, 8-hour sessions; Equations 1–5)

Group	n	Mean rate (plates/h)	SD (plates/h)	Variance	Min (plates/h)	Max (plates/h)	Mean accuracy (%)	SD accuracy (%)
All participants	24	554	130	16,949	350	791	89.5	6.0
Skilled	9	670	60	3,636	—	—	95.8	2.4
Semi-skilled	9	559	72	5,170	—	—	88.8	4.7
Unskilled	6	373	20	384	—	—	81.0	5.3
Female	15	552	136	18,493	—	—	89.3	6.4
Male	9	558	123	15,055	—	—	89.9	5.3

ANOVA (hourly rate by experience level): $F = 46.01$, $df = 2, 21$, $p < 0.001$. Pearson r (hourly rate vs. plate accuracy) = 0.863, $p < 0.001$.

Gender difference negligible (female 552 plates/h; male 558 plates/h).

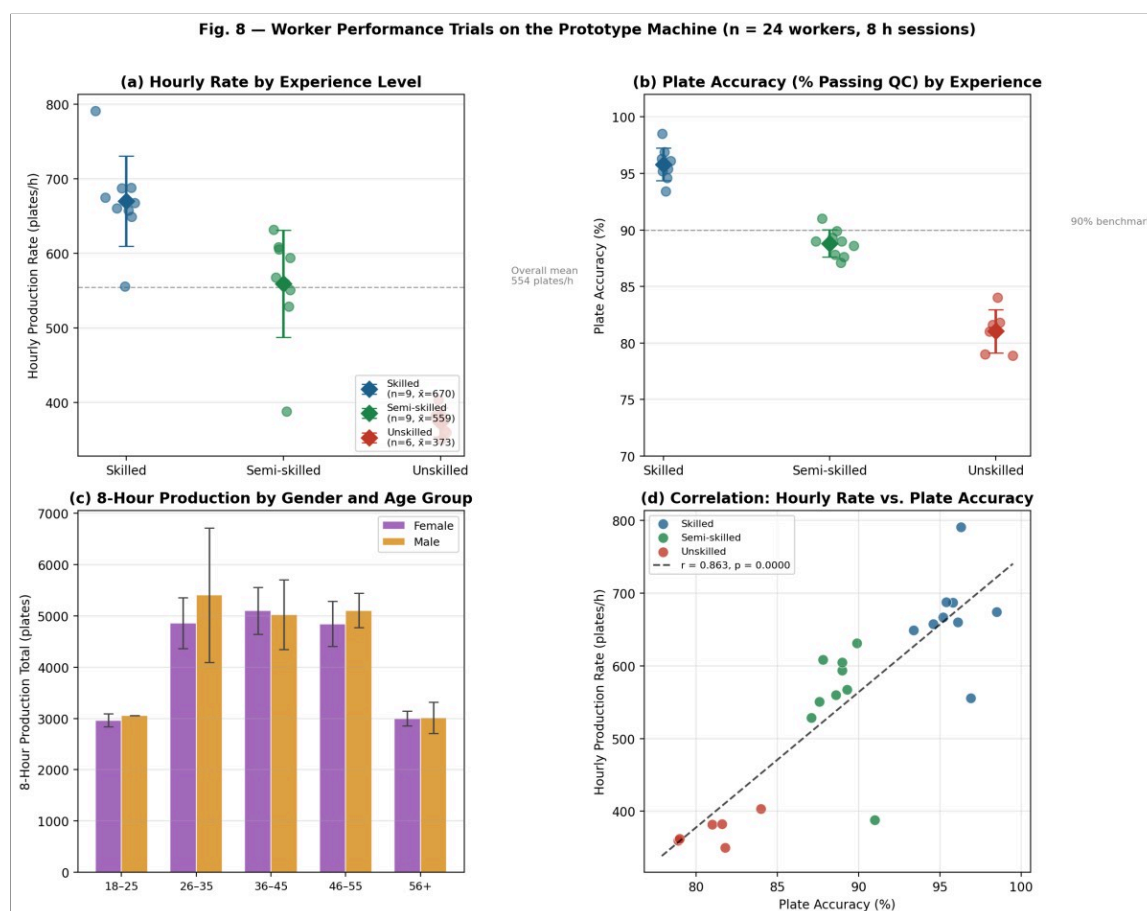


Figure 8. Worker performance trials (n = 24, 8-hour sessions): (a) hourly rate by experience level (mean $\pm$ 1 SD); (b) plate accuracy by experience level; (c) 8-hour production total by gender and age group; (d) correlation between hourly rate and plate accuracy (Pearson $r = 0.863$, $p < 0.001$).

Table 9. Prototype performance against survey-derived design targets

Parameter	Prototype (half scale, 200 W)	Target (full scale, 373 W)	Basis in survey
Production rate	450–750 strokes/h	500–700 plates/h (projected)	58.1% preferred 500–700 plates/h
Steady-state power	350–400 W measured (connected load: 550 W prototype; 723 W full scale)	Total connected load $\leq$ 746 W (1 HP); design at 723 W	70.3% preferred total load $\leq$ 1 HP (746 W)
Die temperature	130 ± 5 °C	100–150 °C controlled	40.5% reported heating problems
Fabrication cost	$\approx$ ₹32,000	₹50,000–₹1,00,000	58.1% accepted this band
Ease of operation	Push-button; < 30 min training	Minimal training	33.8% reported difficulty of operation
Safety features	Enclosure, e-stop, belt guard: all functional	All mandatory features	45.9% reported safety concerns

4. Discussion

The machine closes all eight gaps identified at the outset, though not all to the same degree. On cost, the ₹32,000 prototype sits an order of magnitude below the ₹3–5 lakh of a commercial hydraulic press. On power, demand falls from the 2.2–3.7 kW of a three-phase hydraulic machine to 550 W (prototype) and 723 W (full-scale design) on a single phase, both within the 1 HP (746 W) total-load ceiling that 70.3% of respondents preferred, which is what makes operation on a village supply realistic in the first place. Usability is served by push-button control and a dial thermostat, safety by the interlocked enclosure and emergency stop, and maintainability by standard sections, ordinary fasteners and a modular layout that a district workshop can service. Temperature held within ± 5 °C at prototype scale, which is adequate but is the weakest of the eight and is the reason a digital controller is planned (Astrom *et al.*, 1995) [26].

The survey data are worth dwelling on, because they carry a message that is easy to miss. Respondents did not rank throughput first. They ranked cost, safety and ease of operation first, and they agreed with

one another most tightly on exactly those three. Throughput mattered, but it was not the binding constraint. This inverts the priority order that the commercial machines embody, and it explains why those machines, for all their output, have not diffused into forest-fringe villages. Designing to the users' own ranking rather than to a specification sheet is the substantive contribution here.

The Pareto result reinforces the point. Six complaints account for roughly four-fifths of everything respondents raised, and the top five for 70%. Cost, power, weight, output, safety and maintenance are therefore where design effort pays; the remaining complaints are real but secondary. It is worth noting that this ranking was stable enough that fifth and sixth place were tied on frequency, so the vital few should be read as a group of six rather than as a strict ordering.

One substitution made under duress turned out to be an advantage. The direct-current motor and switched-mode controller, adopted only because the intended alternating-current geared motor was unavailable, allow the stroke rate to be varied through pulse-width modulation. That means the operator can adjust pressing speed to suit leaves of different thickness and moisture content without touching the

mechanism, which is genuinely useful when a single machine must handle both Sal and Siali. The production design should keep this capability rather than revert to a fixed-speed drive.

Set against the two closest precursors, the machine occupies a middle ground. It offers better temperature control and lower operator fatigue than either the biomass-fired machine^[12] or the grassroots motorised design^[11], while staying inside their affordability envelope. Against a commercial hydraulic press (Table 1) it trades peak throughput for a large reduction in capital and running cost, and the survey suggests that this is the trade the intended users would themselves make. At a projected full-scale cost within ₹50,000–₹70,000, the machine falls within reach of a self-help group borrowing through a livelihood scheme or a microfinance lender, which is the condition on which any livelihood gain depends (TRIFED, 2018)^[7].

The present study has two limitations. First, the full-scale output figure is a projection from half-scale stroke rates rather than a measured value, and needs confirmation on a full-scale build. Second, plate quality was judged by visual inspection and manual flexural loading rather than standardised testing, so claims about strength and moisture resistance remain qualitative; a formability protocol such as limiting dome height testing (Mohanty *et al.*, 2021)^[27] would put these on a quantitative footing.

5. Conclusion

A compact, low-power leaf plate moulding machine was designed, built at half scale and evaluated against requirements elicited from the people intended to use it. Benchmarking of four existing technology families across eight design dimensions showed that none satisfies more than four simultaneously in a tribal self-help group setting. A survey of 74 stakeholders identified low machine cost, operational safety and ease of operation as the dominant requirements, with strong agreement among respondents, and a Pareto ranking showed that six problems account for 81.5% of all complaints recorded. These findings produced a quantified target set, and the resulting design, a crank and connecting rod press with electrically heated aluminum dies, met it: the prototype held die temperature within ± 5 °C of the 130 °C set point, drew 350–400 W steady state on a 550 W connected load, cost about ₹32,000 to build, and ran its safety features reliably, while producing 554 plates/hour during trial. The wider lesson is that the constraint on mechanizing this trade has not been throughput but affordability, safety and simplicity, and that designing to that order of priorities produces a different machine from the one the market currently offers.

In future work an improved design with digital temperature control, automatic leaf feeding and plate ejection, solar operation for electricity-deficient villages should be developed with a techno-economic survey and input from the forest dependent people, for the forest fringe villages for even more wider adoptability.

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