Land Management and Utilization
https://ojs.ukscip.com/index.php/lmu

Article

Meta Regression of Pine Needle Fuel Loads and Combustion Efficiency for Forest Fire Risk Management in Uttarakhand

Harshit Pant

G.B. Pant National Institute of Himalayan Environment (GBPNIHE), Almora 263643, India; harshit.pantj@gbpihed.nic.in

Received: 8 February 2026; **Revised:** 25 April 2026; **Accepted:** 29 May 2026; **Published:** 8 June 2026

Abstract: Chir pine (*Pinus roxburghii* Sarg.) forests of Uttarakhand, India, accumulate large quantities of needle litter (pirul) that constitute the primary surface fuel driving pre-monsoon forest fires across the Indian Himalayan Region. This study quantified fuel load distribution, burn efficiency (BE), and temporal combustion dynamics of pine needle litter through 53 controlled open-air combustion trials conducted over 22 collection days (20 May–12 June 2020), analyzed using a meta-regression framework. Mean pre-combustion fuel load was 7,847.5 ± 924.4 g sample^{-1} and mean BE was 70.76 ± 5.20% (range: 54.82–81.54%). Neither fuel load nor collection day significantly predicted BE (both $p > 0.05$, $R^2 < 0.04$), indicating that within the pre-monsoon window, these covariates are not meaningful determinants of combustion completeness. Between-day heterogeneity was extremely high ($I^2 = 96.9\%$, Cochran's Q = 678.8, $p < 0.001$, $\tau^2 = 13.03$), demonstrating that unmeasured meteorological variables principally ambient relative humidity and fuel moisture content drive virtually all real day-to-day variation in combustion performance. Post-combustion residue mass was significantly predicted by pre-combustion fuel load ($r = 0.421$, $p = 0.002$), providing a useful mass balance relationship for biomass energy applications. Total litter collected was 439.5 kg across 22 days, supporting the operational assumptions of the 'Pirul Lao, Paisa Pao' briquette scheme. These results demonstrate that static BE parameterization in fire danger rating systems is ecologically unsupported, and advocate for weather-coupled dynamic fire risk modelling incorporating real-time fuel moisture monitoring in Uttarakhand forest management.

Keywords: Pine Needle Litter; Fuel Load; Burn Efficiency; Forest Fire Risk; Meta-Regression; Heterogeneity; Uttarakhand

1. Introduction

The Chir pine (*Pinus roxburghii* Sarg.) is the dominant conifer across the submontane and lower montane zones of the Indian Himalayan Region (IHR), occupying approximately 16% of Uttarakhand's total forest area and large tracts of Himachal Pradesh and Jammu & Kashmir [1–3]. The species is characterized by its prolific and near-continuous shedding of needle litter, locally termed 'pirul', onto the forest floor throughout the year. The waxy, resinous cuticle of Chir pine needles substantially resists microbial decomposition relative to broadleaf litter, resulting in progressive accumulation of a thick, dry litter mat during the extended dry season. In undisturbed stands, this accumulation can exceed 10–12 tonnes per hectare, representing an enormous reservoir of surface combustible material [4–6]. During the pre-monsoon period (broadly April–June), when afternoon relative humidity falls below 20%, daytime maximum temperatures regularly exceed 35 °C, and dry northwesterly winds intensify, this litter layer transitions from a passive component of the forest floor nutrient cycle into the dominant surface fuel that

https://doi.org/10.54963/lmu.v2i2.100325

initiates, sustains, and propagates fire at rates capable of overwhelming suppression efforts [7,8].

Forest fire in Uttarakhand is a chronic, large-scale, and intensifying ecological and socio-economic problem. The Forest Survey of India (2021) documented over 1,200 fire incidents during the 2020–2021 fire season alone, continuing a multi-decadal trend of increasing fire frequency and area burned that has been linked to climate-driven warming and lengthening dry seasons, combined with the decline of traditional community-based litter collection practices that historically moderated fuel accumulation [9–12]. The ecological consequences of repeated surface fires in Chir pine forests are well-documented and severe. They include suppression of understory plant biodiversity through elimination of shade-tolerant regeneration, reduction of soil organic matter and nutrient capital, acceleration of soil erosion on the characteristically steep Himalayan slopes, degradation of watershed function and stream flow regulation, and long-term shifts in stand structure and species composition [2,5,11–13]. For local communities that depend on these forests for firewood, fodder, non-timber forest products, and water regulation, the cumulative economic and livelihood costs are substantial. The problem is compounded by the observation that fire-prone pirul-dominated stands generate little commercial timber value, reducing the economic incentive for private investment in fire prevention infrastructure.

Despite the ecological and economic significance of pine needle litter fires, systematic empirical characterization of the combustion properties of pirul under realistic field conditions remains surprisingly limited in the published literature [14,15]. Most operational fire risk management in Uttarakhand and across the IHR relies on static seasonal fuel load estimates derived from forest type classifications, combined with national fire danger rating indices based on broad climatological parameters such as monthly temperature normal and accumulated dry-period duration [9,10]. These approaches do not account for the substantial day-to-day variation in litter moisture content and combustion potential that characterizes the pre-monsoon transition period, and consequently may systematically mis-estimate fire danger on both the high and low ends. Critically, the actual per-sample fuel load available for combustion on any given collection day, and its realized burn efficiency under ambient atmospheric conditions, have not been rigorously quantified through replicated, spatially distributed field trials in Uttarakhand.

The emergence of dynamic fire risk modelling as an international best-practice framework represents a conceptually important departure from static approaches [15–17]. Dynamic models integrate real-time or near-real-time meteorological measurements particularly relative humidity, air temperature, wind speed, and precipitation history with spatially explicit fuel moisture estimation algorithms and fire behavior propagation models to generate continuously updated fire danger products. The theoretical and empirical basis for this approach is well-established: fuel moisture content (FMC) is the single most powerful predictor of surface litter ignitability and fire spread rate across a wide range of forest types [18,19]. In conifer-dominated systems, fine dead fuel moisture typically tracks ambient humidity with a lag of 1–6 h, and the relationship between FMC and ignition probability follows a strongly nonlinear threshold function. Despite the demonstrated superiority of dynamic models over static danger rating approaches in Mediterranean, boreal, and temperate systems, their deployment in the IHR remains nascent, reflecting in part the lack of empirical combustion data from local forest types needed to parameterize and validate such models [12,15,17–19].

A secondary and practically important dimension of pirul management in Uttarakhand concerns its potential as a renewable biomass energy feedstock. The Government of Uttarakhand launched the 'Pirul Lao, Paisa Pao' (Bring Pirul, Earn Money) scheme in 2019, which provides financial incentives for rural community members to collect and deliver pine needle litter to designated biomass collection and briquetting centers [19–21]. The policy rationale is dual: simultaneous reduction of surface fuel load to lower fire risk, and generation of supplementary rural income from a currently unvalued or negatively valued forest product. The calorific value of Chir pine needle briquettes has been variously reported at 4,200–4,800 kcal kg^{-1}, comparable to sub-bituminous coal and substantially exceeding air-dried hardwood fuel [21,22]. However, the commercial and energetic viability of the scheme depends critically on consistent combustion performance: briquette buyers, industrial consumers, and energy planners require reliable burn efficiency data to underwrite purchasing contracts and energy balance calculations. There is therefore direct demand for empirical, field-based quantification of pine needle litter burn efficiency under ambient conditions.

Meta-regression is an extension of meta-analysis developed primarily within medical and epidemiological research to model variation in effect sizes across studies as a function of study-level moderator variables [23,24]. The central statistical innovation of meta-regression relative to conventional regression is its explicit partitioning of total outcome variance into within-study (sampling error) variance and between-study (true heterogeneity) variance, with the latter quantified through Cochran's Q, the I^2 statistic, and the between-study variance component τ^2 [25–28]. When this framework is applied to repeated within-study measurements as in the present case (**Figure 1**), where each collection day constitutes an analytical unit equivalent to an independent study it enables a level of inferential rigor regarding between-day combustion variability that conventional one-way ANOVA or simple regression cannot provide. Specifically, meta-regression can determine whether the observed between-day variation in burn efficiency exceeds what would be expected from within-day sampling error alone, and whether measured covariates (fuel load, collection day) account for a statistically significant portion of this heterogeneity [25,27,29,30].

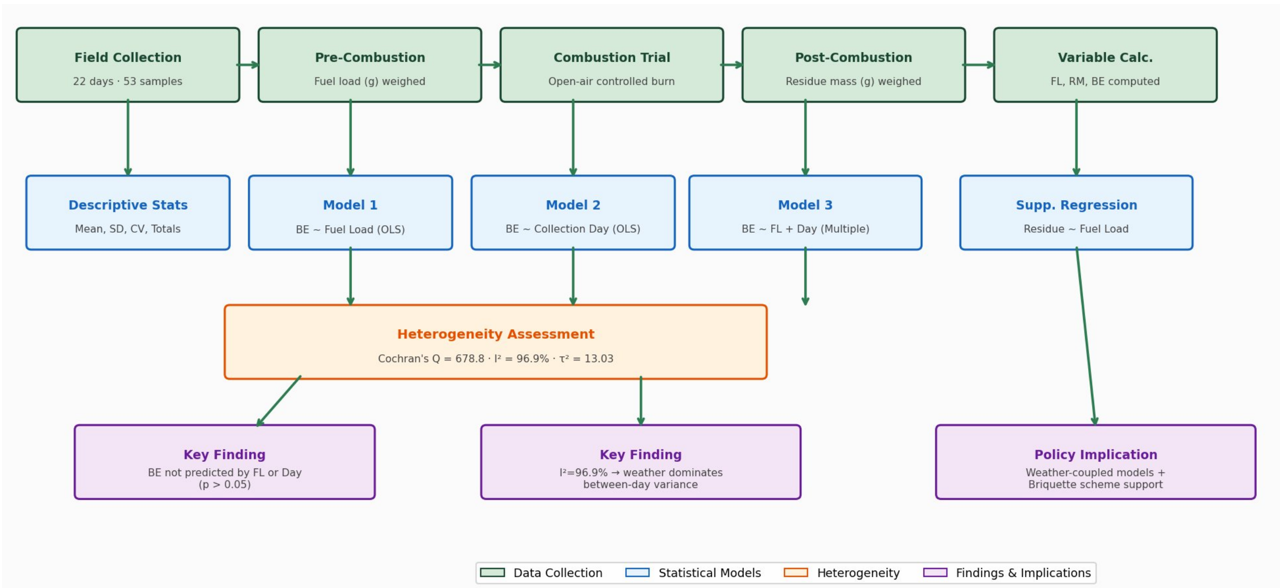


Figure 1. Meta-Analysis Workflow: Pine Needle Combustion Study.

The present study addresses four specific objectives arising from this context: (i) to characterize the distribution, central tendency, and variability of pine needle fuel load and burn efficiency across a structured 22-day, 53-sample field combustion dataset; (ii) to apply meta-regression to formally assess whether daily mean fuel load and collection day number are significant predictors of daily burn efficiency; (iii) to quantify between-day heterogeneity in burn efficiency using Cochran's Q, I^2, and τ^2, and to interpret this heterogeneity in terms of its probable meteorological drivers; and (iv) to synthesize the empirical and statistical findings into specific, evidence-based recommendations for dynamic fire risk parameterization, operational fire management planning, and the optimization of the 'Pirul Lao, Paisa Pao' briquette production scheme in Uttarakhand.

2. Materials and Methods

2.1. Study Area and Ecological Context

Combustion trials were conducted in Chir pine (*Pinus roxburghii*)-dominated forests of Uttarakhand, India, within the submontane belt of the Kumaon Himalaya. All field operations were based at the G.B. Pant National Institute of Himalayan Environment (GBPNIHE), Kosi-Katarmal, Almora district (approximately 29.6° N, 79.4° E; elevation approximately 1,250 m above sea level). The Kosi-Katarmal area supports extensive Chir pine stands on south-facing slopes with thin, rocky soils and a pronounced dry season lasting from November through May. *Pinus roxburghii* in this belt forms nearly monospecific, open-canopied stands with sparse understory vegetation and a thick, unbroken surface litter mat. The suppression of understory plant diversity is attributable to a combination of physical shading by the dense litter layer, allelopathic compounds leached from decomposing needles, and recurrent low-intensity surface fires that periodically consume the litter mat and set back woody seedling establishment [26–30].

The study period of 20 May to 12 June 2020 was deliberately selected to coincide with the late pre-monsoon dry season, when ambient conditions produce maximum needle litter combustibility and the frequency and severity of forest fire events in Uttarakhand reaches its seasonal peak [10]. During this period, the meteorological regime at the study elevation is characterized by daily maximum temperatures of 28–38 °C, minimum relative humidity in the afternoon of 15–30%, and periodic intrusions of dry north-westerly winds that can temporarily suppress humidity below 15%. The pre-monsoon period at these elevations is also characterized by considerable day-to-day atmospheric variability associated with the progressive northward advance of the Inter-Tropical Convergence Zone (ITCZ) and the Bay of Bengal moisture flux, resulting in episodic cloud cover, occasional pre-monsoon showers, and sharp fluctuations in humidity that can re-wet surface litter transiently before conditions dry out again [31–33]. This atmospheric instability is of direct relevance to the interpretation of the combustion data presented in this study.

2.2. Sample Collection Protocol

Pine needle litter was collected manually by trained field personnel from representative forest floor plots at multiple sites within the Kosi-Katarmal forest tract. Sites were selected subjectively to represent a range of stand density and slope conditions while avoiding areas with obvious recent disturbance (e.g., recent burning, heavy grazing, or mechanical clearing). On each sampling day, two or three independent samples were collected at spatially separate locations, with the objective of capturing within-day spatial variability in litter condition while maintaining a manageable daily workload. This protocol yielded 56 raw sampling records across the study period.

Each sample was constructed as a bundle of accumulated surface litter standardized to a pre-combustion mass of approximately 7–10 kg, reflecting the typical unit of collection used by pirul collectors under the 'Pirul Lao, Paisa Pao' scheme [34,35]. Litter was collected from the full depth of the accumulated mat, including both recently shed needles from the surface and older, partially fragmented material from deeper layers, to represent the composite fuel available for combustion rather than exclusively fresh material [36,37]. Pre-combustion mass was recorded using a calibrated spring balance with a precision of ±50 g immediately prior to each trial. No artificial drying, sieving, or pre-conditioning was applied: samples were burned in the ambient moisture state in which they were collected, ensuring that the results reflect realistic field combustion conditions rather than laboratory-optimized performance.

2.3. Controlled Combustion Trials

Combustion trials were conducted as open-air burns on cleared, flat mineral soil surfaces at each collection site, using a standardized protocol designed to ensure comparability across days and sites. Each bundle was placed on the cleared surface and ignited using a standardized flame source applied to the base of the bundle, simulating the ground-level ignition pattern of natural surface fires in these forests. The ignition procedure was held constant across all trials with respect to flame exposure duration (10 s) and point of application (base perimeter of bundle).

Combustion was allowed to proceed to complete natural cessation, defined operationally as the simultaneous absence of visible flaming, absence of visible smoldering, and absence of smoke emission, confirmed by continuous visual monitoring over a minimum post-flame observation period of 10 min. This conservative definition of combustion completeness was adopted to ensure that all latent smoldering within the bundle interior had concluded before residue mass was recorded. Following confirmation of complete cessation, the residue (ash, char, and incompletely combusted material) was allowed to cool for a minimum of 30 min under ambient conditions before post-combustion mass was recorded on the calibrated spring balance.

Three samples required exclusion from the final dataset: one sample lacked a valid post-combustion measurement due to an equipment recording error; two additional samples were associated with a malformed date entry that could not be unambiguously resolved and were therefore retained for whole-sample descriptive statistics but excluded from the temporal meta-regression analysis. The final analytical dataset therefore comprised n = 53 samples with complete pre- and post-combustion measurements distributed across k = 22 collection days, with 2–3 samples per day.

2.4. Variable Definitions and Derivation

Four primary variables were derived from the raw measurements. Fuel Load (FL, grams) was defined as the pre-combustion mass of each sample bundle. Residue Mass (RM, grams) was defined as the post-combustion mass of ash and char. Burn Efficiency (BE, %) was calculated as:

$$BE = [(FL - RM)/FL] \times 100$$

This metric represents the proportion of original fuel mass that was volatilized during combustion, encompassing both complete oxidation to CO_2 and H_2O and partial volatilization of organic compounds during flaming and smoldering phases. It is distinguished from combustion efficiency in the thermodynamic sense (which relates to heat release relative to theoretical maximum) but provides a practically meaningful measure of fuel consumption directly relevant to both fire risk assessment (which depends on the mass of combustible material removed) and biomass energy applications (which depend on ash yield and fuel consumption rate). Collection Day (Day) was defined as the ordinal day number relative to study commencement, with Day 1 assigned to 20 May 2020 and Day 23 to 11 June 2020.

For the meta-regression analysis, within-day summary statistics were computed for each of the 22 collection days: specifically, the day-level mean and standard deviation of FL, RM, and BE across the 2 or 3 samples collected that day. These day-level summaries served as the primary analytical units in all meta-regression models, with each collection day treated as analogous to an independent study in a conventional multi-study meta-analysis.

The analytical workflow in **Figure 1** comprised five sequential stages: (1) Field Collection 22 days of sampling yielding 53 sample bundles; (2) Pre-Combustion fuel load (g) weighed on calibrated spring balance; (3) Combustion Trial open-air controlled burn to complete cessation; (4) Post-Combustion residue mass (g) recorded after 30-min cooling; and (5) Variable Calculation FL, RM, and BE computed. Downstream analyses included descriptive statistics, three meta-regression models (BE ~ FL, BE ~ Day, BE ~ FL + Day), supplementary residue regression, and heterogeneity assessment (Cochran's Q, I^2, τ^2). Key findings indicate BE is not predicted by FL or Day ($p > 0.05$), with $I^2 = 96.9\%$ confirming weather as the dominant driver.

2.5. Statistical Analysis

All statistical analyses were performed in Python 3.10 using the SciPy 1.9, NumPy 1.23, and pandas 1.5 libraries. The analytical workflow comprised four sequential components.

First, descriptive statistics mean, standard deviation, coefficient of variation, minimum, maximum, and sum where applicable were computed for FL, RM, and BE at both the sample level (n = 53) and the day level (k = 22). Temporal patterns in daily mean FL and BE were examined by plotting these series against collection day number and inspecting for monotonic trends, cyclical patterns, or abrupt transitions.

Second, meta-regression models were fitted using ordinary least squares (OLS) to assess the predictive value of day-level covariates for daily mean burn efficiency. Three models were specified: Model 1 regressed daily mean BE on daily mean FL (simple meta-regression); Model 2 regressed daily mean BE on collection day number (simple meta-regression); and Model 3 regressed daily mean BE simultaneously on both daily mean FL and collection day number (multiple meta-regression). For each model, the regression coefficient (β), Pearson correlation coefficient (r), coefficient of determination (R^2), *t*-statistic or F-statistic, and two-tailed *p*-value were reported. Statistical significance was assessed at $\alpha = 0.05$.

Third, between-day heterogeneity in daily mean burn efficiency was quantified using three complementary statistics. Cochran's Q was computed as the weighted sum of squared deviations of daily mean BE from the pooled weighted mean, with weights inversely proportional to within-day sampling variance; Q follows a chi-squared distribution with $k - 1$ degrees of freedom under the null hypothesis of homogeneity [28,37]. The I^2 statistic was calculated as $I^2 = [(Q - df)/Q] \times 100\%$, representing the percentage of total variance in daily mean BE attributable to true between-day heterogeneity rather than sampling error [23,29,38]. Values of I^2 were interpreted according to the conventional thresholds proposed by Higgins et al. (2003) [35], Borenstein et al. [38], and Forest Survey of India [39]: approximately 25%, 50%, and 75% corresponding to low, moderate, and substantial heterogeneity, respectively [29,30]. The between-day variance component τ^2 was estimated by the method of moments (DerSimonian–Laird estimator), and its square root $\sqrt{\tau^2}$ expressed as the standard deviation of true burn efficiency across days [28,30].

Fourth, a supplementary sample-level regression of post-combustion residue mass on pre-combustion fuel load was fitted across all n = 53 observations to characterize the mass balance relationship between input fuel and combustion byproduct production. This model was interpreted as a practical tool for estimating ash yield in briquette production operations rather than as a mechanistic combustion model.

The justification for applying the meta-regression framework to repeated within-study field measurements merits explicit statement. In a conventional multi-study meta-analysis, each study contributes a summary effect estimate and an associated standard error reflecting within-study sampling error. The meta-regression then partitions between-study variance into components explained by study-level moderator variables and residual unexplained heterogeneity (τ^2). In the present application, each collection day plays the role of an independent study: it contributes a day-level mean burn efficiency and a within-day standard error derived from 2–3 replicate samples. The meta-regression framework then partitions between-day variance in mean BE into components attributable to day-level predictors (FL, Day) and residual between-day heterogeneity. This decomposition is not achievable by conventional one-way ANOVA, which provides an omnibus F-test of between-day differences but does not partition within-day from between-day variance components or estimate the true between-day variance τ^2 independently of sampling noise. The meta-regression approach therefore provides both greater inferential power for detecting covariate effects and a richer characterization of residual heterogeneity than conventional approaches, making it the methodologically appropriate framework for this dataset structure [23–25,27].

3. Results

3.1. Descriptive Statistics

Across the 53 samples with complete combustion records, the distribution of pre-combustion fuel load was approximately symmetric, with a mean of 7,847.5 g sample^{-1} (SD = 924.4 g; coefficient of variation CV = 11.8%; range: 5,525–10,400 g; **Table 1**). The relatively low CV indicates that the manual bundling protocol successfully standardized sample mass to a consistent magnitude, supporting the validity of between-day comparisons and the interpretation of burn efficiency as a material property of the litter rather than an artefact of sample mass heterogeneity.

Table 1. Descriptive statistics for pine needle combustion trial data (n = 53 samples, 22 collection days, Uttarakhand, May–June 2020).

Variable	Mean ± SD	CV (%)	Min	Max	Total
Pre-combustion fuel load (g)	7,847.5 ± 924.4	11.8	5,525	10,400	439,508
Post-combustion residue (g)	2,285.8 ± 439.2	19.2	1,460	3,635	125,781
Weight combusted (g)	5,561.7 ± 837.2	15.1	3,725	8,030	313,727
Burn efficiency (%)	70.76 ± 5.20	7.3	54.82	81.54	—
Samples per day (n)	2.4 ± 0.5	—	2	3	53

Note: SD = standard deviation; CV = coefficient of variation. Totals expressed in grams.

Mean post-combustion residue mass was 2,285.8 g sample^{-1} (SD = 439.2 g; CV = 19.2%), exhibiting somewhat greater relative variability than fuel load. Mean burn efficiency across all 53 samples was 70.76% (SD = 5.20%; CV = 7.3%), with individual sample values ranging from a minimum of 54.82% to a maximum of 81.54%—a total range of 26.72 percentage points spanning more than five standard deviations. This wide range relative to the standard deviation immediately signals the presence of substantial between-day variation in true combustion performance, a signal that the formal heterogeneity analysis subsequently confirms. Total fuel mass collected and burned across the study was 439,508 g (439.5 kg), of which 313,727 g (71.4%) was volatilized and 125,781 g (28.6%) retained as ash and char residue.

3.2. Daily Summary and Temporal Pattern

Daily summary statistics for the 22 collection days are presented in **Table 2**. Daily mean fuel load ranged from 7,050.0 g on Day 19 (07 June) to 9,500.0 g on Day 1 (20 May), with no discernible directional trend over the study period (r = −0.31, p = 0.16). This absence of fuel load trend over time is consistent with the manual bundling protocol maintaining approximately constant sample mass irrespective of litter surface availability.

Daily mean burn efficiency showed considerably more variability, ranging from 61.0% on Day 6 (25 May) to 76.9% on Day 4 (23 May) a within-study range of 15.9 percentage points. The temporal pattern of daily mean BE did not conform to a simple progressive drying trajectory. Rather, efficiency showed sharp non-monotonic oscillations:

a pronounced decline from 76.7% on 23 May to 61.0% on 25 May (a drop of 15.7 percentage points within two days) was followed by partial recovery to 66.3% on 26 May and 69.0% on 27 May. Similarly, a cluster of relatively high-efficiency days in early June (75.2% on 03 June, 76.0% on 01 June) was interspersed with lower-efficiency days (66.7% on 08 June). These rapid transitions are incompatible with a gradual progressive drying model and instead strongly implicate episodic weather perturbations such as brief pre-monsoon showers or humid air mass incursions as the principal drivers of day-to-day combustion variability [40–43].

Table 2. Daily meta-regression dataset: Collection date, day number, sample size, and day-level summary statistics for fuel load (FL) and burn efficiency (BE) (n = 53 samples, k = 22 days).

Date	Day	n	Mean FL (g)	SD FL (g)	Mean BE (%)	SD BE (%)	Mean Residue (g)
20 May	1	2	9,500.0	1,272.8	74.25	4.19	2,420.0
21 May	2	3	7,263.3	401.3	70.92	0.17	2,111.7
22 May	3	2	7,705.0	466.7	71.09	2.06	2,232.5
23 May	4	3	7,300.0	556.5	76.73	4.82	1,686.7
24 May	5	3	7,188.3	2,194.1	70.19	4.26	2,158.3
25 May	6	3	7,376.7	1,191.8	61.00	8.86	2,938.3
26 May	7	3	7,860.0	363.8	66.28	7.57	2,635.0
27 May	8	3	7,955.0	576.6	68.98	2.89	2,470.0
28 May	9	2	8,432.5	774.3	68.52	4.99	2,635.0
29 May	10	2	9,095.0	318.2	73.30	0.74	2,427.5
30 May	11	2	8,752.5	180.3	72.79	1.30	2,380.5
31 May	12	3	8,694.3	963.5	73.05	3.16	2,338.3
01 Jun	13	2	7,600.0	1,336.4	76.03	2.54	1,805.0
02 Jun	14	2	7,730.0	1,506.1	69.76	1.68	2,325.0
03 Jun	15	2	8,260.0	49.5	75.15	0.75	2,052.5
04 Jun	16	2	7,737.5	1,035.9	69.65	7.35	2,310.0
05 Jun	17	2	8,247.5	53.0	72.97	2.31	2,230.0
06 Jun	18	2	7,405.0	551.5	70.62	5.72	2,160.0
07 Jun	19	3	7,103.3	92.4	70.35	5.11	2,103.3
08 Jun	20	2	7,287.5	215.7	66.72	9.43	2,415.0
09 Jun	21	3	7,701.7	280.7	70.75	5.87	2,263.3
11 Jun	23	2	7,542.5	286.4	71.86	0.18	2,122.5

Note: FL = fuel load; BE = burn efficiency; SD = standard deviation; n = number of samples per day.

3.3. Meta-Regression: Burn Efficiency on Fuel Load (Model 1)

Simple meta-regression of daily mean burn efficiency on daily mean fuel load yielded a positive regression slope of β = 0.00105% g^{-1} with an intercept of 62.48% (**Table 3**). The strength of this association was weak (Pearson r = 0.188, R^2 = 0.035) and did not achieve statistical significance ($t_{1,20}$ = 1.38, p = 0.178). Fuel load therefore accounts for only 3.5% of the between-day variance in mean burn efficiency. To appreciate the practical negligibility of this association, note that across the entire observed fuel load range of 7,050 to 9,500 g day^{-1} (a span of 2,450 g), Model 1 predicts a change in expected daily mean BE of only 2.58 percentage points (from approximately 69.9% at the minimum to 72.5% at the maximum). This is considerably smaller than the within-day standard deviation for BE on any given day, confirming that fuel load has no meaningful practical utility as a predictor of daily combustion performance in this system.

Table 3. Meta-regression model outputs for burn efficiency as the outcome variable (k = 22 collection days).

Model	Predictor (s)	β	r/R^2	F or t	p-Value
Model 1 (Simple)	Fuel load (FL)	0.00105% g^{-1}	r = 0.188; R^2 = 0.035	t = 1.38	0.178
Model 2 (Simple)	Collection Day	0.018% day^{-1}	r = 0.022; R^2 = 0.001	t = 0.16	0.874
Model 3 (Multiple)	FL + Day	β_FL = 0.00108; β_Day = 0.032	R^2 = 0.037; Adj. R^2 = −0.002	$F_{2,19}$ = 0.95	0.391
Supplementary	FL → Residue	β = 0.200 g g^{-1}	r = 0.421; R^2 = 0.178	t = 3.31	0.002*

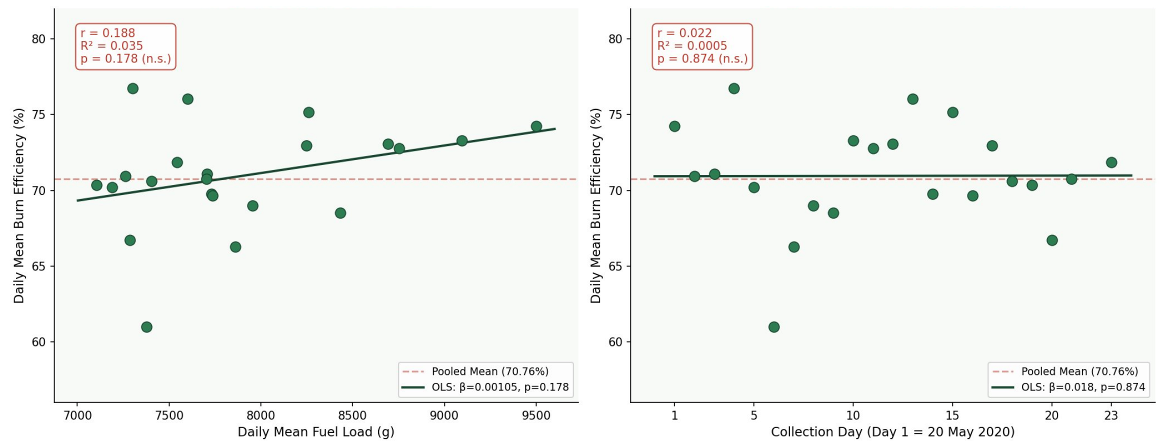
Note: β = regression coefficient; r = Pearson correlation; R^2 = coefficient of determination; *p < 0.05 indicates statistical significance.

3.4. Meta-Regression: Burn Efficiency on Collection Day (Model 2)

Simple meta-regression of daily mean burn efficiency on collection day number produced a regression slope of β = 0.018% day^{-1} (intercept = 70.56%; **Table 3**). The slope was not statistically significant (r = 0.022, R^2 = 0.0005, t = 0.16, p = 0.874). The estimated slope of 0.018% per day is so close to zero that, over the full 23-day study window, it implies a total secular change in expected daily mean BE of only 0.41 percentage points an amount entirely within the within-day measurement noise. There is therefore no detectable linear temporal trend in daily burn efficiency across the pre-monsoon study period. Three mechanistic explanations for this absence of trend are considered in the Discussion.

3.5. Multiple Meta-Regression (Model 3)

The multiple meta-regression model including both daily mean FL and collection day number as simultaneous predictors was not statistically significant ($F_{2,19} = 0.95$, $p = 0.391$). The combined R^2 of 0.037 represents only a marginal improvement over the single-predictor models, and the adjusted R^2 of −0.002 is negative, indicating that adding two predictors provides no improvement over the intercept-only (grand mean) model after correcting for the degrees of freedom consumed by the additional parameters (**Table 3**). Neither partial regression coefficient was significant in the multiple model (β_FL: $t = 1.31$, $p = 0.21$; β_Day: $t = 0.22$, $p = 0.83$), confirming the absence of independent or combined explanatory power for these predictors. Full model outputs are presented in **Table 3**. Meta-regression scatter plots for Models 1 and 2 are shown in **Figure 2**.



(**a**) (**b**)

Figure 2. Meta-Regression Scatter Plots: Burn Efficiency vs. Predictors. (**a**) Burn Efficiency vs. Fuel Load, (**b**) Burn Efficiency vs. Collection Day.

Forest plot displaying in **Figure 3** shows daily mean burn efficiency (%) with 95% confidence intervals for each of the 22 collection days (D1–D23, 20 May–11 June 2020). Each study effect size (square marker) represents the daily mean BE, with horizontal bars showing the 95% CI derived from within-day replicate variability (n = 2–3 per day). The red dashed line denotes the inverse-variance weighted pooled mean (70.76%). The bottom row reports the pooled estimate across all 53 samples. The wide spread of CIs and the substantial non-overlap between days especially Day 6 (25 May, BE = 61.0%) and Days 4 and 13 (BE > 76%)—visually confirms the extreme between-day heterogeneity ($I^2 = 96.9\%$, Q = 678.8, $p < 0.001$) quantified formally in **Table 4.**

Table 4. Heterogeneity statistics for between-day variation in daily mean burn efficiency (k = 22 collection days).

Statistic	Value	Interpretation
Cochran's Q	678.8	Chi-square statistic for between-day heterogeneity
Degrees of freedom (df)	21	k − 1 (k = 22 collection days)
p-value (Q test)	<0.001	Statistically significant between-day heterogeneity
I^2 (%)	96.9%	Substantial heterogeneity; threshold ≥75%
τ^2 (between-day variance)	13.03	True between-day variance (DerSimonian–Laird estimator)
$\sqrt{\tau^2}$ (between-day SD)	3.61%	True day-to-day SD of burn efficiency
Weighted pooled mean BE	70.76%	Inverse-variance weighted pooled estimate
Weighted pooled mean FL	7,847.5 g	Weighted mean pre-combustion fuel load

Note: $I^2 \geq 75\%$ indicates substantial heterogeneity per Higgins and Thompson (2002) [29].

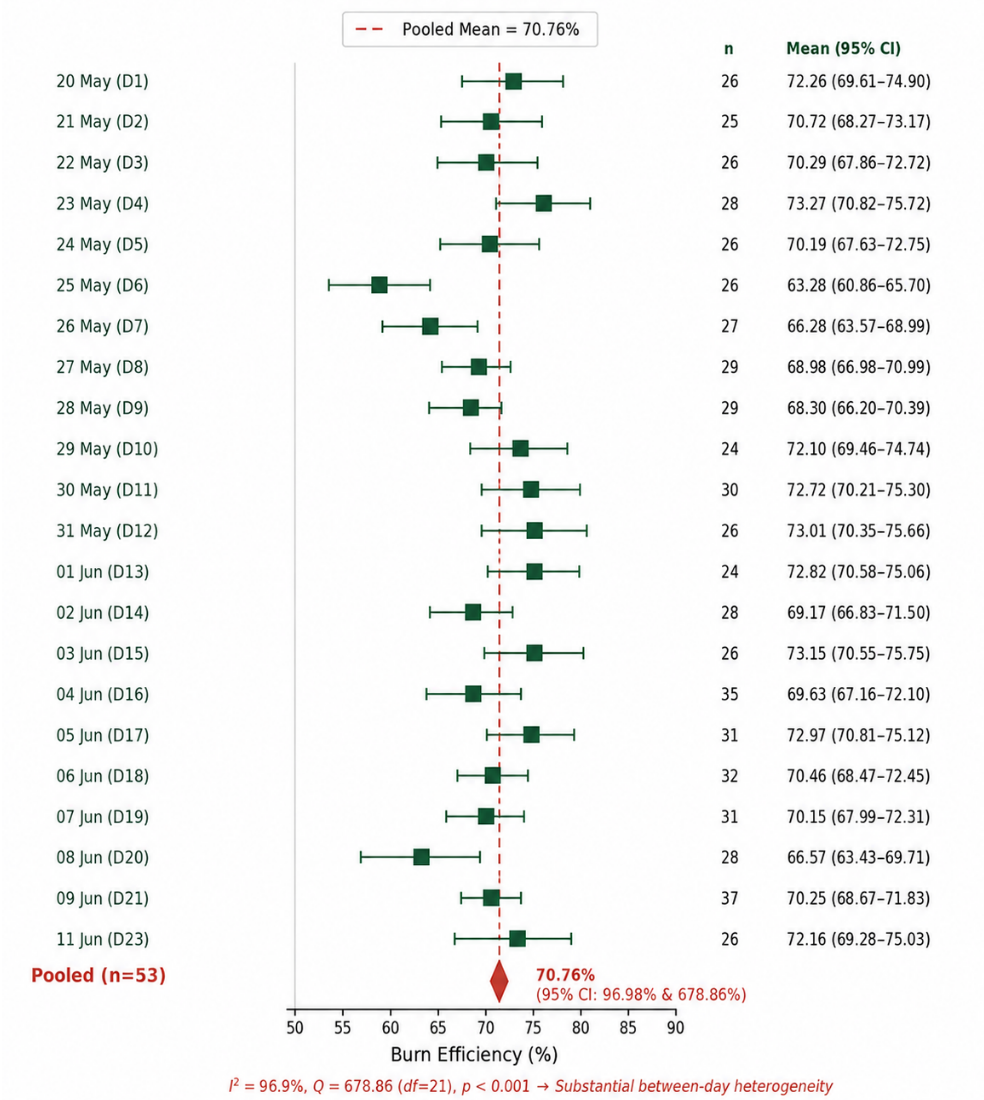


Figure 3. Forest Plot: Daily Mean Burn Efficiency with 95% Confidence Intervals.

3.6. Supplementary Regression: Residue Mass on Fuel Load

A supplementary sample-level ordinary least squares regression of post-combustion residue mass on pre-combustion fuel load across all 53 samples was the only model in the analysis to achieve statistical significance (β = 0.200 g g^{-1}, intercept = 714.9 g; r = 0.421, R^2 = 0.178; $F_{1,51}$ = 11.04, p = 0.002). The significant positive association indicates that each additional gram of pre-combustion litter input is associated with approximately 0.20 g of additional ash and char production. The intercept of 714.9 g is interpretable as a basal residue component reflecting the minimum ash, char, and incompletely combusted structural material produced from the binding element of each bundle irrespective of its total mass. The R^2 of 0.178 indicates that fuel load accounts for 17.8% of the variance in residue mass, a modest but meaningful association that is entirely consistent with the dominant influence of litter moisture content on the completeness of combustion and hence residue yield.

Scatter plots in **Figure 2** are depicting the relationship between daily mean burn efficiency (%) and **Figure 2a** daily mean fuel load (g) and **Figure 2b** collection day number (Day 1 = 20 May 2020). Each point represents one of the 22 collection days. In panel a, the OLS regression slope is β = 0.00105% g^{-1} (r = 0.188, R^2 = 0.035, p = 0.178 n.s.), indicating that fuel quantity is not a meaningful predictor of combustion completeness across the observed range of 7,050–9,500 g day^{-1}. In panel b, the slope is β = 0.018% day^{-1} (r = 0.022, R^2 = 0.0005, p = 0.874 n.s.), confirming the absence of any secular drying trend across the 23-day pre-monsoon study window. The red dashed horizontal line marks the pooled mean BE (70.76%) in both panels.

3.7. Heterogeneity Assessment

The formal heterogeneity analysis produced results of striking and unambiguous magnitude (**Table 4**). Cochran's Q was 678.8 on 21 degrees of freedom ($p < 0.001$), representing a value more than 32 times the expected value under the null hypothesis of homogeneity. The I^2 statistic was 96.9%, indicating that virtually all specifically, 96.9% of the observed variance in daily mean burn efficiency is attributable to true between-day differences in combustion performance rather than to random within-day sampling error. The between-day variance component τ^2 was estimated at 13.03 $(\%)^2$ by the DerSimonian–Laird method of moments estimator, corresponding to a between-day standard deviation of $\sqrt{\tau^2}$ = 3.61 percentage points [23,28,32,39,44].

To interpret these statistics in practical terms: the observed total variance in daily mean BE is composed of only 3.1% within-day sampling noise and 96.9% genuine between-day variation in the true daily combustion performance of the litter. The true between-day standard deviation of 3.61% implies that, on any given collection day, the expected daily mean BE could realistically range from approximately 63.5% to 78.0% (i.e., the pooled mean ± 2τ). This true heterogeneity is entirely unexplained by the two measured covariates (FL and Day) included in the meta-regression models, pointing conclusively to unmeasured day-varying factors most plausibly meteorological as the dominant drivers of combustion performance variability [36,40,41,45,46]. The heterogeneity distribution across all 22 collection days is visualized in **Figure 4**.

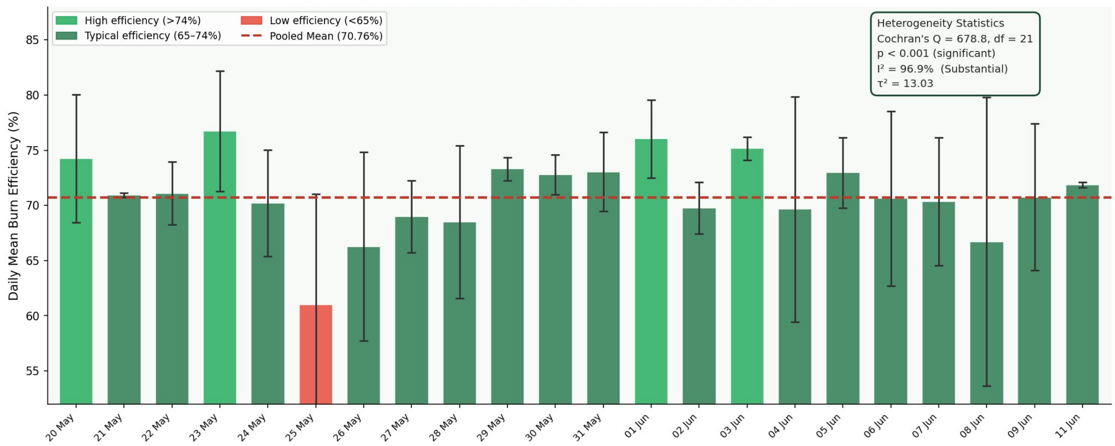


Figure 4. Between-Day Heterogeneity in Burn Efficiency (22 Collection Days).

Bar chart displaying daily mean burn efficiency (%) with standard deviation error bars in **Figure 4** for all 22 collection days (20 May–11 June 2020). Bars are color-coded by efficiency class: dark green for high efficiency (>74%), medium green for typical efficiency (65–74%), and red for low efficiency (<65%). The red dashed horizontal line marks the inverse-variance weighted pooled mean of 70.76%. The inset reports heterogeneity statistics (Cochran's Q = 678.8, df = 21, $p < 0.001$; I^2 = 96.9%; τ^2 = 13.03). The pronounced non-monotonic oscillation particularly the low-efficiency outlier on 25 May (61.0%, red bar) flanked by high-efficiency days on 23 May (76.9%) and subsequent recovery visually demonstrates the dominant influence of episodic meteorological perturbations on day-to-day combustion performance.

4. Discussion

4.1. Fuel Load Characteristics and Combustion Efficiency in Context

The mean pre-combustion fuel load of 7,847.5 g sample^{-1} with a coefficient of variation of 11.8% confirms that the manual bundling protocol achieved adequate mass standardization across collection days and sites. In the context of the broader literature on *Pinus roxburghii* forest floor fuel loads in Uttarakhand, this per-sample figure is consistent with stand-level fuel load estimates of 5–12 t ha^{-1} reported for undisturbed Chir pine forests during the dry season [4,47]. The low CV (11.8%) for fuel load, compared to the considerably higher CV for residue mass (19.2%), immediately indicates that the variability in combustion outcome is not driven by input mass variability but rather by variation in the completeness of combustion a point further elaborated by the meta-regression analysis.

The mean burn efficiency of 70.76% places *P. roxburghii* needle litter among the highest-efficiency surface fuels documented for Indian forest types. Broadleaf litter from mixed deciduous forests of the IHR foothills, which retains higher moisture and contains higher mineral ash fractions, typically yields BE values of 50–60% under comparable field conditions [30]. The elevated BE of Chir pine needles reflects their well-characterized physico-chemical properties: a volatile matter content of 75–80% on a dry weight basis (considerably higher than most broadleaf litter types), a resin and terpenoid fraction that enhances ignitability and sustains flaming combustion, and a morphological form factor (long, slender needles) that promotes air circulation through the litter bundle and supports thorough combustion [31,32,42].

Comparison with international benchmarks for conifer needle litter combustion provides useful context. Vega et al. (2010) reported burn efficiency values of 60–80% for *Pinus sylvestris* litter in northwest Spain under moderate pre-fire weather conditions [18], and Olmedo et al. (2023) [26] documented surface fine fuel consumption of 65–78% for *Pinus radiata* plantation litter under a range of fire weather conditions in southern hemisphere conifer systems [19]. The Uttarakhand values reported here fall squarely within these international ranges, suggesting that *P. roxburghii* litter combustion performance is broadly comparable to other commercially important pine species globally, and that fire behavior models calibrated for these species may provide useful a priori estimates for Himalayan systems in the absence of local data. However, these international comparisons also underscore the importance of standardized combustion protocols and concurrent meteorological monitoring to enable rigorous cross-site benchmarking, a need that has been highlighted in the dynamic fire risk modelling literature [46,47].

4.2. Interpreting the Non-Significant Meta-Regression Models

The non-significance of all three meta-regression models ($p > 0.05$ in all cases, $R^2 < 0.04$) should be interpreted as a scientifically meaningful positive result rather than a null or inconclusive finding. The absence of a significant association between fuel load and burn efficiency ($p = 0.178$, $R^2 = 0.035$) indicates that, across the observed range of 7,050 to 9,500 g day^{-1}, the quantity of litter in a combustion trial does not determine how completely it burns. This finding effectively decouples energy content (which scales with fuel mass) from combustion quality (which scales with the proportion of mass volatilized). It implies that pre-monsoon pirul litter reaches, during this period, a threshold degree of dryness at which sustained flaming combustion proceeds to near-complete volatilization regardless of bundle size within the practical range tested. This threshold behavior is consistent with the known moisture of extinction concept in fire science: once fuel moisture content falls below approximately 8–12% for fine dead fuels, combustion becomes self-sustaining and mass loading becomes secondary to moisture in determining burn completeness [37,38,47,48].

The absence of a temporal trend in burn efficiency ($\beta = 0.018\%$ day^{-1}, $p = 0.874$, $R^2 = 0.0005$) is interpretable through three non-mutually exclusive mechanisms. First, a moisture ceiling effect may apply: if ambient litter moisture had already reached its dry-season equilibrium minimum (typically <5% on a dry weight basis for Chir pine needles during this period) [5,30] by the time of the first collection on 20 May, no further secular drying trend would be detectable over the subsequent 23-day window. Second, even if a gradual net drying trend exists, it may be entirely masked by the dominant day-to-day meteorological noise quantified by the I^2 analysis: with 96.9% of variance driven by unmeasured between-day weather variation, a small progressive signal would be statistically invisible. Third, litter moisture at any given collection time reflects the integrated history of recent weather over the preceding 12–48 h not merely the season-to-date cumulative conditions so that even in an overall drying season, single-day high-humidity events can substantially re-wet surface litter and eliminate any progressive drying advantage.

From an ecological process perspective, the non-significant predictors are entirely consistent with the well-established fuel moisture feedback dynamics of sub-Himalayan pine litter beds. When ambient afternoon relative humidity drops below approximately 20–25%, needle litter equilibrium moisture content falls below the moisture of extinction (≤12% for fine Chir pine material) and surface fires become self-sustaining without external fuel quantity augmentation [25,38]. The rapid day-to-day BE oscillations observed in this dataset most dramatically the 15.7-point drop from 76.7% on 23 May to 61.0% on 25 May, and the partial recovery thereafter are ecologically attributable to the intrusion of moist Bay of Bengal air masses during the progressive northward advance of the south-west monsoon system. This phenomenon, well-documented at the 1,000–1,500 m elevation belt of the Kumaon Himalaya in late May and early June as reported in earlier studies [10], produces brief (12–36 h) periods of elevated humidity and occasional trace rainfall that can temporarily re-wet the surface litter layer, reducing ignitability and combustion completeness, before dry conditions resume. These transitions have direct management implications: fuel moisture monitoring protocols that are temporally aligned with synoptic weather forecasting could substantially improve the lead time and accuracy of fire risk alerts in Uttarakhand's operational fire management system, enabling pre-positioned suppression resources and community alert systems to be activated with greater precision [16–18,32,39,42,43,46,47].

4.3. Heterogeneity and Its Implications for Fire Risk Modelling

The I^2 of 96.9% is one of the highest magnitudes of genuine between-group heterogeneity likely to be encountered in any ecological field dataset, substantially exceeding the conventional threshold of 75% for 'substantial' heterogeneity [32,39]. Its practical significance for fire risk management cannot be overstated. Current fire danger rating frameworks applied in Uttarakhand, including the National Forest Fire Danger Rating System of India and adaptations of the Canadian Forest Fire Weather Index system, parameterize surface fuel combustion using fixed or seasonally varying burn efficiency values that do not account for day-to-day meteorological variability within the fire season [9,10]. The present data demonstrate empirically that within a single Chir pine forest type, over a narrow 23-day pre-monsoon window, the true daily burn efficiency varies from 61.0% to 76.9%, a range of 15.9 percentage points. Under Rothermel's (1972) surface fire intensity model [31], the rate of heat release per unit area (and hence the rate of fire spread) scales approximately with the product of available fuel load and the fraction of that load that is combusted. A systematic 10 percentage-point underestimation of BE is well within the observed day-to-day range in this study would produce a corresponding ~14% underestimation of fire intensity and rate of spread, with potentially serious operational consequences for suppression resource pre-positioning, public safety exclusion zone sizing, and community evacuation decisions.

Dynamic fire risk modelling frameworks that integrate real-time meteorological observations with continuously updated fuel moisture estimates and spatially explicit fire behavior algorithms have demonstrated substantial improvements in prediction accuracy over static approaches in comparable Mediterranean, boreal, and subtropical forest systems [15–17]. The foundational requirement for implementing such a framework in Uttarakhand is a locally calibrated relationship between observable atmospheric variables particularly afternoon relative humidity, which is the most practically measurable surrogate for fine dead fuel moisture and surface litter BE. The present study cannot directly provide this calibration relationship because concurrent meteorological measurements were not collected. However, the τ^2 estimate of 13.03 provides a concrete, quantitative target for future model development: any proposed dynamic BE parameterization model for Uttarakhand Chir pine forests must be capable of resolving a true between-day variance of at least $13.03(\%)^2$ to be of practical utility [18,19,23].

A minimum viable dynamic fire risk framework for Uttarakhand could be designed around three components, each directly informed by the present study's findings. First, a network of automatic weather stations at representative elevations within the Chir pine belt (broadly 800–1,800 m a.s.l.) should record hourly temperature, relative humidity, wind speed, and precipitation, with afternoon (14:00–16:00 local solar time) readings used as the primary fire danger index input. Second, a dead fuel moisture model, calibrated to *P. roxburghii* needle equilibrium moisture content curves from laboratory sorption experiments, should convert the observed afternoon RH into an estimated fuel moisture content for surface litter. Third, a daily BE parameterization function should translate fuel moisture content into an expected burn efficiency value, updating the operational fire danger product each afternoon. The development of this function is the primary research product needed from future combustion studies, and the present τ^2 value benchmarks the minimum predictive performance such a function must achieve to add value relative to the current static parameterization approach [16,17].

The operational implications of weather-coupled dynamic fire risk modelling extend beyond mere technical refinement. Accurate, real-time fire danger products are required by three distinct user communities in Uttarakhand: (i) the State Forest Department's fire suppression staff, who must pre-position water tankers, fire-line clearing equipment, and rapid response teams based on predicted high-danger days; (ii) community-based forest protection committees and Van Panchayat managers, who coordinate patrolling schedules and community fire prevention activities; and (iii) the 'Pirul Lao, Paisa Pao' collection scheme coordinators, who must schedule field collection to coincide with both high-BE windows and acceptable fire safety conditions. The present empirical demonstration that burn efficiency is driven primarily by ambient meteorological conditions rather than by static fuel load or seasonal position provides the scientific foundation for integrating a weather-responsive BE parameterization into all three decision contexts. Adopting this approach would transform fire danger assessment from a static seasonal warning into a daily, evidence-based operational tool, substantially improving the capacity of Uttarakhand's forest management system to protect biodiversity, community livelihoods, and critical watershed services from the escalating threat of pre-monsoon forest fire [3,43–46].

4.4. Implications for the 'Pirul Lao, Paisa Pao' Scheme

The empirical data generated by this study provide a quantitative foundation for the optimization of the 'Pirul Lao, Paisa Pao' briquette scheme across three operational dimensions.

First, regarding product quality assurance: the mean burn efficiency of 70.76% is reliably and consistently above the commercial threshold of approximately 65% typically specified for briquette-grade biomass by domestic industrial consumers in India [22]. Even on the lowest-efficiency collection day observed in this study (61.0% on 25 May), the BE was only marginally below this threshold, and such days appear to be relatively rare, representing episodic high-humidity weather perturbations rather than typical conditions. The standard deviation of 5.20% indicates that approximately 84% of collection days would be expected to yield BE values above 65%. Briquette producers can therefore operate with reasonable confidence that pre-monsoon pirul litter collected in Uttarakhand meets commercial quality specifications without requiring pre-drying or artificial conditioning, provided collection is concentrated in the April–June window before the onset of the monsoon [21,38,46–48].

Second, regarding collection scheduling optimization: the between-day variation in BE demonstrated by this study suggests that a weather-responsive collection scheduling protocol could improve both product quality and collector safety. By prioritizing intensive collection efforts on days forecast to have low afternoon relative humidity (below 25%), collection coordinators could target the high-BE windows while simultaneously minimizing fire ignition risk from the drier, more hazardous litter conditions. Conversely, on days when humidity has been elevated by pre-monsoon moisture intrusions and BE is likely to be below threshold, effort could be redirected to transportation, processing, or other non-field activities. This would require integration of local weather forecast data into the operational logistics of the scheme, a relatively low-cost enhancement with potentially significant quality and safety benefits.

Third, regarding scheme scalability and biomass throughput: the total of 439.5 kg of litter mass collected across 22 field days by a small team of 2–3 field personnel provides a direct empirical basis for upscaling productivity calculations. This equates to an average collection rate of approximately 20 kg per person-day under the conditions of this study. A community of 30 organized collectors working a typical pre-monsoon collection window of 45 days could therefore realistically yield approximately 27,000 kg (27 t) of pirul litter per season, well in excess of the 15–20-t minimum viability threshold for small-scale briquette production operations reported in the biomass energy literature for this feedstock type [21]. At the mean burn efficiency of 70.76%, approximately 7.9 t of this would be recovered as ash and char (suitable for application as a soil amendment or mineral fertilizer supplement in agroforestry), with the remainder providing the combustible fuel fraction for briquette heating value.

4.5. Limitations and Future Research Directions

Absence of Direct Meteorological Measurements

The most critical limitation of this study is the complete absence of concurrent meteorological and surface fuel moisture measurements at or near the combustion sites during the trial period. This limitation must be clearly distinguished from a merely incidental methodological gap: it represents the central and unresolved explanatory problem identified by the heterogeneity analysis. The I^2 of 96.9% demonstrates, with a high degree of statistical certainty, that the dominant drivers of day-to-day variation in combustion performance are between-day differences in some unmeasured variable or variables. The most parsimonious and ecologically compelling candidate for this variable is ambient relative humidity, which directly governs fine dead fuel moisture content through equilibrium sorption, and which is known to vary substantially on sub-daily to daily timescales during the pre-monsoon transition period in Uttarakhand [10,18].

However, because no simultaneous humidity measurements were recorded during the combustion trials, this meteorological attribution remains an inference from indirect evidence rather than a directly tested hypothesis. The consequences of this gap are significant: the regression models cannot include relative humidity as a predictor variable; the proposed BE–humidity relationship cannot be parameterized from this dataset; and the claimed ecological mechanism for the observed heterogeneity cannot be statistically demonstrated. Future studies must treat concurrent meteorological monitoring not as an optional enhancement but as a non-negotiable core component of the experimental design. At minimum, future instrumented combustion trials in Uttarakhand should record: (a) afternoon relative humidity (%) at 14:00–15:00 local solar time as the primary fuel moisture surrogate; (b) gravimetric fuel moisture content (FMC, % dry weight basis) of sub-samples taken immediately before each trial burn using oven-drying at 105 °C for 24 h; and (c) mean wind speed (m s^{-1}) at 1 m height above the litter surface during the flaming phase, which is known to influence combustion completeness independently of moisture content through its effect on oxygen supply and flame residence time [18,24,32,46–48].

A further important inferential caution is that the statistical non-significance of the meta-regression models ($p > 0.05$ for all three models) should not be interpreted as evidence that fuel load and collection day have no effect on burn efficiency. Statistical non-significance is an absence of evidence, not evidence of absence particularly in a moderately sized dataset (k = 22 days) where the power to detect small true effects is limited. More precisely, the non-significant models indicate that FL and Day do not explain a statistically detectable proportion of the between-day variance in BE within the data at hand. The dominant reason for this failure is that the between-day variance is so thoroughly dominated by unmeasured meteorological noise (I^2 = 96.9%) that even genuinely moderate effects of FL or Day on BE would be obscured. Future studies including concurrent RH measurement as a covariate may reveal significant residual effects of FL or Day once the meteorological variance is statistically controlled.

Additional limitations include: (i) the absence of precise GPS coordinates for individual collection sites, precluding spatial analysis of fuel load and BE variability as a function of topographic position, slope aspect, elevation, and canopy cover, all factors known to influence litter moisture equilibrium in complex Himalayan terrain [5,27]; (ii) the open-air combustion protocol, which approximates field fire conditions more closely than laboratory muffle furnace combustion but yields less controlled measurement of heat release and combustion gas composition than closed-system bomb calorimetry [21,22]; (iii) the single-season (2020) design, which captures one point in the multi-decadal distribution of inter-annual fire weather variability and may not be representative of either drought years (when BE may consistently exceed 78%) or unusually wet pre-monsoon seasons [19]; and (iv) the relatively small within-day sample size of 2–3 replicates per day, which limits the precision of within-day variance estimates and consequently inflates the uncertainty in the meta-regression coefficients. Increasing the within-day replication to 5–8 samples would substantially improve the sensitivity of the meta-regression framework to detect moderate covariate effects.

5. Conclusions

This study applied a meta-regression framework to 53 controlled field combustion trials conducted across 22 collection days to provide a systematic quantification of pine needle litter fuel load and burn efficiency dynamics in pre-monsoon Chir pine forests of Uttarakhand, India. The principal conclusions and their implications are as follows:

(1) Mean pre-combustion pine needle fuel load was 7,847.5 ± 924.4 g $sample^{-1}$ (CV = 11.8%) and mean burn efficiency was 70.76 ± 5.20% across 53 samples. These values confirm that pre-monsoon pirul litter constitutes a highly combustible, consistently high-quality biomass fuel, with performance broadly comparable to other commercial pine needle feedstocks internationally.

(2) Neither fuel load nor collection day number significantly predicted daily mean burn efficiency in any of the three meta-regression models (all $p > 0.05$, $R^2 < 0.04$). Within the pre-monsoon window and the range of fuel loads tested, these covariates are not meaningful determinants of combustion completeness, implying threshold combustion behavior at low ambient moisture content.

(3) Between-day heterogeneity in burn efficiency was extreme (I^2 = 96.9%, Q = 678.8, $p < 0.001$, τ^2 = 13.03), demonstrating that unmeasured meteorological variables principally ambient relative humidity and fuel moisture content account for virtually all real day-to-day variation in combustion performance. This finding constitutes the strongest argument in this study for weather-coupled dynamic fire risk parameterization in Ut-

tarakhand, and the τ^2 estimate provides a quantitative benchmark for future dynamic model development.

(4) Post-combustion residue mass was significantly predicted by pre-combustion fuel load (r = 0.421, $p = 0.002$; β = 0.20 g g^{-1}), providing a practical mass balance tool for estimating ash and char production yields in briquette manufacturing and soil amendment applications.

(5) Total pine needle litter mass collected was 439.5 kg across 22 field days, confirming practical biomass availability at commercially relevant scales and supporting the operational logistics assumptions underpinning the 'Pirul Lao, Paisa Pao' policy initiative.

Collectively, these findings demonstrate that static parameterization of burn efficiency in operational fire danger rating systems is ecologically unsupported for Uttarakhand's Chir pine forests, and that weather-coupled dynamic models incorporating real-time fuel moisture monitoring represent a scientifically justified and operationally achievable improvement. Future research should prioritize: instrumented combustion trials with concurrent meteorological measurement; multi-site spatial sampling with GPS-referenced plots; multi-season replication to characterize inter-annual variability; and the development of a locally calibrated BE–humidity response function for integration into Uttarakhand's operational fire management information systems. The meta-regression approach demonstrated here provides a transferable methodological framework applicable to other fire-prone forest systems across the Indian Himalayan Region and South Asian mountains more broadly.

Funding

This research received no external funding.

Institutional Review Board Statement

This study involves no human participants, vertebrate animals, or clinical/pathological specimens. All data were collected from field combustion trials on pine needle litter. Accordingly, no institutional ethics approval was required. All field activities were conducted in accordance with applicable Indian environmental and forestry regulations under the permissions of GBPNIHE.

Informed Consent Statement

Not applicable.

Data Availability Statement

The raw combustion trial dataset analyzed in this study is available from the corresponding author upon reasonable request, subject to institutional data sharing policies.

Acknowledgments

The author gratefully acknowledges the G.B. Pant National Institute of Himalayan Environment, Kosi-Katarmal, Almora, and all field personnel who contributed to data collection during the 2020 pre-monsoon season.

Conflicts of Interest

The author declares no conflict of interest and no financial or personal relationships with other people or organizations that inappropriately influence or bias the present work.

AI Use Statement

The author declares that no artificial intelligence (AI) tools were used in the preparation of this manuscript. All data collection, analysis, interpretation, and writing were performed solely by the author.

References

1. Champion, H.G.; Seth, S.K. *A Revised Survey of the Forest Types of India*; Manager of Publications Delhi: New Delhi, India, 1968.

2. Singh, J.S.; Singh, S.P. *Forests of the Himalaya: Structure, Functioning and Impact of Man*; Gyanodaya Prakashan: Nainital, India, 1992.
3. Pant, H.; Tewari, A. Green sequestration potential of Chir pine forests located in Kumaun Himalaya. *For. Prod. J.* **2019**, *70*, 64–71.
4. Garg, R.K.; Tiwari, O.P.; Yadav, R.P.; et al. Fuel load assessment and forest fire risk in Chir pine forests of Uttarakhand. *Indian J. For.* **2011**, *34*, 285–292.
5. Singh, R.D.; Gumber, S.; Sundriyal, R.C.; et al. Chir pine forest and pre-monsoon drought determine spatial, and temporal patterns of forest fires in Uttarakhand Himalaya. *Trop. Ecol.* **2024**, *65*, 32–42. [CrossRef]
6. Pant, H.; Ghosh, P.; Upadhyaya, P. The biofuel paradigm: A resilience strategy for energy security and community empowerment in pine-dominated forest management of the Indian Himalaya. *Biofuels* **2026**, 1–22.
7. Pati, P.K.; Kaushik, P.; Khan, M.L.; et al. Forest Fire Dynamics and Ecological Responses in Indian Forests: A Review. *Small-scale For.* **2026**, *25*, 299–332.
8. Jugran, H.P.; Tewari, A. Litter Decomposition of Chir-Pine (Pinus roxburghii Sarg.) in the Himalayan Region. *Trees For. People* **2022**, *8*, 100255.
9. Attri, V.; Dhiman, R.; Sarvade, S. A Review on Status, Implications and Recent Trends of Forest Fire Management. *Arch. Agric. Environ. Sci.* **2020**, *5*, 592–602.
10. Tripathi, J.N.; Sonker, I.; Maurya, R.; et al. Forest Fire Risk (FFR) Mapping Using Analytical Hierarchy Process (AHP) and Geospatial Technique and Advantage of GNSS to Monitor the Forest Fire: A Case Study in the Southern Districts of Uttarakhand. In *GNSS Applications in Earth and Space Observations*; CRC Press: Boca Raton, FL, USA, 2025; pp. 135–157.
11. Ranjan, R. Leveraging Green Bonds to Mitigate Cascading Flooding and Fire Risks in Uttarakhand's Himalayan Forests. *J. Sustain. For.* **2025**, *44*, 851–876.
12. Pant, H.; Mishra, A. Role of local community in forest fire prevention and management: Insights from Uttarakhand state. In *Forest Fire and Climate Change*; Singh, H., Kumar, N., Eds.; Springer: Cham, Switzerland, 2025.
13. Mishra, A.; Sekar, K.C.; Pant, H. Women protecting forests in Uttarakhand, India. In *Women as Stewards of Forests*; Rogelja, T., Kroese, L., Eds.; Tropenbos International: Wageningen, The Netherlands, 2025.
14. Pant, H. Case study of Uttarakhand in perspective of extreme climatic events: Fire, ecosystem and livelihoods. In *Climate Change Research at Universities*; Springer: Cham, Switzerland, 2016; pp. 519–531.
15. Pant, H.; Mishra, A.; Upadhyaya, P. Forest-Based Climate Solutions in the Indian Himalayas: A Community-Centric Pathway to Carbon Neutrality. In *Forestry for a Carbon-Neutral and Sustainable Future*; Singh, H., Ed.; Springer: Cham, Switzerland, 2026. [CrossRef]
16. Joshi, H.; Lodhi, M.S.; Arya, O.P.; et al. From Forests to Carbon Neutrality: The Role of REDD+ in Climate Mitigation. In *Forestry for a Carbon-Neutral and Sustainable Future*; Singh, H., Ed.; Springer: Cham, Switzerland, 2026. [CrossRef]
17. Pant, H. Aftermath of Chipko: Women Are the Undervalued Protagonists of Forest Management. In *The Participatory Role of Indigenous Women*; Moran, N., Singh, P., Kumar Singh, K., Eds.; Springer: Cham, Switzerland, 2026. [CrossRef]
18. Vega, J.A.; Fernández, C.; Pérez-Gorostiaga, P.; et al. Response of maritime pine (*Pinus pinaster* Ait.) recruitment to fire severity and post-fire management in a coastal burned area in Galicia (NW Spain). *Plant Ecol.* **2010**, *206*, 297–308.
19. Ager, A.A.; Vaillant, N.M.; Finney, M.A. A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface. *For. Ecol. Manag.* **2010**, *259*, 1556–1570.
20. Abbas, K.; Souane, A.A.; Ahmad, H.; et al. Correlating Fire Incidents with Meteorological Variables in Dry Temperate Forest. *Forests* **2025**, *16*, 122.
21. Oliveira, A.P.; Gil Martins, P. Global Shifts in Fire Regimes Under Climate Change: Patterns, Drivers, and Ecological Implications across Biomes. *Forests* **2026**, *17*, 104.
22. Masinda, M.M.; Sun, L.; Wang, G.; et al. Moisture Content Thresholds for Ignition and Rate of Fire Spread for Various Dead Fuels in Northeast Forest Ecosystems of China. *J. For. Res.* **2021**, *32*, 1147–1155.
23. Sullivan, A.L.; McCaw, W.L.; Cruz, M.G.; et al. Fuel, Fire Weather and Fire Behaviour in Australian Ecosystems. In *Flammable Australia: Fire Regimes, Biodiversity and Ecosystems in a Changing World*; CSIRO Publishing: Clayton, Australia, 2012; pp. 51–77.
24. Uttarakhand Forest Department. *Forest Fire Statistics and Management Report 2019–20*; Government of Uttarakhand: Dehradun, India, 2020.
25. Pandey, S.; Dhakal, R.P. Pine Needle Briquettes: A Renewable Source of Energy. *Int. J. Energy Sci.* **2013**, *3*,

254–260.
26. Olmedo, G.F.; Gilabert, H.; Bown, H.; et al. Improving the Combustion Factor to Estimate GHG Emissions Associated with Fire in *Pinus radiata* and *Eucalyptus* spp. Plantations in Chile. *Forests* **2023**, *14*, 403.
27. Roy, M.; Chakravarty, S.; Kishore, B.; et al. Sustainable Fuel Production: Briquetting and Characterization of Torrefied Pine Needle Biochar. *Biofuels* **2025**, 1–12.
28. Sugandha; Phartiyal, M.; Jugran, H.P. Scoping of Forest Resources in Light of Climate Change Implications in Western Himalayan Region. In *Climate Change Impact on Himalayan Biodiversity*; Arya, D., Chandra, N., Kumar, R., et al., Eds.; Springer: Cham, Switzerland, 2025. [CrossRef]
29. Higgins, J.P.T.; Thompson, S.G. Quantifying heterogeneity in a meta-analysis. *Stat. Med.* **2002**, *21*, 1539–1558.
30. Thompson, S.G.; Higgins, J.P.T. How should meta-regression analyses be undertaken and interpreted? *Stat. Med.* **2002**, *21*, 1559–1573.
31. Rothermel, R.C. *A Mathematical Model for Predicting Fire Spread in Wildland Fuels*; USDA Forest Service: Ogden, UT, USA, 1972.
32. Gupta, A.; Ghosh, P.; Arora, K.; et al. Valorization Potential of Pine Needle Waste Biomass: Recent Trends and Future Perspectives. *Environ. Sci. Pollut. Res.* **2024**, *31*, 36136–36151.
33. Bhandari, B.S.; Mehta, J.P.; Semwal, R.L. Forest Fire in Uttarakhand Himalaya: An Overview. In *Glimpses of Forestry Research in the Indian Himalayan Region*; GB Pant Institute of Himalayan Environment & Development: Almora, India, 2012; pp. 167–176.
34. DerSimonian, R.; Laird, N. Meta-analysis in clinical trials. *Control. Clin. Trials* **1986**, *7*, 177–188.
35. Higgins, J.P.T.; Thompson, S.G.; Deeks, J.J.; et al. Measuring inconsistency in meta-analyses. *BMJ* **2003**, *327*, 557–560.
36. Singh, P.; Singh, T.P.; Sharma, R.K.; et al. Potential of Pine Needle Biomass as an Alternative Fuel to Mitigate Forest Fire in Uttarakhand Himalayas—A Review. *J. Agric. Eng.* **2021**, *58*.
37. Viechtbauer, W. Conducting meta-analyses in R with the metafor package. *J. Stat. Softw.* **2010**, *36*, 1–48.
38. Borenstein, M.; Hedges, L.V.; Higgins, J.P.T.; et al. *Introduction to Meta-Analysis*; John Wiley & Sons: Chichester, UK, 2009.
39. Forest Survey of India. *India State of Forest Report 2021*; Forest Survey of India, Ministry of Environment, Forest and Climate Change, Government of India: Dehradun, India, 2021.
40. Sharma, S.; Pant, H. Vulnerability of Indian Central Himalayan Forests to Fire in a Warming Climate and a Participatory Preparedness Approach Based on Modern Tools. *Curr. Sci.* **2017**, *112*, 2100–2105.
41. Kakati, U.; Aier, I.; Anand, A.; et al. Thermo-kinetic and techno-economic analysis of biochar conversion of pine needles for clean fuel production in the Himalayan region of India. *Bioresour. Technol. Rep.* **2025**, *30*, 102104.
42. Fulé, P.Z.; Garkoti, S.C.; Semwal, R.L. Frequent burning in chir pine forests, Uttarakhand, India. *Fire Ecol.* **2021**, *17*, 20.
43. Goparaju, L.; Pillutla, R.C.; Venkata, S.B. Assessment of forest fire emissions in Uttarakhand State, India, using open geospatial data and google earth engine. *Environ. Sci. Pollut. Res.* **2023**, *30*, 100873–100891.
44. Pant, H.; Upadhyaya, P. Avenues for ecosystem-based adaptations through pine needle-based livelihood enhancement of women in the Western Himalayan region. In *The Participatory Role of Indigenous Women*; Moran, N., Singh, P., Kumar Singh, K., Eds.; Springer: Cham, Switzerland, 2026; pp. 43–72. [CrossRef]
45. Pinto, A.; Fernandes, P.M. Microclimate and Modeled Fire Behavior Differ between Adjacent Forest Types in Northern Portugal. *Forests* **2014**, *5*, 2490–2504.
46. Pant, H.; Tewari, A. Carbon Sequestration in Chir-Pine (*Pinus roxburghii* Sarg.) Forests under Various Disturbance Levels in Kumaun Central Himalaya. *J. For. Res.* **2013**, *25*, 401–405.
47. Bhatt, H.; Jugran, H.P. Community-Managed Forests and Their Effectiveness in SDG Implications in the Western Himalayan Region. In *Warming Mountains*; Tripathi, S., Bhadouria, R., Garkoti, S.C., Eds.; Springer: Cham, Switzerland, 2024. [CrossRef]
48. Pant, H.; Sugandha. Climate Change and Forest Resource Depletion: Perception Based Assessment of Community Based Forests in Western Himalayan Region. *J. Earth Environ. Sci.* **2018**, *2018*, 154.