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Development and performance evaluation of a manually operated intra-canopy vertical boom sprayer for NEH Region

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Abstract
Smallholder farmers in hill and mountain agro-ecosystems continue to rely on hand-operated knapsack sprayers that apply chemicals mainly to the top of the plant canopy, resulting in poor penetration, non-uniform pest control and high operator fatigue. This paper reports the design, fabrication and field evaluation of a compact, manually guided, engine-powered intra-canopy boom sprayer developed for row crops in hill farming conditions, using maize as the test crop. The sprayer combines a horizontal boom (two flat-fan nozzles) for top-of-canopy coverage with a vertical boom (four flat-fan nozzles, 40 cm spacing) for lateral, intra-canopy coverage, mounted on a mild-steel frame with pneumatic drive wheels and a rear caster wheel. A 20-litre plastic tank supplies a 10-12 LPM double-outlet reciprocating pump driven by a 1.13 hp two-stroke petrol engine, delivering 200-400 psi working pressure through adjustable sliding boom attachments. Nozzle type, operating pressure (1.5 kg cm^{-2}) and forward speed (1.5 km h^{-1}) were selected from prior laboratory and soil-bin optimization. Field evaluation was carried out on Sikkim Sankul Makka-2 maize (row spacing 50 cm, plant height 450 mm, vegetative stage, 120-day duration) at a farmer's field in Samlik village, Sikkim. The developed sprayer achieved a theoretical field capacity of 0.15 ha h^{-1}, an actual field capacity of 0.11 ha h^{-1} and a field efficiency of 73.33 %. Spray deposition, quantified with water-sensitive paper and DepositScan analysis, averaged 69.77 % coverage, 419.9 µm VMD, 70.81 deposits cm^{-2} and 70.35 µL cm^{-2} deposition on above-leaf surfaces, against 59.67 % coverage, 349.2 µm VMD, 58.66 deposits cm^{-2} and 58.14 µL cm^{-2} on under-leaf surfaces. At a fabrication cost of ₹22,600, the machine returned an operating cost of ₹78 h^{-1}, a benefit-cost ratio of 1.56 and a payback period of 1.7 years. These results demonstrate that a low-cost, single-operator intra-canopy boom sprayer can deliver satisfactory field capacity, uniform canopy penetration and favourable economics for row-crop plant protection in hilly terrain, offering smallholder farmers a mechanized, gender-neutral alternative to knapsack spraying.

Keywords: Boom sprayer, Intra-canopy spraying, Hill agriculture, Maize, Field efficiency and Cost economics

Introduction
Indian agriculture contributes about 14 % of national GDP while still employing roughly half of the country's workforce, and food-grain production reached approximately 354 million tonnes in 2024-25 (Dolli and Divya, 2020) [9]. Sustaining this output depends heavily on effective plant protection, since pests, weeds and diseases cause substantial pre- and post-harvest losses; consequently, pesticide, herbicide and fungicide application has become one of the most frequent field operations undertaken by Indian farmers (Gupta, 2004) [10]. Most available plant-protection equipment — hand-operated knapsack sprayers, engine-powered knapsack sprayers, and horizontal triplex power (HTP) gun sprayers — apply spray predominantly from above the canopy, leaving the middle and lower plant strata, where many insect pests and disease propagules reside, inadequately covered.

In hill and mountain farming systems such as those of Sikkim and the wider North-Eastern Himalayan region, this problem is compounded by small, sloping, terraced fields that are poorly suited to tractor-mounted or self-propelled boom sprayers, and by a predominance of manual, often gender-differentiated, labour for spraying operations (Dewangan *et al.*, 2010) [7]. There is consequently a clear need for a compact, lightweight, single-operator sprayer capable of directing spray laterally into the crop canopy — an intra-canopy boom sprayer — while remaining simple enough to fabricate and maintain with locally available materials and skills (Anibude *et al.*, 2016 and Dash *et al.*, 2020) [2, 6].

Building on laboratory nozzle characterization and soil-bin simulated canopy trials (reported separately), which identified the flat-fan nozzle operated at 1.5 kg cm^{-2} and 1.5 km h^{-1} forward speed as the optimum configuration for uniform intra-canopy deposition, the present study reports the mechanical design, fabrication, and field-scale performance and economic evaluation of the resulting sprayer on maize, the principal test crop for hill-farming plant-protection mechanization in this region. The specific objectives were to: (i) design and fabricate a manually guided, engine-powered intra-canopy vertical boom sprayer using locally available materials; (ii) evaluate its performance under actual field conditions on maize; and (iii) assess the cost economics of the developed machine relative to its expected working life.

Materials and Methods
Design considerations
The sprayer was designed around three sets of considerations. Functional requirements specified that the machine be simple to fabricate from locally available materials, easily assembled and dismantled for inspection and repair, manually operated with manually adjustable pressure, low in power consumption, and mechanically simple with few wearing parts. Engineering considerations addressed spray-boom width, material and folding mechanism; nozzle type, spacing and height; and pump type and pressure-control strategy. General considerations placed overall priority on fabrication simplicity, use of locally sourced materials, cost-effective construction and ease of assembly/disassembly for repair.

Machine description and components
The developed sprayer (Table 1) integrates a horizontal boom (two flat-fan nozzles, for top-of-canopy spraying) and a vertical boom (four flat-fan nozzles at 40 cm spacing, for lateral intra-canopy spraying) fabricated from CPVC pipe, mounted on a mild-steel (MS) frame built from 25 × 3 mm circular pipe, flat plate and angle iron. The frame carries two pneumatic drive wheels at the front and a caster wheel at the rear for manoeuvrability, a detachable 20-litre plastic spray tank, and a sliding boom attachment that allows the vertical boom to be adjusted in height and forward position to match crop geometry. A flexible PVC hose (8.5 mm diameter, 2.5 m length on each side) conveys liquid from the tank to quarter-inch brass ball valves and T-joints that direct flow to the boom nozzles (Fig. 1), with a pressure gauge and control valves at the pump outlet for maintaining the desired working pressure.

Fig 1: Prototype Vertical Boom Intra-canopy Sprayer

Table 1: Specification of the developed intra-canopy vertical boom sprayer.

Sl. No.	Particular	Specification
1	Equipment name	Manually operated intra-canopy boom sprayer
2	Pump type	Horizontal triplex pump (HTP)
3	Power source — movement	Manual (operator-guided)
4	Power source — spraying	Petrol engine
5	Number of nozzles	Six (2 horizontal + 4 vertical), flat-fan type
6	Tank capacity / material	20 L / Plastic
7	Spray boom configuration	Vertical + Horizontal (CPVC)
8	Frame material	MS square pipe
9	Boom height (adjustable)	105 cm
10	Overall dimensions (L×W×H)	1300 × 1030 × 1040 mm
11	Weight (without water)	29.7 kg
12	Fabrication cost	₹22,600

Pump and engine selection
The pump discharge capacity was calculated from the rate of area coverage (83.4×10^{-4} ha min^{-1}) and an assumed spray application rate of 700 L ha^{-1}, giving a required discharge $Q = A \times Dt = 5.838$ L min^{-1}. Applying a 50 % safety margin to accommodate pump wear and declining volumetric efficiency over time raised the design discharge to 8.76 L min^{-1}, for which a market-available reciprocating pump rated at 10-12 L min^{-1} was selected. The hydraulic power requirement, computed as $Pr = Op \times Q$ at an assumed pump pressure of 1 MPa, was 145 W; applying a pump efficiency of 60 % and a further 1.5 factor of safety gave a required shaft power of 362.5 W (0.485 hp), and applying a mechanical transmission efficiency of 60 % gave a required engine power of 0.80 hp. A commercially available two-stroke petrol engine rated at 1.13 hp was accordingly selected, providing 200-400 psi working pressure through the pump's two discharge outlets (Table 2).

Table 2: Specification of the sprayer pump and engine unit.

Particular	Value
Pump / engine type	High-pressure double-discharge-outlet pump with JX35 multipurpose engine
Engine power	1.13 hp
Working pressure	200-400 psi
Discharge	10-12 LPM (2 discharge outlets)
Engine type	Single-cylinder, 4-stroke, petrol

Field evaluation procedure
Field performance was evaluated at a farmer's field in Samlik village, Sikkim, on maize variety Sikkim Sankul Makka-2 at the vegetative growth stage (120-day duration), with plant height 450 mm and row spacing 50 cm (**Table 3**). Prior to the run, the sprayer was calibrated over a short trial

distance to confirm stable pressure and speed. The nozzle type (flat-fan), operating pressure (1.5 kg cm^{-2}) and forward speed (1.5 km h^{-1}) (Fig. 2), applied in the field trial were the optimum combination identified from laboratory patternator and soil-bin canopy testing.

Fig 2: Field Evaluation of Intra-Canopy Vertical Boom Sprayer

Table 3: Agronomic parameters of the maize crop at the field-evaluation site.

Sl. No.	Particular	Detail
1	Crop	Maize
2	Variety	Sikkim Sankul Makka-2
3	Height of crop	450 mm
4	Stage of crop	Vegetative
5	Duration of crop	120 days
6	Row-to-row spacing	50 cm

Ten plants along a row were selected, and water-sensitive paper tags (26 × 76 mm) were fixed at above-leaf and under-leaf positions on each plant. After the run, tags were retrieved once dry, sealed individually and scanned at 600 dpi, and the images analysed with DepositScan software to determine percentage coverage, VMD, deposit density and deposition rate at each leaf position. Actual field capacity was computed as the area covered divided by total time (productive plus non-productive, i.e., tank filling, turning and adjustment); theoretical field capacity as (working width × speed)/10; and field efficiency as the ratio of actual to theoretical field capacity, expressed as a percentage (Kepner *et al.*, 2005) [12].

Cost economics

The cost of operation was estimated from fixed costs (depreciation, interest on investment, and taxes/housing/insurance) and variable costs (repair and maintenance, fuel and lubricants, and labour), following standard farm-machinery costing procedures (Witney, 1988; Hunt, 2008; Sahay, 2008) [11, 15]. Depreciation was computed by the straight-line method, D = (C-S)/(L×H), with salvage value S taken as 10 % of purchase price; interest on investment as I = [(C+S)/2H] × (i/100) at 10 % annual interest; taxes, housing and insurance at 2 % of purchase price per annum; and repair and maintenance at 5 % of purchase price per annum. Payback period was calculated as PBP = IC/ANP (initial cost divided by average net annual profit) and the benefit-cost ratio as total benefit (average net annual benefit × machine life) divided by total investment cost.

Results and Discussion

Description of the developed sprayer

The completed machine (specifications in Table 1) weighs 29.7 kg (dry) and measures 1300 × 1030 × 1040 mm overall, with an adjustable boom height of up to 105 cm to accommodate different crop stages. In operation, the horizontal boom sprays from above while the vertical boom directs spray laterally into the canopy from both sides; because the vertical boom covers one side of two adjacent rows per pass, complete coverage of a given row requires two passes (an outward and a return pass). This configuration was designed specifically to reduce operator labour, increase field coverage rate, and achieve more uniform spray penetration than is possible with a conventional knapsack sprayer, while remaining light enough for a single operator to manoeuvre on sloping terraced fields.

Field capacity and field efficiency

According to Table 4 and Fig. 3 summarize the field performance results. At the selected forward speed of 1.5 km h^{-1}, the theoretical field capacity was 0.15 ha h^{-1} while the actual field capacity, accounting for time lost in tank refilling, turning and adjustment, was 0.11 ha h^{-1}, giving a field efficiency of 73.33 %. This efficiency compares favourably with field efficiencies typically reported for knapsack and small tractor-mounted sprayers operating in similarly fragmented hill terrain, where turning and repositioning losses are proportionally larger than on open, level fields.

Table 4: Field performance of the developed intra-canopy vertical boom sprayer on maize.

Sl. No.	Particular	Value
1	Average speed of operation	1.5 km/h
2	Theoretical field capacity	0.15 ha/h
3	Actual field capacity	0.11 ha/h
4	Field efficiency	73.33 %

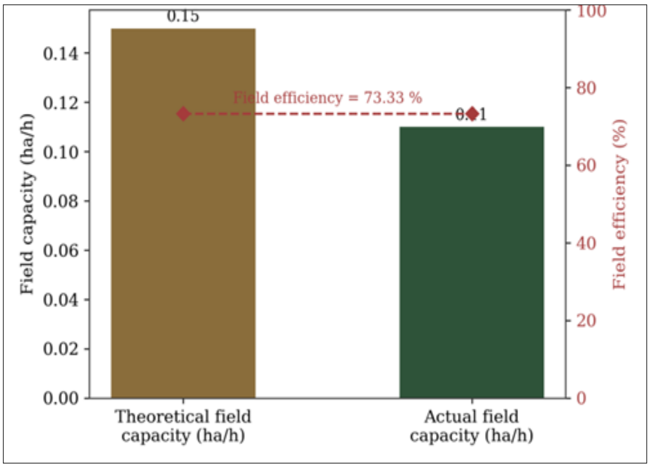

Fig 3: Theoretical and actual field capacity, and field efficiency, of the developed sprayer (maize field trial, Samlik, Sikkim).

Field spray-deposition characteristics

Regarding to Table 5 and Fig. 4 present the spray-deposition results by leaf position from the field trial. Above-leaf surfaces consistently recorded higher percentage coverage (69.77 % vs 59.67 %), larger VMD (419.9 vs 349.2 µm), higher deposit density (70.81 vs 58.66 deposits cm^{-2}) and higher deposition rate (70.35 vs 58.14 µL cm^{-2}) than under-leaf surfaces, mirroring the pattern observed in the earlier laboratory soil-bin trials and reflecting the more direct exposure of the upper canopy to the spray cone, together with droplet momentum and swirl effects that assist — but do not fully equalize — under-leaf penetration.

Table 5: Spray-deposition characteristics from the field test with respect to leaf position

Parameter	Above leaf	Under leaf
Percentage coverage (%)	69.77	59.67
VMD (µm)	419.90	349.20
Deposits/cm^2	70.81	58.66
Deposition (µL/cm^2)	70.35	58.14

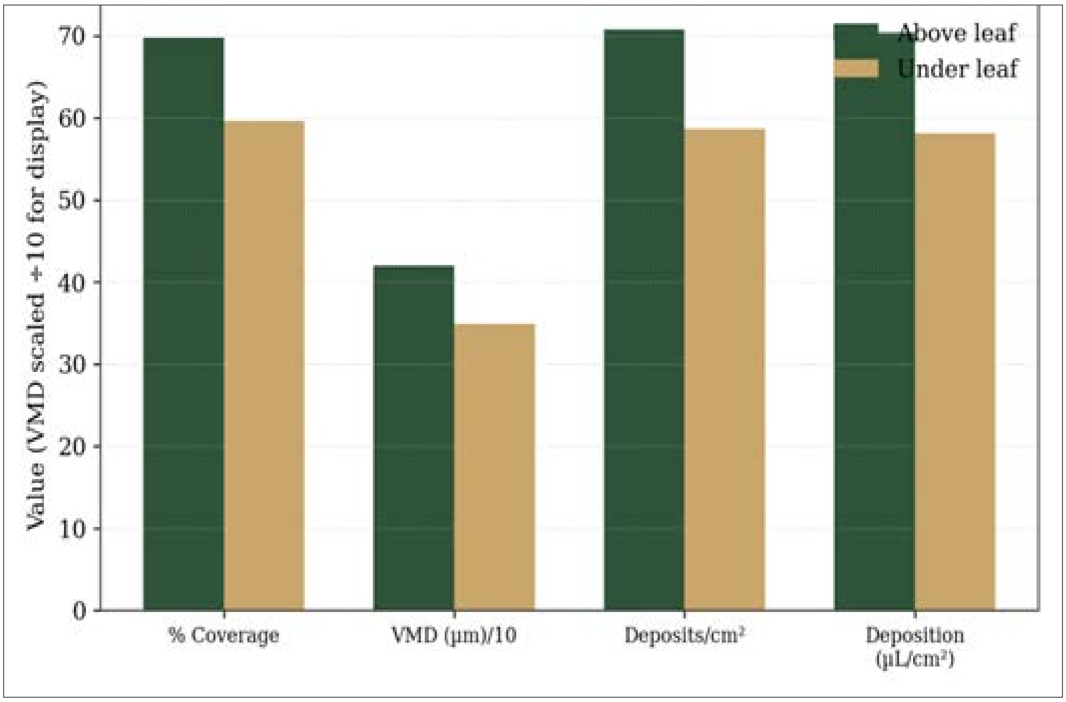

Fig 4: Field spray-deposition characteristics of the developed sprayer by leaf position (VMD values scaled ÷10 for common-axis display).

The decline in deposit density (deposits cm^{-2}) alongside an increase in percentage coverage at the above-leaf position indicates a shift toward fewer, larger coalesced droplets rather than a proportionally denser droplet population — consistent with the effect of dribbling from the nozzles and larger droplet coalescence on the upper, more exposed leaf surface, whereas the under-leaf surface received comparatively fewer but more discretely resolved droplets.

Cost economics

The complete machine was fabricated at a total cost of ₹22,600. Based on the fixed- and variable-cost components described in section 2.5, the total cost of operation was estimated at ₹78 per hour. The resulting benefit-cost ratio was 1.56 and the payback period 1.7 years (Fig. 5), indicating that the investment is recovered well within the expected working life of the machine and that the sprayer is economically attractive for smallholder adoption relative to continued reliance on hired labour for hand-operated knapsack spraying.

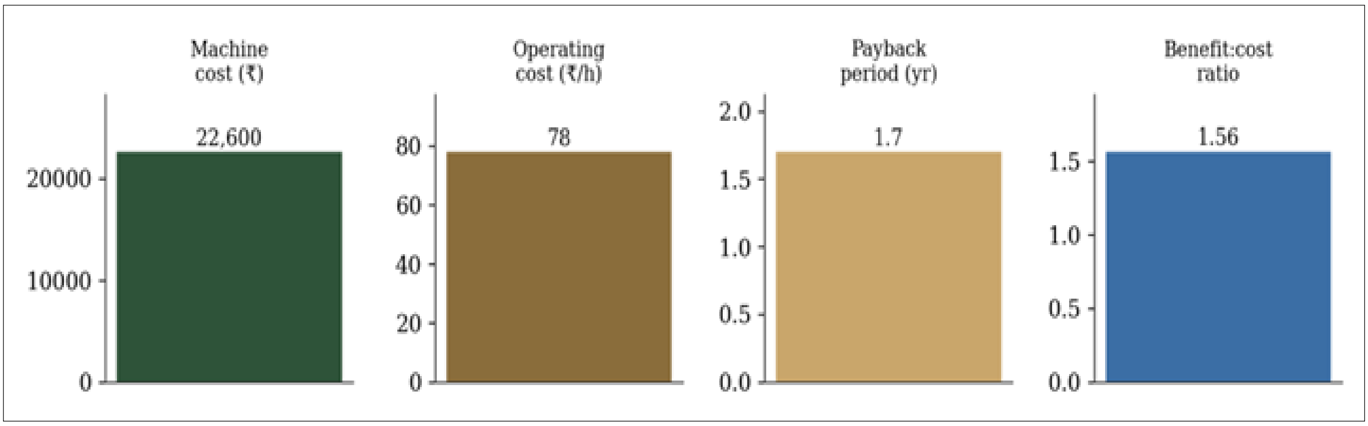

Fig 5: Cost-economics summary of the developed intra-canopy boom sprayer.

Overall development workflow

According to Fig. 6 summarizes the overall research and development sequence linking nozzle selection and soil-bin canopy simulation (reported in the companion laboratory study) to the design, fabrication, field evaluation and economic assessment reported here, illustrating how laboratory-optimized operating parameters (flat-fan nozzle, 1.5 kg cm^{-2}, 1.5 km h^{-1}) were carried through directly into field deployment.

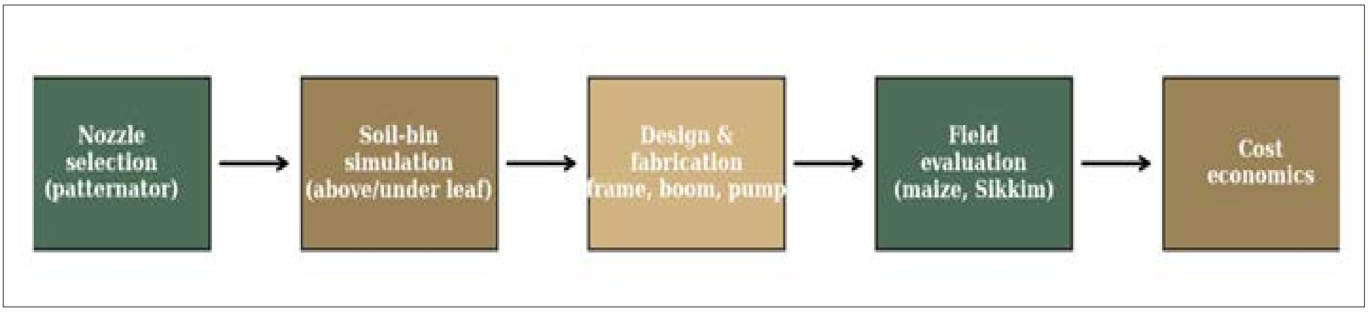

Fig 6: Overall research and development workflow, from nozzle characterization to field-deployed sprayer and cost-economic evaluation.

The results confirm that a manually guided, engine-powered intra-canopy boom sprayer combining horizontal and vertical booms can achieve satisfactory field capacity and canopy-penetration performance under hill-farming conditions, while remaining light enough (29.7 kg dry) for single-operator manoeuvrability on small, sloping fields. The field efficiency of 73.33 % and actual field capacity of 0.11 ha h^{-1} are consistent with, and in several respects favourable to, efficiencies reported for hand-operated and small tractor-mounted sprayers in comparable terrain, where non-productive time (turning, refilling, and repositioning) constitutes a larger share of total operating time than on level fields. The systematically higher above-leaf relative to under-leaf deposition observed in the field mirrors the laboratory soil-bin findings, confirming that the vertical, lateral boom configuration — while a substantial improvement over conventional top-only spraying — still leaves scope for further optimization of nozzle orientation or the addition of air-assistance to close the above/under-leaf deposition gap. Economically, the ₹22,600 fabrication cost, ₹78 h^{-1} operating cost, benefit-cost ratio of 1.56 and payback period of 1.7 years together indicate a machine that is affordable and rapidly self-financing for smallholder and cooperative ownership models typical of hill agriculture in Sikkim and the wider North-Eastern Himalayan region.

Conclusions

Based on the study undertaken, following conclusions can be drawn.

1. A manually guided, petrol-engine-powered intra-canopy vertical boom sprayer, combining a two-nozzle horizontal boom and a four-nozzle vertical boom on an MS/CPVC frame with a 20 L tank and 10-12 LPM pump, was successfully designed, fabricated and field-tested for row-crop spraying under hill farming conditions.
2. The developed sprayer, weighing 29.7 kg and costing ₹22,600 to fabricate, achieved a theoretical field capacity of 0.15 ha h^{-1}, an actual field capacity of 0.11 ha h^{-1} and a field efficiency of 73.33 % on maize at 1.5 km h^{-1} forward speed.
3. Field spray-deposition results (69.77 % coverage, 419.9 µm VMD above-leaf vs 59.67 % coverage, 349.2 µm VMD under-leaf) confirmed the laboratory-derived optimum operating combination (flat-fan nozzle, 1.5 kg cm^{-2}, 1.5 km h^{-1}) delivers adequate, though not fully symmetric, canopy penetration.
4. The machine's cost economics — ₹78 h^{-1} operating cost, benefit-cost ratio of 1.56 and payback period of 1.7 years — indicate favourable economic viability for smallholder adoption.
5. The developed intra-canopy boom sprayer offers a low-cost, gender-neutral, single-operator alternative to conventional knapsack spraying for row crops such as maize in hilly terrain, and the design and evaluation framework presented here can be extended to other row crops and terrain conditions in hill and mountain agriculture.

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