

## Bridging the Knowledge-Practice Gap through Participatory Field Distillation of Eucalyptus Essential Oils in Punjab, Pakistan

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### ABSTRACT

Smallholder farmers in Pakistan struggle to adopt eucalyptus essential oil extraction (EOE) technologies due to limited technical knowledge and weak institutional support, resulting in suboptimal yields and inefficient practices. This study evaluates participatory field distillation demonstrations using a Training-of-Trainers (ToT) approach to enhance farmers' knowledge and practices in Attock District, Punjab. Hands-on sessions and practical demonstrations covered key extraction processes, while pre- and post-intervention interviews assessed changes in knowledge and practices. Paired t-tests indicated significant improvements in harvest timing, extraction procedures, oil yield, and safety practices, with a large overall effect (Cohen's *d* = 1.16; 95% CI: 1.03–1.28). Heterogeneity was substantial ( $I^2 = 67%$ ,  $p = 0.0013$ ), reflecting variable training outcomes, and Multiple Correspondence Analysis (MCA) further supported positive shifts in farmers' perceptions and readiness to adopt EOE technology. While causal inference is limited by the absence of a control group, the findings suggest that participatory field-based ToT demonstrations are associated with meaningful improvements in farmers' technical knowledge and practices. The study offers practical insights for extension agencies and policymakers seeking to design scalable capacity-building programs to support sustainable essential oil production and rural livelihoods in Pakistan.

## 1. Introduction

Agriculture Pakistan's essential oil industry, though modest in scale, holds significant potential within the global market (Anjum, Muhammad, Siddiqui, Anjum, et al., 2024). In 2021-22, the country exported approximately \$4.68 million worth of essential oils, primarily to the United Arab Emirates, China, and the Netherlands (Khalid, 2023). Production is concentrated in select regions, with crops like mint, eucalyptus, and rose being prominent. However, the industry faces challenges such as limited technological advancement, lack of standardized extraction methods, and insufficient infrastructure for large-scale production. Despite these hurdles, recent studies indicate that smallholder-level distillation, coupled with improved agronomy and cooperative marketing, can enhance economic viability and quality control (Shahin et al., 2021). Globally, the essential oils market is experiencing rapid growth, driven by increasing demand in sectors like

cosmetics, aromatherapy, and food industries. The market size was valued at \$12.47 billion in 2024 and is projected to grow to \$27.82 billion by 2032, exhibiting a compound annual growth rate (CAGR) of 10.69% (Sonigra & Meena, 2025). Advancements in extraction technologies, such as supercritical CO<sub>2</sub> extraction, microwave-assisted hydro-distillation, and enzyme-mediated methods, have significantly improved oil yield and quality (Al-Mazroa et al., 2015). These innovations present Pakistan with opportunities to strengthen production capacity and integrate into the global value chain through sustainable and efficient extraction techniques. However, this study emphasizes the importance of steam distillation for eucalyptus essential oil extraction due to its relative advantages: the method is simple to install and operate, equipment can be locally manufactured at low cost, and it is more likely to be accepted and adopted by small landholders compared to advanced technologies.

Enhancing farmers' technical knowledge through participatory training can improve adoption of essential oil extraction practices, enabling income diversification, value addition, and more sustainable livelihoods for smallholders. Participatory field distillation demonstrations, led by agricultural extension personnel, have proven effective in bridging this knowledge-practice gap. Such initiatives involve farmers directly in the learning process, allowing them to observe and engage in the distillation of eucalyptus oil using appropriate technologies (Ahmad et al., 2023; Dhakad et al., 2018). Studies have shown that hands-on demonstrations significantly improve farmers' understanding and adoption of essential oil extraction practices, leading to increased oil yields and quality. For instance, research in the Pothwar region of Punjab assessed the adoption levels of essential oil extraction practices among lemon growers, highlighting the importance of practical demonstrations in promoting new technologies (Anjum, Muhammad, Siddiqui, & Yaseen, 2024). Additionally, research indicates that integrating value-added products like essential oils into agroforestry systems can improve profitability for small-scale farmers, emphasizing the need for targeted awareness campaigns and demonstration plots (Shukla et al., 2025).

Despite the economic potential of essential oil production in Pakistan, smallholder farmers continue to face low productivity and reduced income due to inadequate knowledge and limited exposure to modern extraction methods. Previous studies have documented traditional harvesting and distillation practices and highlighted the potential of essential oils for rural livelihoods; however, few have rigorously evaluated participatory training approaches to improve farmers' practical skills and adoption of improved techniques. In particular, the effectiveness of Training-of-Trainers (ToT) models in bridging the knowledge-practice gap remains underexplored. Without targeted interventions that directly address the knowledge-practice gap, opportunities for sustainable livelihood improvement and participation in the high-value essential oil market remain largely untapped.

By implementing such field-based interventions, Pakistan can empower smallholder farmers with the knowledge and skills necessary to enhance their productivity and income. This approach not only strengthens farmer livelihoods but also aligns with the global trend of quality-focused, sustainable essential oil production, ensuring that Pakistan can compete more effectively in international markets while improving rural economic resilience.

Consequently, the present study aims to evaluate the impact of participatory field distillation demonstrations on farmers' knowledge of eucalyptus essential oil extraction. It is hypothesized that the dissemination of information through participatory demonstration will significantly increase respondents' knowledge compared to their pre-intervention levels. By examining the effectiveness of such initiatives, the study seeks to provide insights into strategies that can empower farmers, enhance their livelihoods, and contribute to the growth of the essential oil industry in Pakistan. .

## 2. Materials and Methods

### Universe of Study

The study was conducted in Northern Punjab, Pakistan, located between the Indus and Jhelum rivers at approximately 73.07° E longitude and 33.6° N latitude. Among the four main districts in this region, this study focuses exclusively on registered smallholder eucalyptus growers in Attock District, Punjab, Pakistan, as the sampling frame (Figure 1). Findings are therefore applicable specifically to this population.

### Determination of sample size and data collection

A list comprising 520 registered eucalyptus crop growers was obtained from the Director of Agriculture (Extension and Adaptive Research) Attock. A sample size of 222 was determined using the formula for finite population correction formula (Yamane's formula) (Chaokromthong & Sintao, 2021). Hence, the initial sample size ( $n_0 = 385$ ) was calculated assuming a 95% confidence level, 5% margin of error, and maximum variability ( $p = 0.5$ ), and was subsequently adjusted for the homogeneous finite population of eucalyptus growers ( $N = 520$ ) using the Yamane correction formula (Eq. 1). Moreover, steam distillation was chosen as a low-cost, safe, and easy-to-operate method suitable for smallholder farmers, while solvent extraction and cold pressing are less practical locally.

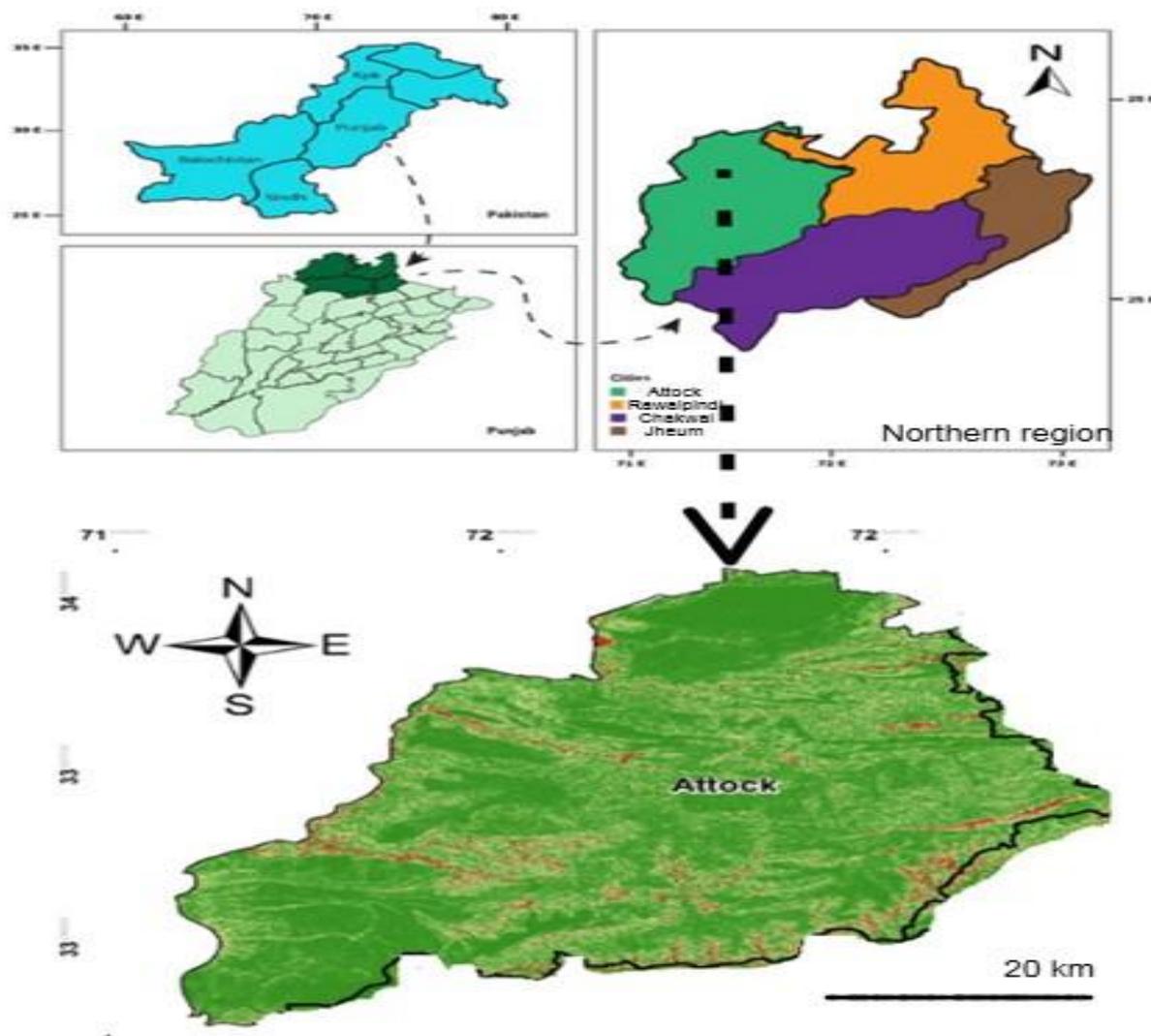
$$n = N * n^{\circ} \quad \text{Equ\#1}$$

$$N + n^{\circ} - 1$$

$$n = 520 \cdot 385 = 200,200$$

$$520 + 385 - 1 = 904$$

$$n = 222$$



**Figure 1.** Map of the study area

### Training Intervention

The study employed a training-of-trainers (ToT) approach previously used by the authors in related studies on essential oil extraction (EOE) practices. ToT specialists were selected from postgraduate students with an agricultural extension background and received prior hands-on training on EOE practices from a commercial essential oil processing facility. The trained specialists then conducted face-to-face, field-based training for the selected respondents using a pre-structured schedule, covering raw material selection, basic extraction procedures, and equipment handling. This careful selection of trainer responsibilities ensured the validity and effectiveness of ToT used in this study. A baseline survey was conducted

before the intervention, followed by a post-training assessment using the same research instrument. Detailed survey instrument is attached as supplementary material SA-1.

### Data analysis

After data collection, descriptive statistics were computed from the recorded values. The dataset was analyzed twice prior to, and then after, the on-farm distillation provided to the growers. A paired t-test was subsequently applied to assess differences in their knowledge levels of EOE practices. Finally, Multiple Correspondence Analysis (MCA) was used to examine the structural relationships among categorical variables in growers' perceptions rather than to assess the impact of the training intervention. The

details of growers' perceptions regarding eucalyptus essential oil production are summarized in Table 1 based on the MCA. This technique reduces complex categorical data

into fewer dimensions, making patterns and relationships easier to interpret, typically through a biplot (Husson & Josse, 2014).

**Table 1: Description of the categorical variables of eucalyptus oil**

Variable	Categories	Description
Awareness level	Low / Medium / High	Level of growers' knowledge regarding eucalyptus essential oil extraction.
Farm size	Small / Medium / Large	Landholding size under eucalyptus cultivation.
Market channel	Direct sales / Middleman / Export	Mode through which growers sell eucalyptus oil in local or international markets.

### 3. Results and Discussion

#### Participant Demographics

All respondents were male smallholders, mostly over 40 years old, with literacy up to middle or secondary school education. These characteristics reflect the typical profile of eucalyptus growers in the study area.

#### Pre-demonstration knowledge level of eucalyptus growers on essential oil extraction

Results indicated in Table 2 reveal that awareness of the optimal harvest stage for oil extraction was very low, with only 14% (n = 32) of respondents reporting knowledge,

while 86% lacked this understanding. Similarly, knowledge about mean crop yield per acre (24%), harvested plant material (22%), and the distillation unit (28%) was also limited. Technical aspects such as the installation procedure (21%), operational functions (13%), merits of the distillation unit (25%), safety measures (13%), and extraction time (9%) were largely unfamiliar to the majority, with over 70–90% of respondents reporting no prior knowledge. Likewise, knowledge about oil yield per acre was weak, with only 17% aware. In contrast, relatively higher awareness was observed for packing practices: 56% of growers were familiar with the use of plastic-based packaging, while 31% knew about PVC-based packaging.

**Table 2: Pre-demonstration knowledge level of eucalyptus growers on essential oil extraction**

Variables	Knowledge %(f)	
	Yes	No
Optimal harvest stage for oil extraction	14(32) ± 0.023	86(190) ± 0.020
Mean crop yield per acre	24(54) ± 0.028	76(168) ± 0.022
Harvested plant material for oil extraction	22(49) ± 0.025	78(173) ± 0.027
Essential oil distillation unit	28(63) ± 0.03	72(159) ± 0.031
Components and installation procedure of the unit	21(46) ± 0.017	79(176) ± 0.028
Operational functions of the distillation unit	13(29) ± 0.012	87(193) ± 0.022
Merits of using a distillation unit	25(56) ± 0.028	75(166) ± 0.029
Safety measures prior to oil extraction	13(29) ± 0.023	87(193) ± 0.022
Extraction time (hours)	09(21) ± 0.016	91(201) ± 0.019
Oil yield per acre (kg)	17(38) ± 0.021	83(184) ± 0.025
Plastic-based packing material for essential oil	56(125) ± 0.023	44(97) ± 0.033
PVC-based packing material for essential oil	31(69) ± 0.031	69(153) ± 0.030

Note: figures in parenthesis are frequencies | '±' = 'standard error'

Note: Yes/No responses were coded as binary variables (1 = Yes, 0 = No) and analyzed as proportions; standard errors therefore represent sampling variability.

The eucalyptus growers in Punjab had limited prior knowledge regarding most technical aspects of essential oil extraction before receiving training. The findings clearly demonstrate that eucalyptus growers possessed very limited baseline knowledge of essential oil extraction prior to their participation in the training of trainer's program. This

knowledge gap is most evident in critical technical areas such as harvest timing, distillation procedures, and operational safety, where more than 70–90% of respondents reported having no prior understanding. Such deficiencies are consistent with earlier reports that rural farmers in Pakistan often rely on traditional practices and lack access

to specialized knowledge regarding essential oil production (Anjum, Muhammad, & Siddiqui, 2024; Anjum, Muhammad, Siddiqui, Anjum, et al., 2024). The relatively higher awareness of packaging practices may reflect farmers' prior experience in marketing agricultural products, where plastic and PVC materials are commonly used, rather than specific knowledge of essential oil preservation. The very low awareness of *extraction time and oil yield parameters* highlights a disconnect between growers' existing practices and scientific recommendations, which is likely to limit both productivity and quality of eucalyptus oil if not addressed. These results justify the need for structured capacity-building interventions, as also emphasized by Riaz et al., (2021) who noted that targeted training significantly improves growers' technical skills and adoption of improved distillation methods. Overall, the data underscores the importance of pre-training assessments to identify critical knowledge gaps, ensuring that training programs are designed to enhance growers' understanding of optimal harvesting, distillation techniques, and safety practices for sustainable essential oil production in Punjab.

#### Post-demonstration knowledge level of eucalyptus growers on essential oil extraction

These findings of table 3 reveal substantial knowledge gains among eucalyptus growers. For the optimal harvest stage, 62% (56% good, 6% excellent) reported strong understanding, while 31% rated average. Similarly, knowledge of the mean oil yield per acre improved, with 55% (46% good, 9% excellent) reporting higher competence, compared to 19% average and 27% fair. For harvested plant material, 31% rated good/excellent, while a majority (53%) still considered their knowledge average. In the case of the distillation unit, 50% (42% good, 8% excellent) expressed higher confidence, whereas 32% rated average. Moreover, knowledge of installation procedures was more moderate, with 28% rating good/excellent and 54% average. Similarly, operational functions received 51% good/excellent responses, while 27% rated average. The merits of using a distillation unit were viewed positively by 30% of growers, though 51% remained average. For safety measures, 58% (49% good, 9% excellent) showed improved knowledge, while 26% remained average. In the case of extraction time, 31% rated it good and no excellent, with 55% still at the average level. Finally, PVC-based packing material knowledge improved, with 36% rating good/excellent, though 44% remained average.

**Table 3: Post-demonstration knowledge level of eucalyptus growers on essential oil extraction**

Variable	Knowledge response %(f)				
	1	2	3	4	5
Optimal harvest stage for oil extraction	0(0) ±0.0	07(15) ±0.016	31(69) ±0.030	56(125) ±0.033	6(13) ±0.016
Mean oil yield per acre	0(0) ±0.0	27(59) ±0.030	19(42) ±0.026	46(101) ±0.033	9(20) ±0.019
Harvested plant material for oil extraction	0(0) ±0.0	16(36) ±0.025	53(116) ±0.033	28(60) ±0.030	3(10) ±0.014
Essential oil distillation unit	0(0) ±0.0	18(41) ±0.026	32(72) ±0.031	42(91) ±0.033	8(18) ±0.018
Components and installation procedure of the unit	0(0) ±0.0	18(39) ±0.026	54(121) ±0.033	21 (46) ±0.027	7(16) ±0.017
Operational functions of the distillation unit	0(0) ±0.0	22(49) ±0.027	27(61) ±0.030	46(101) ±0.033	5(11) ±0.014
Merits of using a distillation unit	3(7) ±0.0	16(35) ±0.025	51(114) ±0.033	25(56) ±0.028	5(10) ±0.014
Safety measures prior to oil extraction	2(4) ±0.0	14(32) ±0.023	26(57) ±0.028	49(109) ±0.033	9(20) ±0.019
Extraction time (hours)	0(0) ±0.0	14(31) ±0.023	55(122) ±0.033	31(69) ±0.030	0(0) ±0.00
PVC-based packing material for essential oil	0(0) ±0.0	20(44) ±0.027	44(99) ±0.033	25(55) ±0.028	11(24) ±0.02

Note: Response scale: "1 =poor, 2 =fair, 3 = average, 4 = good, 5= excellent"; ± = 'standard error'; Pre = Responses recorded before demonstration training; Post = Responses recorded after demonstration training.

The results demonstrate that the training and demonstration sessions were effective in enhancing growers' knowledge of

eucalyptus essential oil extraction. Compared to the baseline findings, where knowledge levels were very low, post-

demonstration ratings shifted markedly toward the “good” and “excellent” categories, particularly for critical factors such as *harvest stage*, *oil yield per acre*, *distillation unit*, and *safety measures*. These improvements are consistent with previous studies which reported that hands-on training and demonstrations significantly increase farmers’ technical knowledge and confidence in adopting improved practices (Roy et al., 2013; Singh et al., 2018).

However, certain areas such as *installation procedures* and *extraction time* still received predominantly “average” ratings, suggesting that these more technical aspects may require repeated exposure, practical exercises, or follow-up sessions to ensure full comprehension. Similar challenges were noted by Manning (2024), who found that farmers often struggle to grasp complex technical processes without continuous guidance. Interestingly, packaging knowledge (PVC-based materials) showed broader variation in responses, reflecting growers’ differing levels of prior experience with marketing and storage practices.

Overall, these findings confirm that demonstration-based learning is a powerful tool for bridging knowledge gaps in essential oil extraction, especially for eucalyptus growers in Punjab. Yet sustained improvements will depend on continuous extension support, refresher training, and opportunities for farmers to practice and refine their skills in real-world settings.

**Pre- and Post-Demonstration Comparison of Knowledge Levels among eucalyptus aromatic crop growers**

A comparative analysis of pre- and post-demonstration responses among small landholders revealed substantial improvements in their knowledge and perceptions regarding essential oil extraction technology. These differences were further validated through one-tailed paired *t*-tests, confirming significant knowledge gains in the post-training

**Table 4: Paired t-test Results**

Variable	Mean (Pre)	Mean (Post)	Mean (Diff)	t_value	p_value
Harvest Stage	1.89	3.20	1.32	14.78	0.00
Extraction Time	1.80	2.72	0.92	10.04	0.00
Oil Yield	1.93	2.73	0.80	11.32	0.00
Harvested Material	1.79	3.13	1.33	16.68	0.00
Distillation Unit	1.50	2.50	0.99	10.40	0.00
Installation Procedure	1.97	2.28	0.30	4.38	0.00
Operational Functions	2.20	2.81	0.61	7.57	0.00
Distillation Merits	1.64	2.70	1.05	14.16	0.00
Safety Measures	1.78	2.99	1.22	12.86	0.00
PVC Packing	1.50	2.36	0.86	9.26	0.00

Note: p-value: <0.05 = “statistically significant”

phase. The magnitude of change across specific knowledge domains was further quantified using Cohen’s *d* effect sizes, as illustrated in the forest plot.

H<sub>1</sub>: The knowledge levels of aromatic crop growers are significantly higher after the demonstration than before.

H<sub>1</sub>:  $\mu_{post} > \mu_{pre}$

**Paired t-test**

Pre-demonstration knowledge was recorded as Yes/No (coded 1 = Yes, 0 = No), while post-demonstration knowledge was recorded on a 5-point Likert scale. Paired *t*-tests were conducted on the numeric coding to approximate changes in mean knowledge scores (Table 4), and effect sizes and overall trends were also analyzed to summarize improvements, emphasizing associations rather than strict pre–post comparisons. The study relied on self-reported data, which may be subject to recall or reporting bias, though pre- and post-demonstration assessments were used to reduce this risk.

While the paired *t*-test results (Table 4) confirmed statistically significant improvements across most training variables, the effect size analysis and corresponding forest plot provided deeper insights into the magnitude of these changes. This dual approach ensures that both statistical significance and practical significance are addressed, strengthening the reliability of the findings.

The one-tailed paired *t*-test revealed a statistically significant increase in the knowledge levels of aromatic crop growers following the demonstration ( $p < 0.05$ ). This finding confirms that the training intervention effectively enhanced growers’ understanding compared to their pre-demonstration knowledge. Substantial mean differences were observed across most variables, with  $p$ -values  $< 0.001$ .

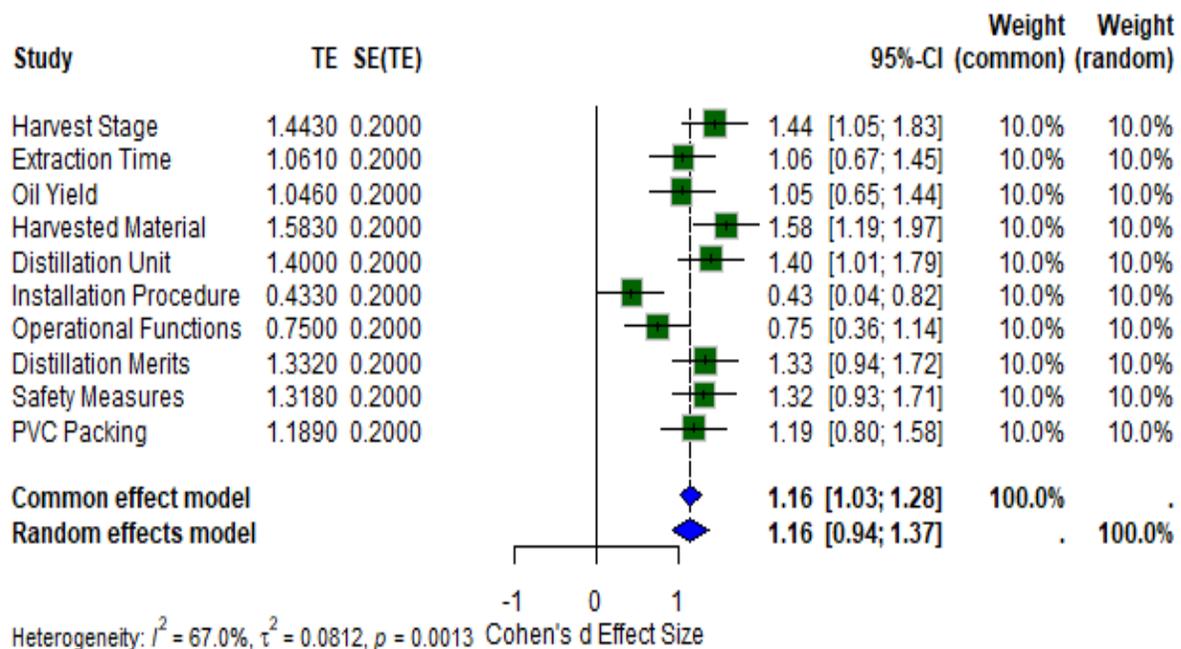
While this study focused on participatory training and field demonstrations to enhance the adoption of Eucalyptus Essential Oils technology, it is recognized that socio-economic factors such as access to credit, land tenure, and income also influence technology adoption, and barriers limiting adoption as reported in previous studies (Anjum et al., 2024). The findings confirm that the demonstration-based training produced significant positive shifts in essential oil extraction practices among growers. Large effect sizes across multiple domains suggest that the training-of-trainers approach was highly effective in transferring practical knowledge. The very large improvements in harvest-related variables indicate that growers quickly adopted more appropriate harvesting and material handling practices, which are critical for maximizing oil yield and quality. The smaller effect on installation procedures may reflect the technical complexity of equipment setup, which often requires continued technical support beyond initial training.

These results are consistent with prior extension research showing that hands-on demonstrations enhance knowledge

retention and practice adoption more effectively than traditional learning approaches (Nettle et al., 2022; Prajapati et al., 2025). The observed effect sizes exceed the conventional benchmark for educational interventions, underscoring the strong practical impact of the training program.

**Cohen’s d effect sizes**

The forest plot (Figure 2) visually illustrates the magnitude and confidence intervals of these effect sizes, effected by Cohen’s *d*, confirming the substantial overall impact of the intervention. The pooled analysis indicated a large overall effect (Cohen’s *d* = 1.16), which was statistically significant under the common-effect model (95% CI: 1.03–1.28) and consistent under the random-effects model (95% CI: 0.94–1.37). Strongest effects were observed in most training attributes such as harvested material (*d* = 1.58), harvest stage (*d* = 1.44), and distillation unit (*d* = 1.40), while installation procedure (*d* = 0.43) and operational functions (*d* = 0.75) showed comparatively weaker contributions. Heterogeneity was substantial ( $I^2 = 67.0\%$ ,  $p = 0.0013$ ), suggesting variability across factors.



**Figure 2.** Forest Plot of Cohen’s d Effect Sizes for Knowledge Gains on Essential Oil Extraction Technology (Pre- vs. Post-Demonstration)

Note: Effect sizes (Cohen’s *d*) indicate the magnitude of knowledge improvement across domains; error bars represent 95% confidence intervals; Cohen’s *d*: ‘small effect’ = 0.2; ‘medium effect’ = 0.5; ‘large effect’ = 0.8 or above.

Positive values indicate significant gains, supporting the one-tailed test hypothesis of increased knowledge post-training.

The findings of this study highlight the perceived importance of specific factors influencing essential oil extraction among eucalyptus growers in Punjab, Pakistan. The forest plot revealed a significant overall effect, particularly emphasizing *harvest stage*, *harvested material*, and *distillation unit* as the strongest contributors. These results align with earlier research indicating that the timing of harvest and the quality of plant material substantially determine oil yield and composition in Eucalyptus species (Achmad et al., 2018; Heikal, 2017).

Similarly, the role of distillation equipment has been emphasized by Machado et al., (2024), who demonstrated that improvements in distillation design enhance recovery and maintain oil quality. While moderate effects were noted for operational and safety measures, the relatively weaker contributions of installation procedure and operational functions may reflect growers limited technical expertise or resource constraints during training programs. The observed heterogeneity ( $I^2 = 67\%$ ) suggests that not all factors exert uniform influence across growers, which could be attributed to variability in local practices, access to technology, and differences in training adoption levels. Comparable findings were reported by Karki (2020) in Pakistan, where farmers' perceptions of distillation methods and harvesting techniques varied with their exposure to extension services and prior experience.

While government and NGO programs in Punjab provide general agricultural extension and training support, few initiatives focus specifically on participatory, field-based training for essential oil extraction, aside from some past projects on non-eucalyptus species. The hands-on Training-of-Trainer's approach used in this study allowed smallholder farmers to directly engage with distillation processes, potentially offering more effective knowledge transfer and practice adoption than conventional programs. The participatory ToT approach demonstrated in this study could be institutionalized within Pakistan's agricultural extension system by integrating it into ongoing farmer capacity-building programs. Leveraging existing extension staff and field officers could facilitate wider adoption and sustainability of essential oil extraction practices among smallholders. Overall, the results justify that while growers

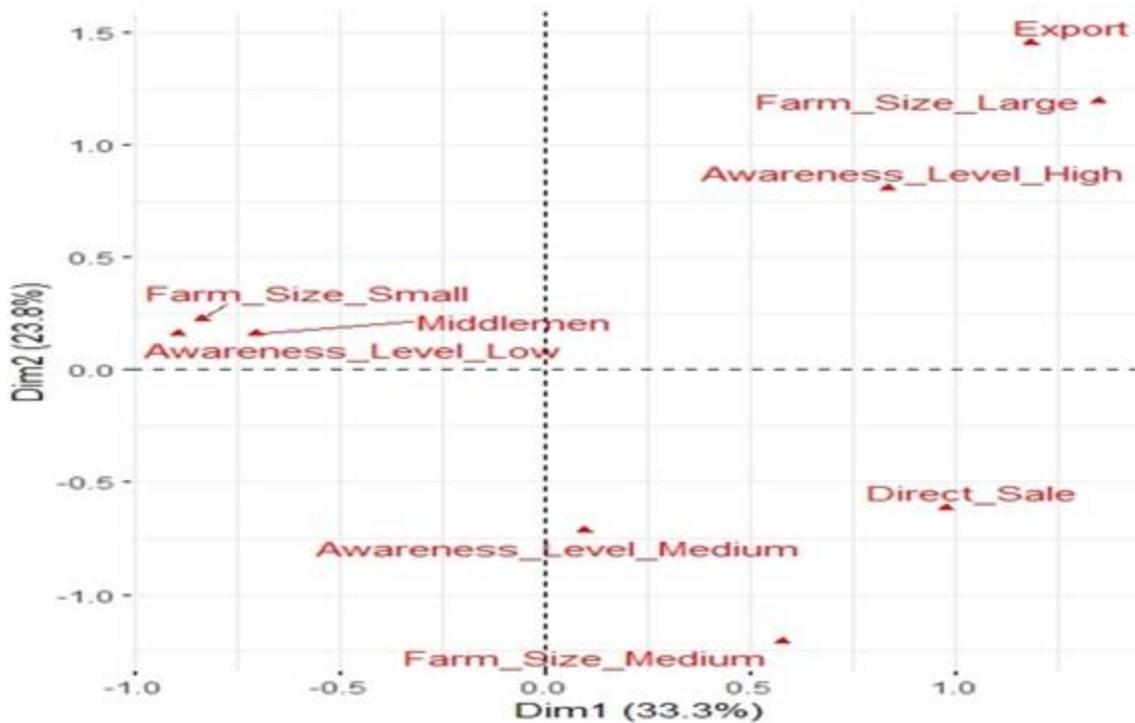
acknowledge multiple determinants of oil extraction, targeted interventions focusing on harvest timing, raw material quality, and improved distillation practices are most likely to enhance the efficiency and sustainability of eucalyptus oil production in the region.

These findings highlight that hands-on demonstrations and Training-of-Trainers (ToT) approaches are highly effective in enhancing growers' technical competencies in key operational areas. In contrast, installation procedures and operational functions showed relatively smaller effects, suggesting that these aspects may require additional targeted training or follow-up sessions to ensure sustained adoption. Overall, the forest plot clearly illustrates that the intervention successfully bridged critical knowledge gaps, strengthened growers' confidence in essential oil extraction, and can serve as a model for capacity-building strategies in similar agricultural extension contexts.

### Multiple Correspondence Analysis (MCA) Results

Multiple Correspondence Analysis (MCA) was applied as an exploratory tool to examine structural relationships among farm size, market channel, and awareness level among eucalyptus oil growers, rather than to assess training effects. The first two dimensions explained 57.1% of the total inertia, capturing most of the variation in the categorical variables. The MCA biplot (Figure 3) revealed distinct clusters: small-scale farmers were closely associated with local markets and lower awareness, large-scale farmers clustered with contract/export markets and higher awareness, and medium-scale farmers fell between these groups, reflecting intermediate market engagement and awareness levels. Eigen values are presented in supplementary table SA-2.

While this study did not explicitly assess climate resilience, the adoption of eucalyptus cultivation and essential oil extraction can contribute to farm-level adaptation. Eucalyptus is a drought-tolerant crop, and essential oil production provides an alternative income source, helping smallholders diversify their livelihoods and reduce vulnerability to climate variability. However, the promotion of eucalyptus cultivation for essential oil production could theoretically reduce land available for food crops, in this study most smallholders used marginal or less productive plots. As a result, income diversification through essential oil production is unlikely to negatively affect local food security and may instead enhance smallholders' resilience.



**Figure 3.** Multiple Correspondence Analysis (MCA) showing relationships among categorical variables

Note: MCA biplot of farm size, market channel, and awareness level of the respondents, with the first two dimensions explaining 57.1% of total inertia.

The correlations, which show distinct trends of commercialization and market integration, imply that farm size is highly correlated with awareness level and market channel. These trends provide valuable insights into extension and policy targeting by illuminating the underlying structure of farmers' decisions and awareness across several categories. This suggests that farmer traits are not independent; rather, they create typologies in which awareness, market accessibility, and farm size all work together to influence market involvement for eucalyptus oil. The clustering patterns demonstrate the importance of customized extension strategies, which enable awareness campaigns to be tailored to the needs of different grower types. Increasing small-scale farmers' knowledge may facilitate their entry into official markets, boosting supply chain efficiency and revenue opportunities. These results are in line with earlier research on smallholder commercialization, which found that market accessibility and awareness are important factors influencing value chain involvement (KC et al., 2022). Furthermore, Nguyen et al (2021) demonstrated that farm size and market accessibility had a substantial impact on awareness and adoption behaviors in non-timber forest product value chains. The technology used in this study is low-risk, simple to operate, and does not pose significant long-term health or safety

concerns beyond the immediate training sessions. Hence, adoption of distillation technology appears feasible for smallholder farmers, as local manufacturing support can provide affordable units. While initial costs may still be a consideration, targeted support and simple financing mechanisms can enable uptake without imposing undue financial burden.

#### 4. Conclusion

The study concludes that capacity-building efforts rooted in hands-on, participatory methods can bridge critical knowledge gaps among small landholders. Such training not only improves growers' technical competency but also fosters greater confidence in adopting and applying essential oil extraction technologies. By strengthening farmers' skills, the intervention contributes to the broader goals of sustainable resource utilization, income diversification, and rural development through aromatic crop-based enterprises. Before the training, growers had limited understanding of critical aspects such as harvest timing, selection of plant material, distillation unit operation, extraction procedures, and safety measures, which constrained their ability to fully benefit from eucalyptus cultivation.

Post-demonstration results revealed substantial improvements, with most participants moving from poor or

fair ratings to good and excellent levels of understanding, particularly in areas like optimal harvest stage, safe distillation practices, and packaging methods. These improvements were statistically validated through paired *t*-tests and further supported by strong Cohen's *d* effect sizes, emphasizing the practical significance of the change. The findings highlight that hands-on, participatory training not only bridges key knowledge gaps but also builds growers' confidence in adopting essential oil extraction technologies, thereby contributing to sustainable resource use, income diversification, and the promotion of aromatic crop-based rural enterprises.

This study was limited to a specific group of small landholders in Punjab, Pakistan, which may not fully represent growers in other regions. The research employed pre-post design without a control group, which limits the ability to draw strong causal conclusions regarding the observed changes in knowledge and practices. In addition, knowledge improvement was assessed only in the short term, immediately after the demonstration, without follow-up to evaluate long-term retention or practical application in the field. This study did not analyze social or peer-learning interactions within the community, which may also influence adoption of essential oil extraction practices. Furthermore, reliance on self-reported data may have introduced response bias or led to an overestimation of actual knowledge gains. Sensitivity and subgroup analyses across different farmer typologies were not conducted and are acknowledged as a study limitation.

Future research could track actual adoption of essential oil extraction technologies to assess how knowledge and skills gained through participatory training translate into sustained practice. Second, exploring women's participation more fully, could inform gender-inclusive strategies, as their involvement may influence adoption, management practices, and overall outcomes. It should incorporate control or comparison groups, longitudinal follow-ups to assess sustained adoption, and broader geographic coverage across diverse agro-ecological regions to enhance causal inference and generalizability. Similarly, Future studies could consider environmental and sustainability aspects of eucalyptus cultivation, including water use and potential ecological impacts, to ensure that essential oil production remains environmentally responsible. Further, research could examine value-chain factors to enhance smallholders' market access and adoption of eucalyptus essential oil technologies.

## Policy Implications

The findings suggest that policy efforts should prioritize integrating the proposed approach into existing national extension systems rather than creating parallel structures. This includes embedding it within district-level extension services, providing targeted training for extension personnel, and adopting a phased scaling strategy supported by dedicated funding. Continuous monitoring and feedback mechanisms are essential to ensure effective and sustainable implementation.

## 5. References

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### Supplementary Table S-A1

Dim	Eigenvalue	% of Variance	Cumulative %
1	0.45	33.3	33.3
2	0.32	23.8	57.1

Note: Eigenvalues were obtained from MCA analysis in R (FactoMineR). The first two dimensions, explaining 57.1% of total variance, are illustrated in Figure 4