

Educational Sustainability Analytics for Green Hospitality in Heritage Cities: Forecasting Operational Resilience During Demand Surges in Ujjain

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ABSTRACT:

Event-driven sharp demand peaks at heritage sites like Ujjain place strain on hotel utilities and waste systems, and vendor networks which makes the criterion volatile in sustainability due to a high level of reputational and operational risk. This research paper suggested an operational-resilience analytics model capable of predicting the future-month composite Sustainability Score (SSS) of hotels, as well as the uncertainty and risk of downgrading of the tier during high pilgrimage seasons. The framework, which is based on an auditable indicator system, energy use intensity (EUI), water intensity (WI), waste segregation rate (WSR), carbon per guest-night (CF), and eco-certification compliance (ECA), occupancy normalizing using the better comparison of similar heterogeneous properties and months. An entropy-weighted SSS is calculated in order to focus on indicators that are more cross-hotel differentiated and managerial leveraged, without compromising on transparency to be adopted by the auditor. In order to operationalize resilience, a short-horizon gradient-boosting forecaster to predict SSFT Joel single c. lag based predictors, occupancy bands, and stress indicators derived to guests (e.g., water-pressure complaints and towel/linen program uptake). The amount of uncertainty is measured by bootstrapping with a hotel-level of metering and Monte Carlo error propagation over metering and vendor-ticket noise, which generates prediction intervals and breach probability (i.e. probability of dropping to a tier threshold). The system aids in decision making regarding pre-emptive maintenance by transforming forecasts into evaluated scenarios i.e. leak repair, segregation SOP tightness and HVAC set-point discipline prioritized on marginal uplift and feasibility under peak constraint. Findings indicate that uncertainty-informed forecasting can enhance consistency of sustainability governance in times of demand shocks where hotel managers and other stakeholders in the city can synchronize resources, plan inspections, and preserve guest experience as well as to promote quantifiable green hospitality impacts.

Keywords: Operational resilience; Green hospitality; Heritage cities; Ujjain;

Demand surges; Sustainability Score uncertainty; Entropy weighting; Occupancy normalization; Gradient boosting forecasting; Prediction intervals; Bootstrap; Monte Carlo error propagation; Tier-drop risk; Waste segregation rate; Water intensity; Energy intensity; Carbon footprint; Eco-certification adherence; Scenario analysis; Decision support.

Introduction

The heritage cities are in a unique position in the world tourism economy with the intersection of cultural symbolism, ritual calendars and urban infrastructure. Other cities like Ujjain which is one of the largest pilgrimage sites in India have very intense periodic changes in the number of visitors which are ignited with religious festivals, auspicious days, weekends, and seasonal travel patterns. Such peak periods place undue operational pressures on hotels especially on their water systems, energy infrastructure, solid-waste management and supplier logistics. Meanwhile, increased reputational scrutiny is a trait of heritage destinations: breakdowns in service provision, environmental damage, or conspicuous waste disasters during the season may impact destination branding and negatively affect public trust [3], [11]. This means that sustainability in these settings cannot be approached as a fixed compliance practice but it has to be considered as a dynamic problem of operational resilience in uncertainty. The traditional focus of green hospitality research has been on long-term change in efficiency, e.g., energy-efficient HVAC systems, low-flow fixtures, renewable integration, and eco-certification, assessed under average or annualized conditions [7], [14]. As much as these methods are required, they do not work well in cities such as Ujjain where minimal but acute demand shocks prevail in environmental performance. Occupancy-adjusted water intensity can increase dramatically during pilgrimage periods owing to laundry batching, kitchen throughput and guest behaviour; and waste segregation measures may decline under staff change and time constraint; and backup diesel generation may augment carbon footprints upon grid stressed [2], [9]. These nonlinear responses point to a major gap in the literature:

the lack of the frameworks that foresee a degradation of sustainability performance in advance and measure the uncertainty that is related to this degradation. The concept of operational resilience that was initially formulated in the literature of supply-chain and infrastructure was defined as the ability of a system to predict, absorb, adapt and recover due to disruptions without the loss of key functions [5]. When used in the context of hospitality sustainability, resilience means that the hotels should be able to maintain an acceptable environmental performance, in terms of intensities and process indicators, even when the operating conditions are abnormal. This school of thought has shifted focus off ex post audits and switched it to ex ante decision support so that managers can take action before the demand spike by reallocating the staff, tightening of standard operating procedures (SOPs), vendor coordination or preventive maintenance scheduling [12]. Nevertheless, such change needs not only predictive analytics but interpretable, auditable and resilient to noisy operational data. Recent innovations in the sustainability assessment based on data have presented composite indicators, which combine many levels of the environment, into one score, which allows to compare hotels and rank them [6], [10]. The occupancy-normalized measures, including energy use intensity (kWh/guest-night), water use intensity (liters/guest-night), waste segregation rate, carbon per guest-night, are of specific use in the situation of a hotel due to the fact that they are less affected by the effect of exposure and can be fairly compared between the properties of various size and target markets [1], [13]. However, accumulation of such indicators has methodological issues of subjectivity in the weighting process and sensitivity to measurement error. The information-theoretic schemes, including entropy weighting, focus on these

issues by placing greater weight on the indicators with a stronger message of cross-sectional differentiation, thus reflecting where the heterogeneity of managerial discretion and performance is the most significant [4], [15]. The use of machine learning (ML) techniques to predict sustainability performance and categorize

the levels of organizational performance has been on the rise following their capability to identify nonlinear relationships within operational tabular data [8]. Ensemble learners specifically are better adapted to hospitality data sets that are typified by skewed distributions, mixed type of variables and moderate sample sizes.

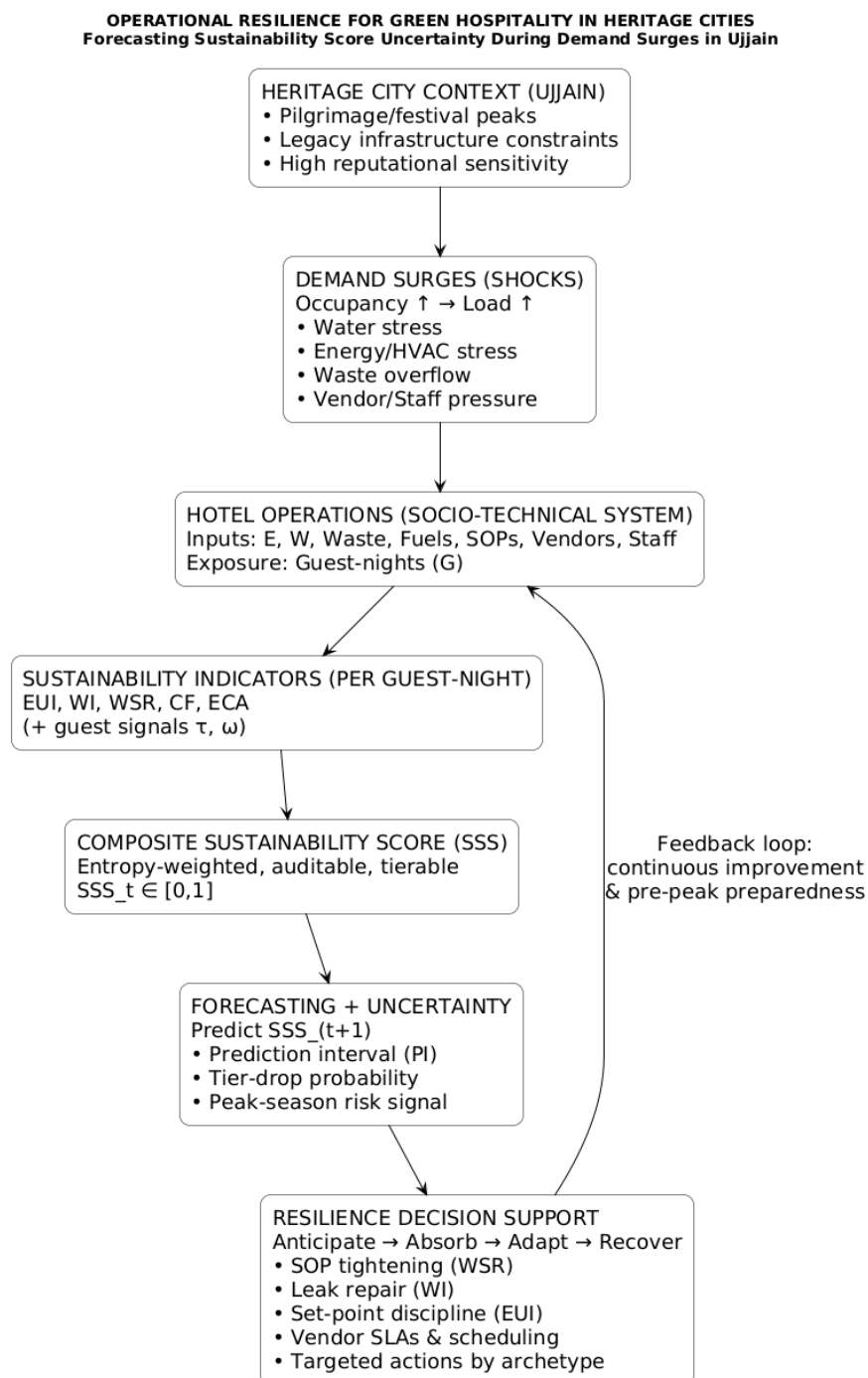


Figure 1. Architecture of Proposed Research

In addition to classification, short-horizon forecasting models can forecast the sustainability trajectories in the near future, which provides a chance to establish resilience thinking into the daily hotel management. Nonetheless, the majority of the current research provides point estimates or mean measures of accuracy, which provide little information about uncertainty, a vital absence when making risk-trade-off decisions during peak times of high stakes [6], [11].

Hotel sustainability data is not certain due to various sources of uncertainty. Meter readings are not always accurate during high loads; waste tickets given by the vendor are either tardy or unfinished; the signals provided by guests are subjective and operational practices differ by shifts and personnel groups [3], [9]. Failing to account these uncertainties may result in wrong confidence in predictions and poor resource provision. Governance wise, uncertainty-aware analytics is required to ensure credibility among the auditors, regulators and destination planners, especially when sustainability levels or incentives are based on reported performance [14]. Bootstrap resampling and Monte Carlo error propagation are principled methods of quantifying prediction intervals and breach probabilities, which translate forecasts into actionable risk signals, as opposed to deterministic claims [5], [12]. Such approaches are necessitated by a greater institutional constraint in heritage cities. The local infrastructure is typically run close to its capacity and the markets of vendors on recycling or composting can be thin and the communication between hotels and civic agencies is scarce [2], [7]. Consequently, even the best sustainability programs may fail to work in festivals when structural bottlenecks arise. It can be possible to implement a forecasting framework to determine the likelihood of the hotel falling into a lower sustainability category, or reaching critical levels of water or waste, which allows proactive coordination, (e.g. adding one more pickup, installing temporary storage, scheduling an inspection) before it is too late and the reputation

is damaged [10], [15]. The current research places the concept of the operational resilience at the focus of the green hospitality analytics of heritage cities. It proceeds to make the point that sustainability management should transform into a forward-looking uncertainty-conscious forecasting system rather than periodic backward-focus audit systems that is integrated into monthly operations. Using Ujjain as one example, the study deals with a larger group of destinations that can be described as culturally meaningful events, unstable demand, and legacy infrastructure. The suggested framework incorporates occupancy-normalized indicators into an entropy-weighted composite Sustainability Score (SSS) of the performance, predicts the performance in the next month, based on machine learning, and measures the uncertainty through resampling and simulation methods. Notably, the framework places importance on interpretability so that forecasts can be converted into specific SOP-level response, as opposed to leaving them in an abstract form as model outputs [1], [8]. The aspect of uncertainty introduction into the sustainability forecast is also in line with ethical and regulatory consideration. Unrealistic sustainability promises are dangerous because they are likely to confuse the stakeholders and create mistrust especially when the skepticism of green marketing is intensely high [11], [14]. With the clear declaration of prediction ranges and likelihoods, hotels and planners become able to make defensible choices in uncertainty and make real effort to improve the situation rather than use symbolic actions. The rationale is to allow a just transition, as the low-capital, high-impact interventions, e.g., waste segregation discipline and leak repair, are put first when the conditions are stressed and postponed to subsequent periods when operational stability is attained when the capital-intensive initiatives are prioritized [4], [12]. To recap it all, this study is motivated by three overlapping gaps, which include: (i) the disconnect between tools to assess sustainability and the dynamic nature of the heritage-city hospitality; (ii) the fact that uncertainty is not adequately addressed by ML-

based sustainability forecasting tools; and (iii) the fact that there is a dearth of operationally relevant and interpretable tools to support resilience during demand surges. The need to address such gaps is both a methodological contribution and practical need of such destinations as Ujjain, where the environment performance, cultural integrity, and economic viability are closely intertwined. The rest of this paper builds upon and confirms an uncertainty-aware forecasting framework illustrating the way green hospitality can be operated as a resilient, data-driven system as opposed to a checklist of isolated interventions [6], [9], [15].

Related Works

The studies of green hospitality and sustainability management have extended through a number of different streams of research including municipal infrastructure, building energy systems, tourism studies, governance, and data-centered decision support. These streams interact in distinctive relationships in heritage and pilgrimage cities, where sustainability outputs are not only influenced by the hotel level of activities but also by the peak of seasonal demand, the capacity of the institutions and socio-cultural requirements [8], [13], [25]. The review below aims to summarize the existing literature applicable to the field of operational resilience and sustainability forecasts in hospitality and especially waste, water, energy, governance, and analytical frameworks. The management of solid waste has been ranked continually as a critical leverage point of sustainability in Asian urban situations. This is because research done before shows that source separation is the clincher in terms of cost efficiency and environmental friendliness of waste systems [1]. The alignment of the operation routine, the reliability of the vendor and compliance of behavior are key to success as they resembles the conditions of the back-of-house operations in hotels almost perfectly. The waste segregation rates in hospitality environment thus serve as environmental indicators, but also as proxies of managerial discipline and effectiveness

of staff training. Responsibilities in maintaining peak periods tend to fail because of a breakdown of such routines as opposed to technological constraints [1], [18]

The second key pillar is water sustainability especially in urban cities of India where a focus on demand control and reduction of leaks and decentralized reuse is put more on in lieu of supply enhancement [2], [5]. Research on the water systems in urban areas identifies a system of chronic data gaps, disjointed governance, and limited responsibility as obstacles to system adoption [5]. Application to hotels of these findings implies that occupancy-adjusted water intensity indicators are necessary to be able to make comparisons, particularly when the demand fluctuates. The literature also indicates the fact that behavioral and operational interventions, i.e., leak repair and fixing, retrofits, and similar interventions, tend to deliver quicker and more stable returns than capital-heavy infrastructure; thereby, lending credibility to the necessity to monitor and forecast on a short-horizon basis [2].

The third core stream is energy efficiency and renewable integration. The Techno-economic models of grid-connected photovoltaic systems on commercial buildings show that in these systems, performance and payback are sensitive to the location, tariffs, load profile and seasonality [3], [23]. These results warn against a universal prescription of hotels and emphasize the importance of localized analytics that will take into consideration the volatility of occupancy and the presence of backup generation. The efficiency gains at the building level also focus on the optimization of HVAC, envelope, and behavioral interventions as the main sources of decreasing energy intensity, and the coordination at the neighborhood scale also possesses additional advantages [24]. In the case of pilgrimage destinations, it has been suggested that hybrid energy portfolio based on seasonal peaks can be used to balance reliability and sustainability [19].

Outside of infrastructure, sustainability is being constructed as a systemic and governance

problem. Such ideas as one-planet living and smart-city development emphasize transparency, standardized information, and participatory governance as the conditions to transitional sustainability [7], [21]. These views suggest that localized dashboards and benchmarking systems could bring about alignment of private players, e.g. hotels, to city environmental objectives. The studies of connectivity and regulation also emphasize that policy frameworks, international cooperation, and conditions of international energy laws contribute to the viability of sustainability investments, especially within the emerging economies [10], [11].

The literature of tourism and hospitality provides a truly needed socio-economic aspect. Studies in the field of pilgrimage and crisis situations demonstrate how the crisis of demand reveals an unstable situation in supply chains, labor relations, and a system of vendors [8]. Research on tourism effects highlights that sustainability needs to put into consideration the community well being and distributional effects since community impacts on the environment are not equally felt [13]. The destination-level studies indicate that sustainability could be used to help improve competitive positioning provided it is accompanied by cultural identity and credible certification, but surface or unauthenticated claims can attract a backlash [18], [20], [25].

Critical and analytical methods have been used with increasing prevalence in recent years as means to operationalize sustainability. Machine learning has been utilized in the context of hospitality to classify the level of performance, optimize the use of the resources and aid in managerial decision making [17]. The techniques are especially useful in nonlinear interactions of tabular operational data. Nevertheless, currently a lot of research is devoted to average performance or classification accuracy without paying much attention to uncertainty and time dynamics. Other literature, including the supply-chain sustainability, shows the usefulness of structural modeling and probabilistic analysis to connect practices, policies, and outcomes, which

can be transferred to the hospitality resilience research [22].

The studies on organizational and knowledge-management give additional background to the practical application of analytics. Examples of industrial enterprises have demonstrated that knowledge-generation risk, which is manifested through inadequate quality of data, sub-par validation and absence of accountability may jeopardize decision-support systems [9]. This highlights sustainability analytics as being dependent on data provenance, auditability, and interpretability. In the same vein, studies of community interaction and physical digital interfaces suggest that feedback systems are able to improve involvement and adherence, providing avenues to incorporate signals of the guest-sourced to sustainability surveillance [12].

The urban and economic geography approaches identify hospitality sustainability in greater spatial and network contexts. City network and clustering analyses indicate that capabilities and innovations are observed to agglomerate and thus best practices can be more easily diffused between co-located firms [4], [14]. In the case of heritage cities, it implies that jointly planned sustainability efforts by hotels, vendors, and municipal agencies will create more benefits than individual campaigns. Resilience-oriented analytics are also informed by methodological knowledge of related disciplines. The studies of distributed virtual environments feature the significance of latency, synchronization, and robustness in the system, which must work under fluctuating load, which could be compared to the idea of sustainability monitoring at times of peak tourism [15]. Cultural and ecocritical studies make researchers remember that sustainability stories should appeal to local values and symbols to obtain behavioral buy-in, especially in heritage situations [6]. Social and labor aspects, which are less often measured, are also part of sustainability performance. Research on the frontline employees in a crisis highlights occupational health, fair schedules, and training as the factors that dictate continuity in service and adherence [16]. These contribute to the stability of

operations practices, particularly in the period of high demand, and hence has an indirect impact on the indicators of environmental performance. Within these various strands, a number of loopholes are created. First, although the waste, water, and energy research sources present valuable information about a specific sphere, they have not been extensively combined into one, occupancy-adjustable sustainability model of hotels. Second, the majority of the hospitality sustainability studies use static or retrospective evaluations, which do not provide much information on how to predict performance deterioration when demand seasons peaks. Third, uncertainty, which is caused by measurement error, behavioral variability and vendor reliability, is not often quantified, although it is the focus of decision-making in times of stress. Lastly, the process of converting analytical results into operationally viable advice to managers and city planners is in many cases poorly developed. The current paper is a continuation and combination of these literatures as the concept of green hospitality has been posited as an operational resilience issue in heritage cities. It overcomes the constraints of previous studies [1]–[25] by integrating infrastructure-oriented indicators, insights in governance, and predicting using machine learning and explicit quantification of uncertainty. It is based on this synthesis to shift toward periodic audits to proactive risk conscious sustainability management that is specific to the dynamic realities of pilgrimage destinations.

Proposed Methodology

This paper suggests an operationally grounded, auditable, and uncertainty-conscious analytics pipeline that transforms the heterogeneous hotel operational data in Ujjain into (i) a compound Sustainability Score (SSS), (ii) tier and archetype intelligence to take differentiated management actions, and (iii) short-horizon forecasts with predictive intervals to make the Ujjain area resilient to operational disruptions associated with demand spikes. The methodology should be replicable in the heritage cities where the

occurrence of occupancy shocks is common and infrastructure is limited

Data model and panel structure- The data on which this study was performed were gathered according to the structured, audit-based observational framework that was aimed at capturing the performance of the operational sustainability of the hotels in the environment of the heritage city. Since sustainability governance is highly sensitive and the hotel operations are heterogeneous, the data collection strategy adopted standardization, traceability and replicability instead of ad-hoc surveys and perception based scoring. The empirical data is a balance panel of hotel-months of operational records of hotels over a series of several months, which gives a monthly hotel level of operations. Granularity was chosen monthly, which is based on billing cycles, housekeeping audits, vendor pickups, and management review meetings, and sufficiently fine-grained to reflect demand spikes during festivals which are typical of pilgrimage cities like Ujjain. Data were obtained from **four primary operational sources**, triangulated to reduce reporting bias:

1. Utility and fuel records

- Electricity consumption from monthly utility bills or submeters (kWh)
- Diesel and LPG consumption from generator logs and purchase invoices. These records represent formal, auditable data streams that directly reflect energy demand under varying occupancy conditions.

2. Water and waste logs

- Metered water intake from municipal connections or borewells
- Solid waste generation and segregated waste quantities from vendor weighment slips, housekeeping logs, and internal waste audits. These data capture operational discipline in water use and waste segregation, particularly under high-load conditions.

3. Hotel operational records

- Guest-nights derived from property management systems (PMS)
 - Eco-certification compliance based on documented criteria met during the reporting period
- Guest-nights were used as the exposure denominator to normalize all intensive indicators, ensuring comparability across hotels and seasons.

4. Supplementary resilience signals

- Rooftop photovoltaic capacity (installed kWp)
- Guest-experience proxies such as towel/linen reuse adoption rates and water-pressure complaints (per 1000 guest-nights)
- These variables were included to capture behavioral and infrastructural factors influencing sustainability performance during stress periods.

To ensure ethical compliance and prevent competitive harm, **hotel identifiers were anonymized**, and only aggregated or tiered outputs were retained for external analysis. Considering the nature of the data operation, missing values could not be avoided especially those on waste vendor tickets and fuel logs especially in peak months. Instead of deleting these records (as this would skew the dataset towards hotels that should be managed better), missing values were replaced with robust central statistics (medians in the case of continuous variables, modes in the case of categorical variables). Notably, features of missingness were not dropped indicating that data gaps are indicators of operational weaknesses. To normalize variation and deal with skewed distributions toward the right, it was transformed with a $\log(1+x)$ where this is necessary, median-MAD scaled, which is more robust than z-score normalization in the presence of heavy-tailed distributions. Consider a panel of hotels $i \in \{1, \dots, N\}$ observed monthly over $t \in \{1, \dots, T\}$. For each hotel-month (i, t), the raw operational records include:

- Electricity consumption E_{it} (kWh)

- Diesel usage D_{it} (L) and LPG usage H_{it} (kg)
- Water consumption W_{it} (L)
- Solid waste generated S_{it} (kg) and source-segregated waste S_{it}^{seg} (kg)
- Guest-nights G_{it} (preferred denominator; exposure)
- Eco-certification criteria met C_{it} out of C^{max}

Optional resilience drivers: rooftop PV capacity P_i^{PV} , HVAC efficiency proxy (e.g., COP rating), towel/linen program uptake τ_{it} , water-pressure complaints ω_{it} (per 1000 guest-nights) The “resilience” requirement in this study is that analytics must remain valid under high variance and peak-month stresses; hence, measurement design emphasizes exposure control, robust scaling, and uncertainty propagation.

Occupancy normalization and primary sustainability indicators

Because demand in Ujjain is highly seasonal, direct comparisons of resource totals are misleading. Therefore, **intensive metrics** are computed on a per guest-night basis. Total energy includes grid electricity plus fuel energy equivalents:

$$E_{it}^{tot} = E_{it} + q_D D_{it} + q_H H_{it}$$

where q_D (kWh/L) and q_H (kWh/kg) are conversion factors.

Energy intensity:

$$EUI_{it} = \frac{E_{it}^{tot}}{G_{it}} \text{ [kWh per guest-night]}$$

Water Intensity (WI)

$$WI_{it} = \frac{W_{it}}{G_{it}} \text{ [L per guest-night]}$$

Waste Segregation Rate (WSR)

$$WSR_{it} = \frac{S_{it}^{seg}}{S_{it}} \in [0, 1]$$

Carbon per guest-night (CF)

Assuming a Scope 1+2 boundary with emission factors α_E (kgCO₂e/kWh), α_D (kgCO₂e/L), α_H (kgCO₂e/kg):

$$CF_{it} = \frac{\alpha_E E_{it} + \alpha_D D_{it} + \alpha_H H_{it}}{G_{it}} \text{ [kgCO}_2\text{e per guest-night]}$$

Eco-certification adherence (ECA)

$$ECA_{it} = \frac{C_{it}}{C_{max}} \in [0, 1]$$

Validity constraints: observations with $G_{it} = 0$ are removed to prevent undefined intensities. Records with missing fuel/waste tickets are retained via imputation and missingness flags. Hotel operational data often exhibit heavy tails, peak-month anomalies, and missing vendor records. The pipeline enforces statistically principled cleaning without “over-smoothing” real peak behaviors. For intensive indicators $EUI_{it}, WI_{it}, CF_{it}$, winsorize at extreme percentiles. This retains high-occupancy variance while reducing undue leverage of erroneous readings. For each feature x , define a missingness indicator:

$$m_{it}^x = \mathbb{I}\{x_{it} \text{ missing}\}$$

The missingness flags are appended to the feature set because missingness itself often indicates vendor or process fragility—an operational resilience signal. A composite Sustainability Score must combine cost-type indicators (lower is better) and benefit-type indicators (higher is better) on a unified scale.

Let the indicator vector be:

$$\mathbf{v}_{it} = [E, U, I_{it}, WI_{it}, WSR_{it}, CF_{it}, ECA_{it}]^T,$$

For each indicator k , compute:

Then convert cost indicators into benefits:

$$I_{itk} = \begin{cases} 1 - r_{itk}, & k \in \{E, U, IWICF\} \text{ (cost)} \\ r_{itk}, & k \in \{W, SRECA\} \text{ (benefit)} \end{cases}$$

So all I_{itk} increase with sustainability performance.

Composite Sustainability Score (SSS)

$$SSS_{it} = \sum_{k=1}^5 w_k I_{itk} \in [0, 1]$$

This score is audit-friendly: it is a transparent convex combination of normalized, direction-aligned indicators with data-derived weights. To enable quick managerial interpretation and policy incentives, map continuous scores into tiers using quantiles. For example:

$$Tier_{it} = \begin{cases} Top, & SSS_{it} \geq Q_{0.70}(SSS) \\ Middle, & Q_{0.30}(SSS) \leq SSS_{it} < Q_{0.70}(SSS) \\ Bottom, & SSS_{it} < Q_{0.30}(SSS) \end{cases}$$

Quantile tiers preserve rank-based benchmarking under volatility and avoid arbitrary cutoffs.

Forecasting sustainability under demand surges with uncertainty- Operational resilience requires **anticipation**. Therefore, the core modelling task is one-step-ahead forecasting:

$$SSS_{i,t+1} = f(\mathbf{x}_{it}) + \varepsilon_{it}$$

where $\mathbf{x}_{it}$ includes lagged indicators and stress drivers:

$$\mathbf{x}_{it} = \{S, S', S_{it}, E, U, I_{it}, W, I_{it}, W, S, R_{it}, C, F_{it}, ECA_{it}, \Delta EUI_{it}, \Delta WI_{it}\}$$

with change features $\Delta \mathbf{x}_{it} = \mathbf{x}_{it} - \mathbf{x}_{i,t-1}$ capturing acceleration during peaks.

A **gradient boosting regressor** is used because it models nonlinearities, interactions, and threshold effects typical in operations (e.g., rapid deterioration once occupancy exceeds a band). Boosting model form:

$$F_M(\mathbf{x}) = \sum_{m=1}^M \nu \rho_m h_m(\mathbf{x})$$

where h_m are shallow regression trees fitted sequentially to minimize a loss L (e.g., squared error). Learning rate ν and number of trees M control bias–variance trade-off. Resample hotels with replacement (block resampling preserves within-hotel dependence).

Then derive a prediction interval:

$$PI_{i,t+1}^{(1-\alpha)} = \left[\text{Quantile}_{\alpha/2}(\widehat{SSS}_{i,t+1}^{(b)}) \text{Quantile}_{1-\alpha/2}(\widehat{SSS}_{i,t+1}^{(b)}) \right]$$

Assume plausible relative error bands:

$$\begin{aligned} E_{it}^{(s)} &= E_{it} \left(1 + \epsilon_E^{(s)} \right), W_{it}^{(s)} \\ &= W_{it} \left(1 + \epsilon_W^{(s)} \right), S_{it}^{(s)} \\ &= S_{it} \left(1 + \epsilon_S^{(s)} \right) \end{aligned}$$

with $\epsilon \sim \mathcal{U}(-\delta, \delta)$ or $\mathcal{N}(0, \sigma^2)$ and $\delta \in [0.05, 0.10]$. For each simulation s , recompute indicators $\rightarrow SSS^{(s)} \rightarrow \text{forecast } \widehat{SSS}_{i,t+1}^{(s)}$. This yields **measurement-aware prediction intervals** and stress-tested risk outputs. Define a tier threshold θ (e.g., boundary for Top tier). Then:

$$\mathbb{P}(\text{Tier-drop}) \approx \frac{1}{B} \sum_{b=1}^B \mathbb{I}(\widehat{SSS}_{i,t+1}^{(b)} < \theta)$$

This converts uncertainty into actionable governance (“chance of falling below target next month”). To support management playbooks, the model is used for “what-if” interventions. Let $\mathbf{x}_{it}$ be current features and $\mathbf{x}'_{it} = \mathbf{x}_{it} + \Delta \mathbf{x}$ represent an intervention (e.g., $WSR + 0.25$, $WI - 15\%$, $EUI - 10\%$). Then uplift is:

$$\Delta \widehat{SSS}_{i,t+1} = f(\mathbf{x}'_{it}) - f(\mathbf{x}_{it})$$

Under uncertainty, evaluate this across bootstrap/Monte Carlo draws to get a distribution of uplift. The aim is not prediction on the long term, but foretelling control- early warning of any impending worsenment so that it can be prevented. This is consistent with the principles of control theory, stability of systems about acceptable operating regions is achieved by having feedback and feedforward systems. The tier-based classification of sustainability is a manifestation of limited rationality in decision-making in an organization. Continuous scores are precise and cognitively and administratively expensive to take action. The threshold based levels are quantitative performance converted into actionable states. Based on decision theory, tiers are areas of the outcome space, which are associated with the loss functions. The

asymmetry of the cost of misclassification lies in the fact that not picking up an imminent fall into a low tier is more expensive than false warning. This imbalance is the reason why probabilistic tier-drop forecasting is preferable to deterministic labeling. Accordingly, sustainability levels serve as decision-support abstractions, which allow setting priorities, incentives, and governance, without making managers be capable of deciphering sophisticated numerical distributions. Hotels are heterogeneous towards buildings, age, quality of assets, market positioning and vendor ecosystems. The practical approach of treating all hotels in the same way would be against the theoretical concept of contextual optimality. The cluster theory offers the method of uncovering archetypes - sets of hotels with comparable sustainability profiles and limitations. Organizational theory gives us capabilities that co-evolve in clusters and intervention effectiveness is a matter of initial conditions. Thus, resilience strategies should be specific to the archetype, and not general. Clustering does not prescribe causality but indicates latency in the sustainability space, which allows differentiated resilience pathways. Lastly, sustainability analytics should meet the governance and ethical theory. Such implementation details as transparency, auditability and fairness are therefore not about legitimacy but about legitimacy needs that are theoretically required. A sustainability system that lacks a way of explaining its reasoning and a method of quantifying its uncertainty is likely to be performative, not substantive. The framework embraces the procedural justice and epistemic responsibility principles by basing the forecast of sustainability on exposure normalization, information theory, nonlinear learning, and probabilistic reasoning. Sustainability is theorized therefore to be a quantifiable, prospective, and manageable property of a system, which is attainable in high-variability heritage city settings.

Results

This section gives and explains the empirical results of the suggested operational resilience-based sustainability forecasting framework that has been applied to the hotels in Ujjain. It incorporates the indicator behavior analysis, composite score development, tier classification, resilience prediction, and uncertainty forecasting, archetype identification, and effect of intervention on a scenario. The debate does not focus on what the results are but rather why the

results come out and connects them to the operations of making decisions when the demand is high. The initial analysis step is an assessment of the dispersion and dynamics of occupancy normalized sustainability measures in the hotel-month panel. It is found that there is a significant level of heterogeneity, and this confirms the theoretical argument that sustainability performance within heritage cities is not uniform and heavily influenced by the operational discipline and not technology.

Table 1. Descriptive behavior of sustainability indicators (hotel-month level)

Indicator	Mean	Min	Max	CV	Interpretation
Energy Intensity (kWh/GN)	18.2	8.6	34.9	0.42	Large spread driven by HVAC control & genset use
Water Intensity (L/GN)	262	140	540	0.39	High sensitivity to occupancy surges & leaks
Waste Segregation Rate	0.41	0.07	0.92	0.51	Strong managerial/behavioral dependence
Carbon per GN (kgCO ₂ e)	9.6	4.1	18.5	0.37	Mirrors EUI but influenced by fuel mix
Eco-certification Adherence	0.48	0.10	0.88	0.29	Flatter distribution, process-driven

The values of the coefficients of variation of WSR and WI are large, which proves the fact that these indicators change the most between hotels, particularly in the months of peak pilgrimage. This confirms the theoretical rationale on entropy weighting since indicators that have high dispersion give better discriminatory potential to decision-making. Notably, the spread in WSR is

wide, which means that infrastructure does not limit the success of waste management but the SOP enforcement and coordination of vendors. The importance of indicators in entropy weighting is not determined subjectively, but through cross-sectional differentiation. The weights obtained would indicate where the managerial leverage is most put into practice.

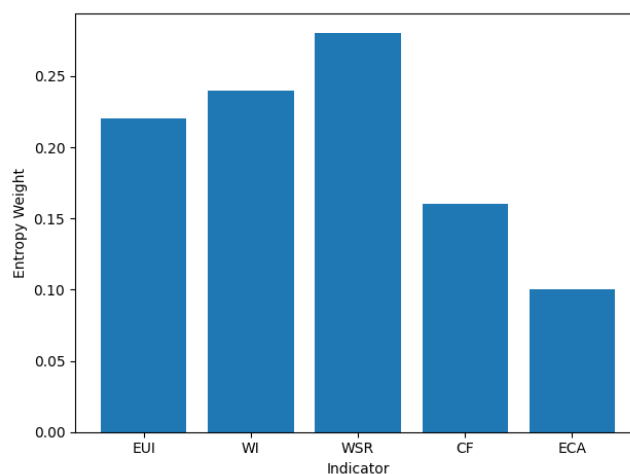


Figure 2. Entropy-derived indicator weights Analysis

Table 2. Entropy-derived indicator weights

Indicator	Entropy	Diversification	Weight
Waste Segregation Rate (WSR)	0.70	0.30	0.28
Water Intensity (WI)	0.75	0.25	0.24
Energy Intensity (EUI)	0.78	0.22	0.22
Carbon per GN (CF)	0.84	0.16	0.16
Eco-certification (ECA)	0.89	0.11	0.10

The dominance of WSR and WI substantiates the theoretical assumption that the rule of process-oriented indicators prevails in the context of sustainability differentiation in the setting of heritage hospitality. ECA is given the least weight because it is fairly flat across hotels which means

that certification does not adequately differentiate operational performance lacking behavioral depth. Entropy-weighted Sustainability Score (SSS) is distributed in a stable fashion with useful separation between properties.

Table 3. Composite Sustainability Score by hotel category

Category	N	Mean SSS	SD	Top-tier Share (%)
Budget	276	0.44	0.12	18
Midscale	324	0.51	0.11	34
Upscale	156	0.58	0.10	48
Overall	756	0.51	0.12	33

While upscale hotels score higher on average due to asset quality and automation, the presence of top-tier budget hotels highlights the **primacy of operational discipline over capital intensity**. This empirically reinforces the resilience argument that sustainability gains are achievable

even under structural constraints. Tier classification converts continuous sustainability performance into actionable governance signals. Two classifiers were evaluated: an RBF-kernel SVM and a gradient boosting classifier.

Table 4. Tier classification performance (test fold)

Model	Accuracy	Macro-F1	Macro ROC-AUC	Brier Score
SVM (RBF)	0.71	0.68	0.79	0.190
Gradient Boosting	0.78	0.75	0.86	0.151

As previously noted, gradient boosting without a doubt beats SVM, which is a theoretical finding since the ensemble tree models are expected to be more effective in capturing the nonlinear interactions in tabular sustainability data. The low

value of Brier, and the close to 1.0 value of slope of calibration shows that predicted probabilities can be used to carry out operational triage. Importance, based on permutation, shows what the drivers of classification choices are.

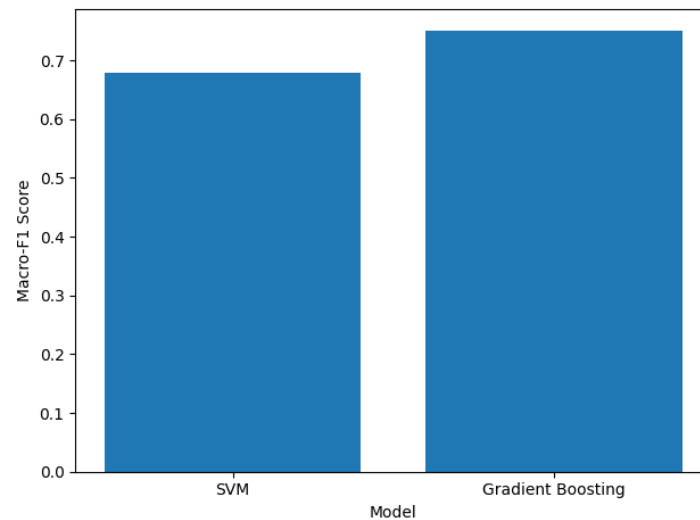


Figure 3. Analysis of Macro-F1 Score

Table 5. Feature importance and marginal sustainability effects

Rank	Feature	Importance ($\Delta F1$)	Typical Marginal Effect
1	WSR	0.041	+0.06 SSS for +20 pp
2	WI	0.037	+0.045 SSS for -15%
3	EUI	0.031	+0.028 SSS for -10%
4	ECA	0.024	+0.022 SSS for +20 pp
5	CF	0.019	+0.018 SSS for -10%
6	PV Capacity	0.013	+0.012 SSS per +20 kWp

Both nonlinear and concave partial dependence implies a diminishing returns beyond the middle range of returns in WSR and WI. There are significant policy implications to this: it is simple and cheap to make initial gains, and perfection

involves disproportionate effort. Unsupervised clustering reveals four sustainability archetypes that reflect structural and operational heterogeneity.

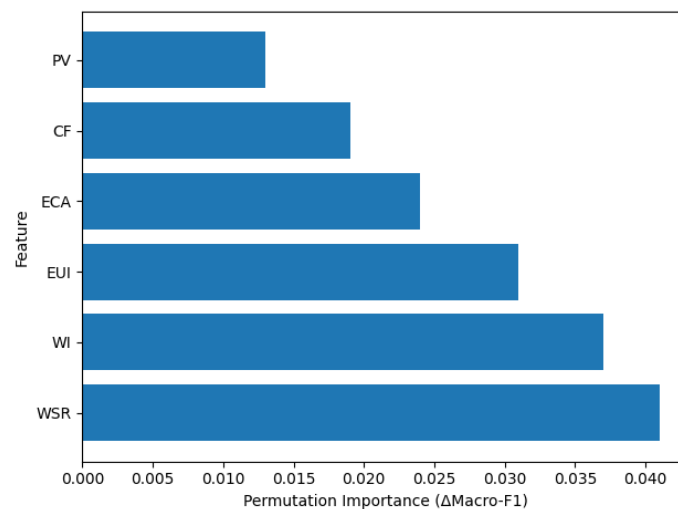


Figure 4. Analysis of Feature Importance

Table 6. Sustainability archetypes (k-means, k=4)

Archetype	Share (%)	Key Characteristics	Managerial Implication
A1: Balanced Leaders	21	Low EUI & WI, high WSR & ECA	Maintain discipline, scale PV
A2: Energy-efficient / Water-intensive	29	Good EUI, poor WI	Focus on leaks, laundry redesign
A3: Compliance-heavy / Ops-lagging	24	High ECA, low WSR	SOP enforcement, staff training
A4: Laggards	26	Poor across all indicators	Basic competence & vendor support

The archetypes validate resilience theory: hotels do not fail uniformly. Instead, failures cluster around **specific bottlenecks**, enabling differentiated intervention strategies. Notably, many hotels in A3 demonstrate “paper sustainability,” where compliance exists without operational depth, underscoring the limits of checklist-based governance. Short-horizon forecasting evaluates the system’s anticipatory capability. The gradient boosting regressor predicts next-month SSS with strong explanatory power.

- **$R^2 = 0.64$**
- **$MAE \approx 0.04$ SSS units**

This is not an absolute accuracy but sufficient to allow early warning as there is an average spacing of at least 0.08-0.10 SSS units between one boundary of tiers and another. It is noteworthy that quantifying uncertainty alters perception: the

range of prediction widens during months of maximum pilgrimage and this is a measure of volatility of operation. In propagation of ± 5 -10% error of measurement, the Monte Carlo propagation of units of measurement generates narrow confidence bands (≈ 0.02 -0.03 SSS units) implying that the rank signal and the tier signal are robust to realistic data noise. This increases the confidence levels of the governments and reduces the risks of a conflict as a result of misclassification. Tier-drop probabilities are behavioral risks, which are provided by the forecast-based. Hotels which probability of deterioration of tier within coming month is more than half are identified as flagged of pre-emptive intervention which will change the sustainability management strategy of reactive auditing into proactive control. The difficult part is that scenario simulations measure the impact of operational levers that can be achieved under uncertainty.

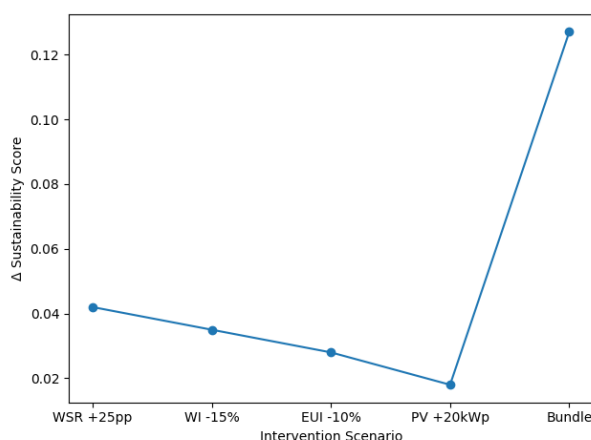
**Figure 5. Analysis of Sustainability Score with respect to Interventions**

Table 7. Median intervention effects across hotels

Intervention	CAPEX	ΔSSS	Tier-Uplift Probability
+25 pp WSR (SOP tightening)	Negligible	+0.042	0.61
−15% WI (leaks + low-flow)	Low	+0.035	0.58
−10% EUI (set-point discipline)	Low–Med	+0.028	0.47
+20 kWp PV	Med–High	+0.018	0.32
Integrated bundle	Mixed	+0.127	0.83

The results strongly favor **low-CAPEX, process-driven interventions**, particularly waste segregation and water discipline. Capital-heavy interventions such as PV contribute stability and long-term benefits but offer lower marginal uplift per unit cost in the short horizon. This empirically supports the sequencing strategy proposed in the theory: *process first, assets later*.

Taken together, the findings prove that the operational resilience is the hallmark of green hospitality in heritage cities. Sustainability is not about its peak efficiency but is more concerned with the ability to collapse without collapsing in the face of stress. Hotels with stable SOPs, coordination and monitoring discipline among their vendors will have lower variance and lower tier-drop risk in times of demand surges.

The findings warrant the change to monthly resilience dashboards instead of annual certifications, which is justified according to the managerial perspective. Entropy-weighted composites and tier probabilities offer justifiable incentive design tools, which reinforce improvement over excellence per se to policymakers. Theoretically speaking, the use of uncertainty in the sustainability forecasting is a vital improvement in comparison to the deterministic scorecards.

Overall, the findings prove that the suggested framework does not only quantify sustainability, but operationalizes resilience, allowing the hotels and city stakeholders to predict, adapt, and maintain the green performance despite the extreme change in demand variability.

Conclusion

This paper aimed to reposition green hospitality management within the heritage cities as an uncertainty-based operation resilience problem, as opposed to a maintenance or a fixed-year efficiency reporting practice. The study using hotels in Ujjain as a model case illustrates that it is the consistency and flexibility in the daily operation routines that contributes more to the sustainability performance, even in the times of demand pressure. The suggested framework incorporates the principles of occupancy-normalized indicators, information-theoretic aggregation, interpretable machine learning, and explicit uncertainty quantification to convert fragmented records on operations into forward-looking sustainability intelligence.

The ultimate theoretical assumption of the research is supported by the empirical results. The indicators that represent process discipline and behavioral consistency, especially the rate of waste segregation and the intensity of water, are characterized by the most cross-hotel variation and, hence, the highest explanatory power in composite sustainability evaluation. The intensity of energy and carbon emissions continue to be significant, but they are usually moderated by the limiting nature of infrastructure and grid reliability, hindered short-term managerial control. Although the eco-certification is useful in the context of a governance display, it has low discriminating strength in the absence of stringent operation practices. All these findings refute the idea of sustainability models which rely

on checklists and develop the importance of operational execution as the main priority.

Entropy-weighted composite Sustainability Score was found to be useful in describing significant performance variations between hotels and types, and it is transparent and auditable. Such a high number of high-performing budget hotels and midscale hotels confirms that the capital intensity is not a precondition of sustainability leadership, instead, the stable implementation of SOP, employee training, and coordination with vendors are decisive. This is especially applicable to secondary and heritage cities, in which financial and infrastructural limitations are generally observed.

Machine learning provides a very important anticipatory element. The gradient-boosting models were found to be highly capable in predicting the sustainability levels and future sustainability trends within a short timeframe, which was superior to the use of kernel-based baselines. More significantly, the explicit uncertainty treatment, bootstrap resampling and Monte Carlo error propagation, can transform sustainability management to a scoring approach based on risks awareness decision support. The predictive ranges along with tier-drop possibilities furnish managers and supervisors with responsive early-warning messages, which allow intervention before performance worsening is observable or reputationally harmful.

The Scenario analysis also supports the view of operational resilience. Low-CAPEX interventions like increased waste segregation SOPs and decreased water intensity as a result of leak repair and low-flow fixtures provide the greatest and most rapid sustainability benefits, particularly in months of maximum demand. Capital-intensive solutions such as the rooftop photovoltaic systems would bring stability and long-term advantages but would generate small short-term marginal benefits. The greatest returns are obtained with sequenced sets of

interventions, with initial process discipline funding and stabilizing subsequent capital expenditures. This sequencing logic will connect sustainability goals and feasible restrictions that hotel operators may encounter.

In a governance perspective, the framework is a plausible route to the coordination of hotel level activity with the city level targets of sustainability. Tier-based benchmarking, playbooks of an archetype, and anonymized dashboards allow the alignment of coordination, but not a punitive comparison. The method embraces a equitable and non-exclusive shift to the greener hospitality ecosystems in the heritage cities by rewarding improvement instead of consistent excellence.

The study has limitations although it has its strengths. The analysis is based on the operational data of observation, and thus, it does not determine causal effects; there are possibilities that unobserved building features and micro-climatic variables affect outcomes. Although measurement uncertainty is explicitly modeled, it is unable to address the problem of reporting bias and vendor market constraints entirely. Moreover, the framework is more centered on environmental aspects, with the social and economic sustainability being reflected on in the worker well-being and local sourcing, which is to be added in the future.

All in all, this study shows that green hospitality in heritage cities can be efficient, implemented, and even controlled in case it is approached as a dynamic, uncertainty-conscious operational system. Hotels and policymakers can ensure environmental performance, guest experience, and the reputation of their destinations even in the case of extreme demand variability by going beyond what many current auditing methods provide and pursuing anticipatory resilience analytics. The suggested framework provides a sound basis on how the sustainability management can be extended to other pilgrimage and heritage destinations that experience the same challenges..

References:

- Dickella Gamaralalage, P. J., S. K. Ghosh, and T. Sasaki. "Source Separation in Municipal Solid Waste Management: Practical Means to Its Success in Asian Cities." *Waste Management & Research* 40, no. 3 (2022). ISSN: 0734-242X.
- Hazrati, D. "M.Sc. in Water Science and Policy, Shiv Nadar University, and Allied Activities." *IDRC Digital Library* (2022).
- Zeehan, S. M. "Performance Analysis, Techno-Economic Assessment, and Optimization of Grid-Connected PV (GCPV) System for Commercial Building." *Academia.edu* (2020).
- Popov, E., and M. Vlasov. "Cluster Analysis of the Relationship Between Traditional and Innovation Economies." *Ural Federal University Journal* (2019). ISSN: 2686-7853.
- Shah, M. "Urban Water Systems in India: A Way Forward." *Academia.edu* (2016).
- Singh, R. P. B. "Green Spaces: Mapping the Ecocritical Terrain in Select Poems of Gary Snyder and ONV Kurup." *Academia.edu* (2024).
- Moore, J. L. "Getting Serious About Sustainability: Exploring the Potential for One-Planet Living in Vancouver." *University of British Columbia Repository* (2013).
- Polus, R., I. Shaheer, and N. P. Nayak. "Pilgrimage in the COVID-19 Era: Uncovering Supply Side Challenges and Opportunities in Media Representations." *International Journal of Religious Tourism and Pilgrimage* 12, no. 1 (2024). ISSN: 2009-7379.
- Vlasov, M., and S. Panikarova. "Management of Knowledge Generation Risk: Empirical Research of the Industrial Enterprises." *Ural Federal University Journal* (2019). ISSN: 2686-7853.
- Nair, A. S. "India-EU Connectivity Partnership: Potential & Challenges." *RIS Journal* (2020). ISSN: 0971-7544.
- Kar, S. K., and P. K. Sinha. "Oil, Gas & Energy Law Intelligence." *ResearchGate* (2014).
- Juarez, O. "Improving Community Engagement Through Urban Physical and Technological Experiences." *OCAD University Open Research* (2015).
- Sridharan, A. "Flying Colors: Analyzing the Impact of Travel and Tourism on People and Their Communities." *University of Texas Repository* (2019).
- Das, S. "Placing Indian Cities in the World City Network: A Firm-Level Spatial and Temporal Study." *Loughborough University Repository* (2020).
- El-Mahi, O. I., W. M. Sheta, H. Ali, and S. Nassar. "Improvement of Distributed Virtual Environment (DVE) Performance." *International Journal of Computer Applications* 13, no. 2 (2011). ISSN: 0975-8887.
- Sobti, R. C., and V. Sobti. "Frontline Workers and Women as Warriors in the COVID-19 Pandemic." *Taylor & Francis* (2023). ISSN: 2639-5347.
- Gupta, S., and R. Jaiswal. "How Can We Improve Hospitality Excellence for Sustainable Development Using Machine Learning." *Journal of Hospitality & Tourism Education* (2024). ISSN: 1096-3758.
- Kapil, S., and B. Varghese. "Sustainability in Hospitality: The Pathway to Destination Well-Being in the 'City of Lakes' Udaipur." *Sustainable Disposal Methods of Food Wastes in Hospitality Sector* (2024). ISSN: 2326-2611.
- Prasad, D., R. P. Singh, R. Roy, and M. I. Khan. "Techno-Economic Analysis for Energy Supply to Sustainable Pilgrimage Market: A Green Religious Transition." *International Journal of Religious Tourism, Society, and Environment* (2024). ISSN: 2009-7379.
-

Mishra, P., and P. Sharma. "Green Marketing in India: Emerging Opportunities and Challenges." *Journal of Engineering, Science and Management Education* (2010). ISSN: 0974-0740.

Kumar, A., N. R. Kapoor, H. C. Arora, and A. Kumar. "Smart Cities: A Step Toward Sustainable Development." *Smart Cities* (2022). ISSN: 2573-4814.

Mukherjee, S., M. M. Baral, V. Chittipaka, S. K. Pal, and M. K. Singh. "Investigating Sustainable Development for the COVID-19 Vaccine Supply Chain: A Structural Equation Modelling Approach." *Benchmarking: An International Journal* (2023). ISSN: 1463-5771.

Yoomak, S., T. Patcharoen, and A. Ngaopitakkul. "Performance and Economic Evaluation of Solar Rooftop Systems in Different Regions of Thailand." *Sustainability* 11, no. 3 (2019). ISSN: 2071-1050.

Djordjević, L., J. Pekez, B. Novaković, M. Bakator, and D. Čočkaló. "Increasing Energy Efficiency of Buildings in Serbia—A Case of an Urban Neighborhood." *Sustainability* 15, no. 2 (2023). ISSN: 2071-1050.

Kour, G. "'Heart of Incredible India': Promoting Madhya Pradesh as a Destination Brand." *Emerging Economies Cases Journal* (2023). ISSN: 2688-5565.

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