



SUSTAINABLE LEADERSHIP, ENTREPRENEURIAL BRICOLAGE, AND FRUGAL INNOVATION: A MACHINE LEARNING APPROACH TO SUSTAINABLE PERFORMANCE

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Abstract

This study examines the relation between sustainable leadership, entrepreneurial bricolage, and frugal innovation and how these elements influence sustainable performance. The purpose is to assess the association between these constructs using not only quantitative measures but also sophisticated algorithms. The study assumed a quantitative design. In addition, the Extra Trees machine learning method was also implemented to enhance the predictive ability of the models. The research results supported that sustainable leadership was positively related to frugal innovation and sustainable performance. In addition, the square error of the machine learning model was small, and the R^2 values were high, indicating that the model fit well. These lessons imply that organisations need to implement sustainable leadership and effective knowledge-sharing mechanisms. The practical implications lead to the fact that organisations must adopt sustainable leadership and enact effective knowledge management practices so that organisations can enhance their performance and develop sustainable solutions.

Keywords: Frugal Innovation, Entrepreneurial Bricolage, Sustainable Performance, Sustainable Leadership, Knowledge Heterogeneity

1. Introduction

Sustainable development awareness has taken on one of the most popular subjects in the international arena today, as the challenges of modernity presented are the requirement of economic growth and social justice and the need to respect nature (Adanma & Ogunbiyi, 2024). In that way, frugal innovation and knowledge heterogeneity are fundamental facilitators in altering the developmental pathway towards sustainability. Heterogeneity in knowledge refers to variations in the sense of perspective and expertise that influence ideas and solutions. This diversity introduces innovation and simplifies achieving solutions that fit the needs of the locality (Walrave et al., 2024). Similarly, frugal innovation entails using resources effectively such that they are maximally used to the extent that there is no surplus in an environment where innovation resources are scarce (Dost et al., 2024).

In some countries, local communities hold enough traditional ecological knowledge that can be useful when implementing sustainable practices there (Reyes-García et al., 2024). Therefore, by acknowledging the existence of knowledge heterogeneity, it becomes easier to involve more perspectives and specific knowledge in the problem-solving process, leading to better and contextually accurate solutions (Misra et al., 2024). Frugal innovation is essential in this regard since it enables organisations and communities to address the aspects of sustainability without spending much (Achmad & Wiratmadja, 2024).

Since both the knowledge heterogeneity and frugal innovation have been regarded in the literature as the elements to bring changes for sustainability, their mutual connection has not been thoroughly investigated. Previous research separately analyses the contribution of different types of knowledge to



innovation or the concept of frugal innovation (Achmad & Wiratmadja, 2024; Walrave et al., 2024). This disconnect hinders a thorough understanding of how these components can be combined to promote sustainability. In addition, the magnitude of the proposed strategies has been documented, with only a little consideration being given to the contextual factors that determine the relevance of such strategies in different settings (Gómez et al., 2024; Reyes-García et al., 2024). Therefore, it is imperative for this research to combine and harness the two concepts in the pursuit of sustainable development and generate effective solutions.

There is growing empirical and theoretical attention to how sustainability-oriented leadership and resource-constrained innovation interact, yet important gaps remain that justify this study. Escudero-Cipriani et al. (2024) show frugal innovation is rapidly advancing as a pathway to sustainable outcomes, but explanations remain fragmented and often focus on isolated antecedents rather than integrated mechanisms. Although sustainable leadership has been linked to greater uptake of sustainability practices and to enabling innovation, the precise mechanisms by which leaders transform sustainability commitments into concrete frugal solutions and, ultimately, improved sustainable performance are under-theorised (Hu et al., 2024). Similarly, entrepreneurial bricolage is recognised as a powerful means for recombining scarce resources into novel solutions, yet its role as a boundary condition that strengthens or weakens leadership–frugal innovation pathways needs direct testing (Aaouid et al., 2024). Fu et al. (2024) suggest frugal innovation emerges from combinations of internal capabilities and external conditions, indicating mediation and moderation effects are likely but insufficiently mapped in current research. In addition, scholarship points to the importance of heterogeneous knowledge, both internal (cross-functional, tacit–explicit mixes) and external (partners, users, communities), for frugal problem solving, yet limited studies simultaneously examine internal and external heterogeneous knowledge sharing as distinct mediators between sustainable leadership and frugal innovation (Ur Rehman et al., 2024).

Therefore, these gaps show a clear need for a study that unpacks the micro-processes linking sustainable leadership to sustainable performance via frugal innovation, tests internal and external heterogeneous knowledge sharing as separate mediating channels, and evaluates entrepreneurial bricolage as a moderator of the leadership–frugal innovation link. Doing so would move the literature beyond single-factor explanations, provide actionable guidance for leaders in resource-constrained contexts, and clarify when and how frugal innovation translates sustainability intent into measurable performance gains.

Previous studies have also highlighted the importance of examining the relationship between these variables. In the recent past, Iqbal and Ahmad (2021) have advocated for further studies on the relationship between sustainable leadership and innovation. Moreover, Li et al. (2019) noted that knowledge sharing and innovation should have mediating effects in future studies on hypothesised performance. Moreover, machine learning is a rapidly growing field that, when combined with the traditional statistical method, plays a significant role in supporting sustainability efforts because of its synergistic nature. It provides prediction and pattern identification (Goldenberg et al., 2019), while statistical approaches give reliability and support via rigorous testing capabilities (Ho et al., 2020). Thus, together they can analyse complex and heterogeneous datasets in order to detect areas suitable for frugal innovation in a better way. These techniques are repeatedly being employed by various scholars. Elbasi et al. (2023) and Vianny et al. (2022) integrated machine learning techniques and regression analysis to achieve efficient and sustainable utilisation of water for agriculture, minimise wastage, and increase productivity. This mixed model fosters sustainable growth based on various data perspectives. Therefore, in this study, both statistical and machine learning techniques have been applied. An Extra Trees Regressor machine learning model has been employed to analyse the complex data and to predict the results more accurately.

The study is significant as it uses the Extra Trees Regressor algorithm to gain insights into how heterogeneous knowledge affects frugal innovation. Also, this investigation benefits the literature and practice since it employs the link between the study variables, relying on Effectuation Theory and Upper Echelon Theory. Thus, this integrated approach highlights the role of evidence-based development in the search for prosperity and innovation in regions that are short of resources.



2. Literature Review

2.1 Theoretical Framework

2.1.1 Effectuation Theory. Effectuation theory (Sarasvathy, 2001) offers a new perspective on how entrepreneurs make decisions and act. According to this theory, entrepreneurs manage uncertainty using five basic principles: “bird in hand” focuses on what is available; “affordable loss” takes account of possible losses; “crazy guilt,” the use of heterogeneous networks; “lemonade,” leveraging possibilities from unexpected situations; and finally, “pilot-in-plane,” in charge of direction (Sarasvathy & Botha, 2022; Sarasvathy, 2001). According to Ryman and Roach (2024), the Effectuation Theory implies that entrepreneurs focus on action over prediction, or iteratively experimenting and adapting in order to create innovative solutions.

In the context of frugal innovation and sustainable leadership, Effectuation Theory provides light on this very relevant point (Iqbal, Ahmad, & Halim, 2021; Iqbal, Ahmad, et al., 2021b). The concept of effectuation has relevant facets within sustainable leadership and innovation about adaptability, resourcefulness, and collaborative approaches (Dahle et al., 2020; Xie et al., 2024). Sustainable leaders are thus likely to function more innovatively in complex, uncertain environments where they may not work well with traditional predictive models. It is the effectual mindset of sustainable leaders that allows them to use different sources of resources, engage the stakeholders in novel processes, and pivot as scenarios become unexpected.

2.1.2 Upper Echelon Theory (UET). Hambrick and Mason’s upper echelon theory was developed in 1984 (Hambrick & Mason, 1984). It argues that the values, experiences, and backgrounds of an organisation’s top executives are strong drivers of strategic choices and, ultimately, of organisational performance (Ali et al., 2022). In essence, this theory is based on the fact that the background of executives, from education, through demographics, to antecedent experiences, determines their perceptions, interpretations, and subsequent decisions. This perspective underlines that understanding senior levels’ organisational composition has crucial effects on organisational outcomes, because leaders come into strategic discussions with their own biases and insights (Osei Bonsu et al., 2024).

In the context of sustainable leadership, Upper Echelon Theory is highly relevant (Iqbal, Ahmad, et al., 2021b). By and large, ethics define sustainable leaders who also have a long-term vision and engage with stakeholders. These are the products of their experience and value system in terms of evaluating and guiding decision-making sustainability. Applying Upper Echelon Theory to frugal innovation further emphasises how leadership helps a firm innovate more effectively within constraints (Iqbal, Ahmad, et al., 2021b; Tian & Wang, 2023). Executives from resource-constrained backgrounds can be more effective at initiating a culture that promotes creativity and resilience within an organisation and motivate their teams to use limited resources effectively. If organisational leadership characteristics are in step with sustainable practices, then strategies, designed both to build innovative capabilities and to contribute to the achievement of long-term sustainability goals, can be constructed (Iqbal et al., 2022).

2.2 Sustainable Leadership, Frugal Innovation, and Sustainable Performance

Sustainable leadership has been defined as the management approach to the integration of ethical activities, social accountability, and environmental sustainability in pursuit of economic growth (Armani et al., 2020). This is a kind of value that can be achieved by sustainable leaders not only with respect to profit but also for integrating sustainability into their organisational strategies and decision-making processes. In addition, frugal innovation can be referred to as the process of developing low-cost solutions, resource-efficient solutions suited to the needs of resource-poor markets. It highlights simplicity, efficiency, and accessibility. Its value creation does not presuppose over-expenditure and complexity (Mignenan, 2022). Moreover, sustainable performance can sustain long-term success while bringing economic, social, and environmental outcomes together most effectively (Le, 2022).

Sustainable leadership drives frugal innovation by embedding long-term stewardship, resource mindfulness, and empowerment into organisational routines, which encourages teams to redesign processes



and products for affordability and durability (Ahsan & Khawaja, 2024). Leaders who prioritise sustainability create psychological safety and knowledge flows that mobilise employees to recombine limited resources into high-value solutions, accelerating frugal problem-solving (Fu et al., 2024). Sustainable leadership signals strategic priorities and allocates attention to low-waste, cost-effective alternatives, raising the likelihood that scarce-resource bricolage and user-informed adaptations emerge as firm practices (Ahsan & Khawaja, 2024). Sustainable leaders can therefore amplify experimentation with minimal-input innovations that bring positive social and environmental outcomes by influencing incentives and norms (Awotunde & Aregbeshola, 2025).

Sustainable leadership contributes to sustainable performance by harmonising strategic emphasis, resource deployment, and stakeholder interaction with long-term environmental and social ambitions, which boosts environmental results and business fortitude (Ahsan & Khawaja, 2024). Through encouragement of employee pro-environmental behaviours, knowledge sharing, and innovation, sustainable leaders increase the organisational potential to minimise waste, reduce energy consumption, and develop durable processes, which translate into quantifiable social and environmental benefits (Khan et al., 2023). In addition, leaders who institutionalise sustainability using incentives and cross-boundary co-operation more regularly achieve environment, social and governance (ESG) measurements and report to stakeholder expectations, enhancing reputation and operational returns (Shiferaw et al., 2025). In this way, these mechanisms demonstrate why sustainable leadership generates real changes in sustainable performance through the ESG dimensions (Ahsan & Khawaja, 2024; Khan et al., 2023). Thus, the following hypotheses are formulated:

H1: Sustainable leadership has positive effects on frugal innovation.

H2: Sustainable leadership has positive effects on sustainable performance.

2.3 Frugal Innovation and Sustainable Performance

Frugal innovation promotes sustainable performance by reducing material and energy intensity related to the design pushed simplicity, and employing resource-efficient processes, which reduces environmental footprints and operating costs directly (Fu et al., 2024; Shahid et al., 2023). Frugal solutions are likely to extend the lifecycle of products and enable circular practices that minimise waste and emissions due to their lifecycle thinking and their emphasis on core functionality (Escudero-Cipriani et al., 2024). Frugal strategies enhance the availability of low-cost services, promoting social aspects of sustainability like inclusion and wellness, and creating firm-level efficiencies that enhance sustainability indicators (da Silva et al., 2024). Frugal innovation, in conjunction with collaborative knowledge flows and adaptive bricolage, extends the cost-effective sustainable practices across value chains to create measurable ESG improvements (Ur Rehman et al., 2024).

Beyond this, empirical research has been advanced to prove the mediating role of frugal innovation between sustainable leadership and sustainable performance. For instance, Iqbal et al. (2022) analyse the mechanism of sustainable leadership–environmental performance in the light of the UET. The findings indicate that frugal innovation partially mediates sustainable leadership on environmental performance. Another study by Iqbal et al. (2021) investigates the relationship between sustainable leadership and sustainable performance from the perspective of the UET and effectuation theory, with special emphasis on the mediating role of frugal innovation in small and medium enterprises of China and India. The findings confirmed that frugal innovation indeed plays a mediating role in the link between sustainable leadership and performance. Hence, from the above findings from the literature, the following hypotheses are formulated:

H3: Frugal innovation has positive effects on sustainable performance.

H4: Frugal innovation mediates the relationship of sustainable leadership to sustainable performance.

2.4 Knowledge Heterogeneity and Sharing

Internal heterogeneous knowledge sharing is one of the most important knowledge vehicles for frugal innovations, particularly in organisations with sustainable leadership (AlMulhim, 2021). Open and free sharing of diverse sorts of knowledge and perspectives in an organisation, at all organisational



departments and teams, increases the ability to solve complex problems creatively and optimise resources more (AlMulhim, 2021; Dost et al., 2019). External heterogeneous knowledge sharing, on the other hand, refers to the sharing of heterogeneous knowledge and information between an organisation and its other external stakeholders, suppliers, customers, and industry partners (Hervas-Oliver et al., 2021). Through incorporating external knowledge, organisations learn to build their responsiveness capabilities to fulfil the demands of the market and uphold sustainable practices (Shehzad et al., 2023).

Sustainable leadership promotes internal heterogeneous knowledge sharing by prioritising cross-functional collaboration, psychological safety, and routine exchange of diverse tacit and explicit insights, which makes varied internal expertise accessible for problem-solving (Khan et al., 2023). That internal mix of perspectives and knowledge types enables rapid recombination of scarce resources and redesign of processes, producing the low-input, high-value solutions characteristic of frugal innovation (Chen & Zhang, 2024; Ur Rehman et al., 2024). Mechanistically, leaders who institutionalise regular knowledge flows, learning forums, and boundary-spanning teams increase absorptive capacity and trigger employee bricolage, so ideas born inside the firm are translated into simplified, durable, and affordable offerings (Saif et al., 2024; Saleem et al., 2024). Tian and Wang (2023) link sustainable leadership, internal-knowledge sharing, and innovation, therefore supporting internal heterogeneous knowledge sharing as a mediator that channels leadership intent into frugal innovation outcomes.

Sustainable leadership channels external heterogeneous knowledge sharing by cultivating outward-facing partnerships, stakeholder dialogue, and open boundary practices that bring diverse external expertise, user insights, and partner resources into the firm, which managers then translate into frugal problem-solving (Ur Rehman et al., 2024; Wang et al., 2022). Those external inflows supply novel, low-cost design ideas, alternative supply options, and community-based practices that are recombined into simpler, resource-efficient solutions characteristic of frugal innovation (Shahid et al., 2023). Mechanistically, leaders who prioritise sustainability institutionalise routines for scouting, integrating, and legitimising external knowledge, thereby increasing absorptive capacity for context-appropriate, minimal-input innovations that deliver social and environmental value (Chen & Zhang, 2024). As a result, external heterogeneous knowledge sharing functions as the conduit through which sustainability-oriented leadership converts strategic intent into practical frugal innovations (Shahid et al., 2023; Wang et al., 2022). Hence, the following hypotheses are devised:

H5: Internal heterogeneous knowledge sharing mediates the relationship of sustainable leadership to frugal innovation.

H6: External heterogeneous knowledge sharing mediates the relationship of sustainable leadership to frugal innovation.

2.5 Entrepreneurial Bricolage

As stated by Bhardwaj et al. (2023), entrepreneurial bricolage is a creative approach that is applied when identifying how to use the existing materials and how to look for ways to solve important challenges during a scarcity of resources. This, therefore, anchors adaptability and ingenuity in leveraging existing resources, skills, and knowledge applied by the entrepreneurs to create new value without massive capital outlay. It has an interesting twist in the utilisation of resources and is a core concept in the world of frugal innovation, where every single opportunity tries to extract maximum out of scratch resources (Kumar & Stobdan, 2024).

Entrepreneurial bricolage amplifies the effect of sustainable leadership on frugal innovation because leaders who set sustainability priorities create intent and direction, while bricolage supplies the practical capability to recombine limited resources into viable, low-input solutions, so the same leadership signals produce stronger frugal outcomes when bricolage is high (H. Z. H. Alsharif et al., 2021). Bricolage accelerates experimentation and local adaptation, translating leader-driven priorities into rapid prototyping, cost-effective designs, and user-informed simplifications that characterise frugal innovation (Aaoud et al., 2024;





calculated how many standard deviations a factor was from its mean. It has been done using the following formula:

$$y = \frac{(A - \text{mean})}{\text{standard deviation}}$$

3.3 Feature Scaling

This study applied min-max scaling for data normalisation by transforming feature values into the range [0, 1]. Min-max is capable of protecting confidential data and keeping the efficiency of the data mining method (Sinsomboonthong, 2022). We used the following formula for scaling:

$$\hat{A} = \frac{A - A_{\min}}{A_{\max} - A_{\min}}$$

3.4 Model Development

The pre-processed dataset was divided into features and target variables. In this study, the SP (Sustainable Performance) as a target and different features such as SL (sustainable leadership), EB (Entrepreneurial Bricolage), INKH (internal heterogeneous knowledge sharing), EXKH (external heterogeneous knowledge sharing) and FIN (Frugal Innovation) were selected. The dataset was divided into 80% for training the model and 20% for testing the model.

In this study, the Extra Trees regressor machine learning model was employed. The Extra Trees Regressor describes a significant improvement in ensemble learning (Jafari & Byun, 2024). The model randomly selects a split point for every feature and then chooses the best split point among these options (Qayyum et al., 2022; Sharafati et al., 2020). Probably, this model can be defined as:

$$\hat{b} = \frac{1}{T} \sum_{t=1}^T j_t(A)$$

A grid search was conducted to recognise the best hyperparameters of the extra tree algorithm. Figure 3 represents the process of hyperparameter tuning:

Figure 3

Extra Tree Hyperparameter Tuning Process

```
# Hyperparameter tuning using GridSearchCV
param_grid = {
    'n_estimators': [50, 100, 200],
    'max_depth': [None, 5, 10],
    'min_samples_split': [2, 5, 10],
    'max_features': ['auto', 'sqrt']
}
```

3.5 Research Approach

The research methodology used was quantitative in nature. It was used as it simplifies the assessment and comparison of the variables. In this way, it is possible to make generalisations, such as hypotheses and empirical conclusions, that are valuable for constructing the association between the variables (Jones et al., 2019).

3.6 Participants and Sample Size

The participants were selected from a cross-section of different organisations based in Norway, where the participants had roles related to sustainability as well as management. Since the study focused on experts in the fields of knowledge heterogeneity and frugal innovation, the study approach made it possible for the collected data for analysis to be diverse. The number of measurement items was 47 in total, as shown in Table 1. Therefore, based on the “Item Response Theory” by Sahin and Anil (2017), there should be at least 470 questionnaires. Hence, the distribution of more than 600 questionnaires took place. 540 questionnaires were returned. Certain forms were excluded due to the presence of missing values, and all that was left were 392 questionnaires. Therefore, 392 was the sample size of the study.



3.7 Data Collection Method

The data was collected via Google Forms. They have choices when choosing the questions, such as multiple-choice, Likert Scale, as well as free text response options (Keadkraichaiwat et al., 2024). They are also relatively easy to use and, therefore, can capture a large number of respondents across different geographical regions (Nayak & Narayan, 2019). This method was also used because of its convenience in distribution and versatility (Aldalur et al., 2022).

3.8 Data Analysis Procedure

Structural Equation Modelling was carried out via SmartPLS because of its suitability for comprehending the relationships between variables (Sarstedt et al., 2020), while machine learning was conducted through Python programming. This method is more suitable when there are a few latent factors and when the data is not normally distributed (Jobst et al., 2022). The rationale for choosing this method lies within its capacity to provide an extensive appreciation for the interdependence of the study variables, provide a testing of the hypotheses, and to provide a glimpse into the comprehensiveness of the research variables (Russo & Stol, 2021).

3.9 Measurements and Instrumentation

FIN, SL, as well as SP were evaluated on a “Five-Point Likert Scale”, where level 1 represented “Strongly Disagree” and level 5 represented “Strongly Agree”. Moreover, INKH and EXKH were also evaluated on the same scale, but level 1 stood for “Very Similar” and level 5 meant “Very Different”. Similarly, EB was measured on a “Five-Point Likert Scale”, where level 1 meant “Never” and level 5 represented “Always”. The variables, number of items, and the sources of scales are given in the following table:

Table 1

Number of items and the sources of scales

Variable	Number of items	Source
Sustainable leadership	13	Iqbal et al. (2022) , Adopted from Khan and Quaddus (2015)
Entrepreneurial bricolage	8	Senyard et al. (2009)
Internal heterogeneous knowledge sharing	4	Ye et al. (2016)
External heterogeneous knowledge sharing	5	Ye et al. (2016)
Frugal innovation	5	Iqbal et al. (2022) , Adopted from Weyrauch and Herstatt (2017)
Sustainable performance	12	Obeidat et al. (2023) , Adopted from Yildiz Cankaya and Sezen (2019)

3.10 Ethical Considerations

In conducting this study, several ethical principles were rigorously upheld. All participants were provided with informed consent, receiving full information about the study’s purpose, the voluntary nature of participation and their right to withdraw at any time. In addition, confidentiality and anonymity were ensured. No identities of respondents were gathered, and the data were safely stored and utilised with the aim of research only. Moreover, the study has considered the principle of respect of persons and non-maleficence, where there was no undue influence and recruitment was not coerced with a view to protecting the well-being of the participants. Furthermore, the integrity of the research was upheld by addressing possible conflicts of interest, following institutional ethics principles, and ensuring that data gathering and analysis processes were carried out fairly and impartially.

3.11 Limitations

Although the research provides meaningful data, some limitations are to be considered. The use of self-report questionnaires increases the vulnerability of findings to bias when predictor and criterion



measures are of the same origins and measured using the same method (Lira et al., 2022). Further, despite the large sample, there can be selection bias and low generalisability, especially when participants with certain positions or interests in sustainability are overrepresented (Stone et al., 2024). In addition, the online survey instrument implies that the study does not tightly control the settings of respondents and can be susceptible to response style influences or desirability bias, which influences the validity of the reported behaviours and attitudes (De Beer et al., 2024). These restrictions indicate that one should be cautious about generalising the findings to the general population, and future studies that involve objective data and more diverse samples are necessary.

4. Results

The performance evaluation of ML models, as this study consists of five predictors such as SL, EB, INKH, EXKH, and FIN, analysing the sustainable outcomes. Table 2 shows the optimized hyperparameters for the Extra Trees model in the sustainable performance prediction. The model will be trained with 200 estimators, and the depth is not limited. The minimum sample split is 10 and the minimum samples leaf is 1. All available features are considered at each split with the maximum features parameter set to 1.0, and random state is set to 42 for reproducibility. These settings determine the configuration of the Extra Trees model that is used in the predictive analysis.

Table 2

Optimized Hyperparameters

Hyperparameter	Optimal Value
Number of Estimators	200
Maximum Depth	None (unlimited)
Minimum Samples Split	10
Minimum Samples Leaf	1
Maximum Features	1.0 (all features)
Random State	42

Table 3 and Figure 2 show the predictive performance of the models evaluated, such as the mean baseline, linear regression, Ridge regression, SVR, Random Forest, Gradient Boosting and Extra Trees. The results indicate that the best mean cross-validation R^2 (0.9187 and 0.9186, respectively) and test performance (test $R^2 = 0.9286$, test RMSE = 0.2342) were obtained by Linear Regression and Ridge Regression. Extra Trees, in comparison, has a mean cross-validation R^2 of 0.9067, a test R^2 of 0.9147 and test RMSE of 0.2560 compared to Gradient Boosting with a test R^2 of 0.9139. This is also shown visually in Figure 2, which displays the training and testing performance of the Extra Trees model before and after hyperparameter tuning; the model with tuned hyperparameters has a smaller difference between the training and testing R^2 . However, the findings overall show that Linear and Ridge regressions were the top models of all the models tested.

Table 3

Predictive Performance of Machine Learning Models

Model	CV_R 2_mea n	CV_ R2_s d	CV_MS E_mean	CV_MA E_mean	Trai n_R 2	Train _MS _E	Test _R2	Test _MS _E	Test _RMS _E	Test _MAE	Test _MSE_ _01
Mean baseline	-0.0222	0.031 1	0.6461	0.6234	0	0.642	0.02 72	0.789	0.888 2	0.741 2	0.0493
Linear regressio n	0.9187	0.014 5	0.0505	0.1753	0.92 34	0.049 2	0.92 86	0.054 9	0.234 2	0.192 7	0.0034
Ridge	0.9186	0.014 5	0.0505	0.1753	0.92 34	0.049 2	0.92 86	0.054 8	0.234 2	0.192 7	0.0034



Model	CV_R 2_mean	CV_R2_s d	CV_MS E_mean	CV_MA E_mean	Trai n_R 2	Train _MS _E	Test _R2	Test _MS _E	Test RMS _E	Test MAE	Test MSE_01
SVR (RBF)	0.9134	0.0143	0.0538	0.1817	0.924	0.0488	0.9212	0.0605	0.246	0.2009	0.0038
Random Forest	0.891	0.0253	0.0679	0.1977	0.9859	0.009	0.9045	0.0734	0.2709	0.2129	0.0046
Gradient Boosting	0.9061	0.0197	0.0585	0.1896	0.9374	0.0402	0.9139	0.0661	0.2571	0.206	0.0041
Extra Trees	0.9067	0.0229	0.0581	0.1838	0.9638	0.0232	0.9147	0.0655	0.256	0.2034	0.0041

Figure 4

Extra-Tree vs. Model Comparison

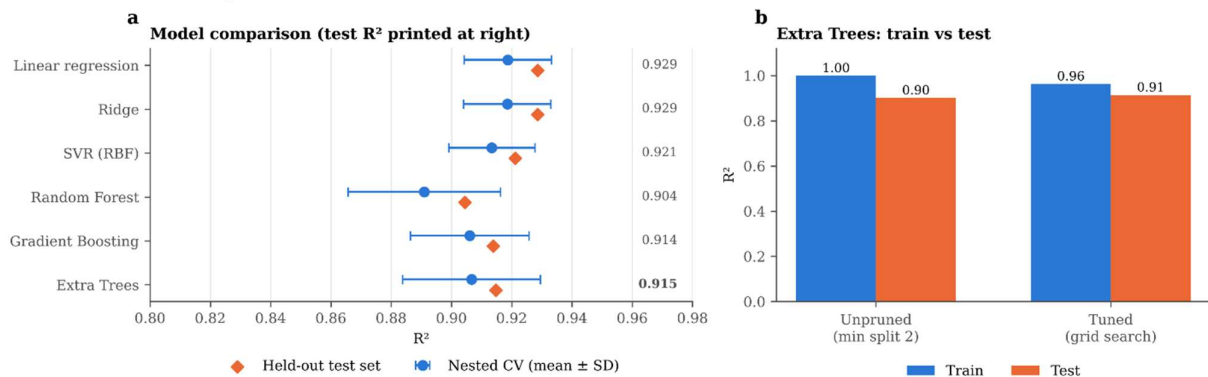
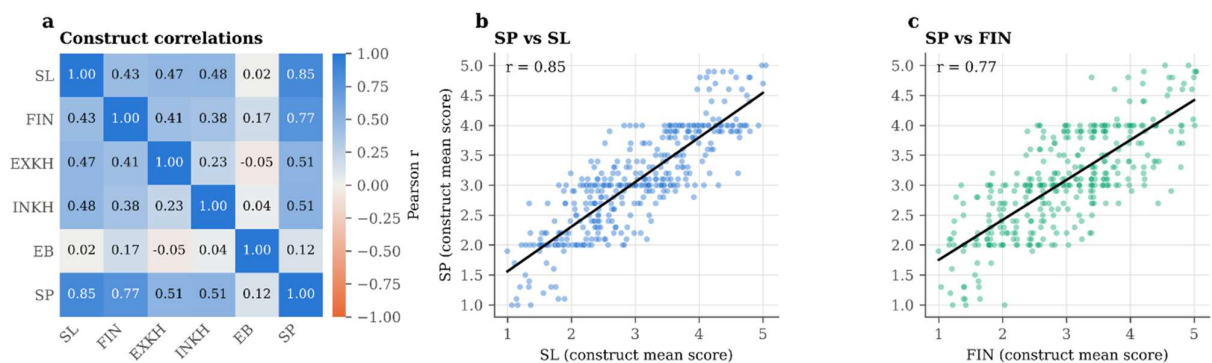


Figure 4 shows a visual comparison of the predictive performance of the Extra Trees model to other machine learning models. The relationship between the study variables is further explored in Figure 5, which shows the correlation between Sustainable Leadership, Frugal Innovation and Sustainable Performance. The correlation patterns offer another insight into the relationships between the variables employed for the predictive analysis.

Figure 5

Correlation among Study Variables

n = 392; five predictors, target = Sustainable Performance (SP)



After conducting a correlation analysis between the study variables, it is important to further assess the selected model to gain insight into the predictive accuracy of the model. The relationship between the



predicted values and the observed values is shown in Figure 6, along with the distribution of the residuals and the learning curve, which gives a visual view of the model's predictive behaviour.

Figure 6

Predicted vs. Observed Values

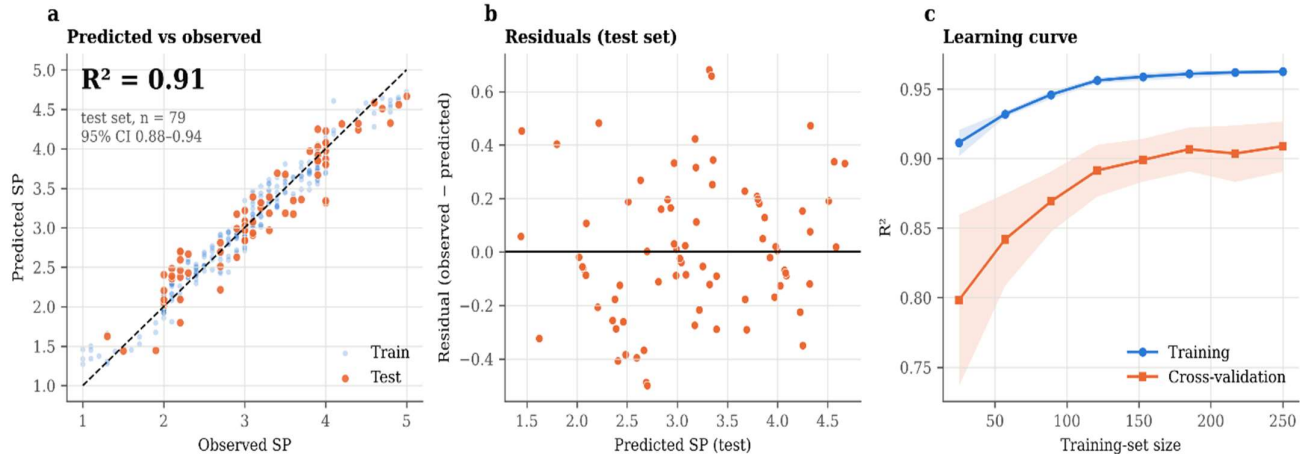


Table 4 reports the measurement model results using different statistical metrics, including the VIF, alpha value, CR, and AVE, which help to examine the internal consistency of the constructs. To examine the internal consistency of the constructs, the study used Cronbach's alpha values, which ranged between 0.863 and 0.955, while the reliability values ranged from 0.907 to 0.960, aligning with the critical value of 0.70. Additionally, the results explain the validity of the constructs, assessed using convergent validity, which ranged from 0.651 to 0.709, as consistent with the threshold value of 0.50. Overall, all the results for the measurement model show that the model can be used to conduct the hypothetical testing.

Table 4

Measurement Model Analysis

Construct	Coding	FL	VIF	Alpha	CR	AVE
Entrepreneurial bricolage	EB1	0.829	2.42	0.928	0.940	0.660
	EB2	0.772	2.13			
	EB3	0.830	2.39			
	EB4	0.800	2.36			
	EB5	0.813	2.29			
	EB6	0.842	2.38			
	EB7	0.826	2.35			
	EB8	0.787	2.31			
External heterogeneous knowledge sharing	EXKH1	0.819	2.11	0.894	0.702	
	EXKH2	0.865	2.57			
	EXKH3	0.852	2.30			
	EXKH4	0.836	2.22			
	EXKH5	0.816	2.02			
Frugal innovation	FIN1	0.836	2.17	0.885	0.91	0.686
	FIN2	0.819	2.06			
	FIN3	0.814	1.95			
	FIN4	0.848	2.31			
	FIN5	0.823	2.09			
Internal heterogeneous knowledge sharing	INKH1	0.809	1.80	0.907	0.709	
	INKH2	0.862	2.20			
	INKH3	0.848	2.08			



Construct	Coding	FL	VIF	Alpha	CR	AVE
Sustainable leadership	INKH4	0.848	2.09	0.955	0.960	0.651
	SL1	0.834	2.86			
	SL2	0.784	2.33			
	SL3	0.815	2.58			
	SL4	0.778	2.20			
	SL5	0.804	2.57			
	SL6	0.791	2.40			
	SL7	0.809	2.53			
	SL8	0.792	2.41			
	SL9	0.821	2.62			
	SL10	0.792	2.38			
	SL11	0.824	2.73			
	SL12	0.821	2.69			
	SL13	0.819	2.70			
Sustainable performance	SP1	0.824	2.56	0.940	0.948	0.651
	SP2	0.798	2.24			
	SP3	0.814	2.40			
	SP4	0.817	2.50			
	SP5	0.789	2.22			
	SP6	0.811	2.45			
	SP7	0.784	2.15			
	SP8	0.779	2.13			
	SP9	0.826	2.59			
	SP10	0.823	2.56			

Note. FL = factor loading; VIF = variance inflation factor; CR = composite reliability; AVE = average variance extracted. Some values in the source table are misaligned; reproduced as supplied.

Table 5 presents the results of the HTMT ratio, conducted to measure discriminant validity. The findings highlight that all the values are consistent with the threshold level of 0.85, as all the ratios rang between 0.048 and 0.182. The results highlight that all the constructs and their related items are distinct from each other and can be interpreted properly.

Table 5
HTMT Ratio

Constructs	EB	EXKH	FIN	INKH	SL	SP
EB						
EXKH	0.062					
FIN	0.182	0.466				
INKH	0.049	0.258	0.433			
SL	0.048	0.514	0.470	0.533		
SP	0.108	0.488	0.743	0.498	0.791	

Table 6 presents the direct effect results, indicating structural path analysis. The results highlight that SL has a positive and significant influence on frugal innovation ($B = 0.192$, $SD = 0.049$, $t\text{-value} = 3.90$, $p = 0.000$, $CI = 0.101, 0.286$), supporting H1. This indicates that frugal innovation translates into low-cost solutions, resource-efficient solutions suited to the needs of resource-poor markets, which result in higher sustainable performance. Similarly, SL shows a positive and significant influence on sustainable performance ($B = 0.562$, $SD = 0.027$, $t\text{-value} = 20.703$, $p = 0.000$, $CI = 0.509, 0.612$), supporting H2. This suggest that when sustainable leadership is utilized in an environment, resulting in higher value creation and sustain long-term success. The influence of frugal innovation is positive and significant on sustainable



performance ($B = 0.436$, $SD = 0.031$, $t\text{-value} = 14.038$, $p = 0.000$, $CI = 0.375, 0.499$), supporting H3. This supports the argument that sustainable leadership increases frugal innovation by integrating resource mindfulness and sustainable practices.

Table 6*Direct Effect Results*

#	Hypotheses	Beta	SD	t-value	P-values	Confidence interval	Decision
H1	SL $\rightarrow$ FIN	0.192	0.049	3.920	0.000	0.101, 0.286	Supported
H2	SL $\rightarrow$ SP	0.562	0.027	20.703	0.000	0.509, 0.612	Supported
H3	FIN $\rightarrow$ SP	0.436	0.031	14.038	0.000	0.375, 0.499	Supported

Table 7 presents the results of indirect or moderation effects. The findings highlight that Frugal innovation significantly mediates the relationship between sustainable leadership and sustainable performance ($B = 0.084$, $SD = 0.0222$, $t\text{-value} = 3.817$, $p = 0.000$, $CI = 0.042, 0.218$), supporting H4. The findings indicate that Internal heterogeneous knowledge sharing mediates the relationship between sustainable leadership and frugal innovation ($B = 0.102$, $SD = 0.024$, $t\text{-value} = 4.338$, $p = 0.000$, $CI = 0.061, 0.149$). The results show that external heterogeneous knowledge sharing mediates the relationship between sustainable leadership and frugal innovation ($B = 0.131$, $SD = 0.026$, $t\text{-value} = 5.085$, $p = 0.000$, $CI = 0.086, 0.193$). The result indicates that entrepreneurial bricolage moderates the relationship between sustainable leadership and frugal innovation ($B = 0.155$, $SD = 0.040$, $t\text{-value} = 3.873$, $p = 0.000$, $CI = 0.075, 0.232$). This highlights that entrepreneurial Bricolage increases local adaptation, which translates into higher leader-driven priorities for rapid prototyping, cost-effective designs, and user-informed simplifications that characterize frugal innovation.

Table 7*Indirect Effect Results*

#	Hypothesis	Beta	SD	t-value	P-values	Confidence interval	Result
H4	SL $\rightarrow$ FIN $\rightarrow$ SP	0.084	0.022	3.817	0.000	0.042, 0.128	Supported
H5	SL $\rightarrow$ INKH $\rightarrow$ FIN	0.102	0.024	4.338	0.000	0.061, 0.149	Supported
H6	SL $\rightarrow$ EXKH $\rightarrow$ FIN	0.131	0.026	5.085	0.000	0.086, 0.193	Supported
H7	SL $\times$ EB $\rightarrow$ FIN	0.155	0.040	3.873	0.000	0.075, 0.232	Supported

Note. The source table is truncated; values for H5–H7 are taken from the text. The text later states that H5 and H7 were rejected, creating an inconsistency in the source file.

Table 8 shows the results of predictive model analysis for all exogenous constructs. The findings suggest that SP has 71% of the variance explained in the model, while having 57% predictive accuracy. Similarly, EXKH and INKH have 22% and 23% explanatory power, while having 22%, and 23% predictive power. Therefore, all the predictive powers are highly relevant and support the model accuracy.

Table 8*Predictive Model Analysis*

Endogenous construct	R-square	Q ² predict
EXKH	0.227	0.222
FIN	0.338	0.230
INKH	0.234	0.231
SP	0.719	0.573



Figure 7
Structural Path Analysis

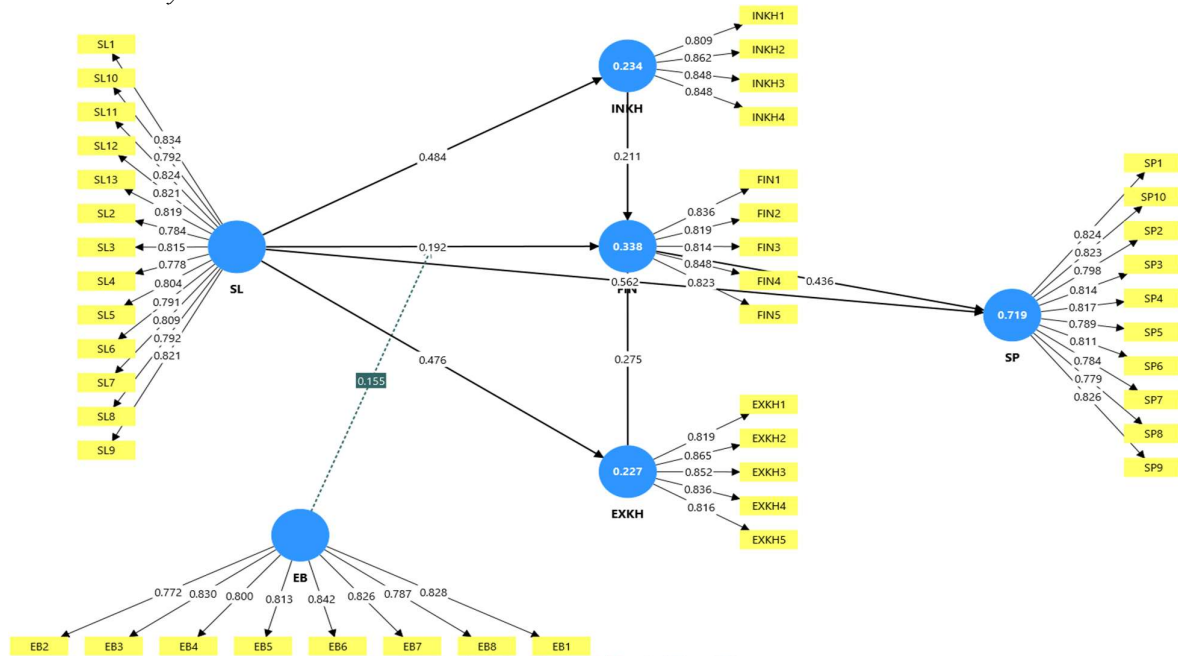
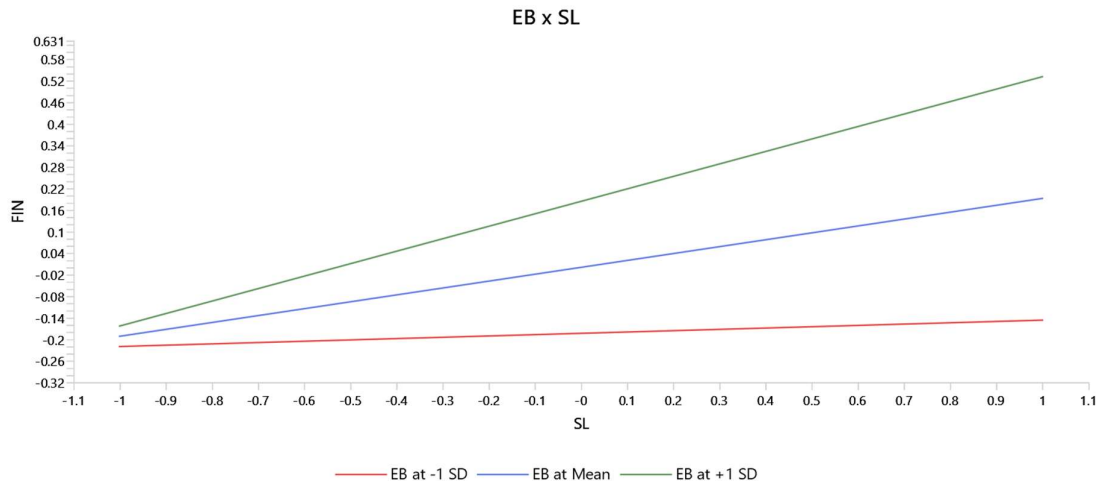


Figure 7 illustrates the moderating role of entrepreneurial bricolage between sustainable leadership and frugal innovation ($B = 0.155$, $SD = 0.040$, $t\text{-value} = 3.873$, $p = 0.000$, $CI = 0.075, 0.232$). This highlights that entrepreneurial Bricolage interacts with firm routines and external knowledge flows to shape when leadership actually yields minimal-resource innovations, making bricolage a plausible and measurable moderator of the leadership–frugal innovation pathway.

Figure 8
Moderating Effect of Entrepreneurial Bricolage



5. Discussion

The results indicate that SL has a positive impact on FIN (H1 was proven true) and also improves SP (H2 was proven true), which is logical given that UET suggests that the values and cognitive frames of top management drive strategic innovation and results (Fu et al., 2024; Iqbal, Ahmad, et al., 2021a). The impact of FIN, in turn, is positive on SP (H3 supported), which supports the idea that resource-efficient (doing less



with more innovations) is the driving force of sustainability results. With respect to mediation, EXKH is a sufficient mediator between SL and FIN (H6 supported) but not INKH (H5 rejected). This indicates the knowledge of the effectuation theory, in which leaders combine external organisations and heterogeneous external knowledge to pursue actions based on means-end principles, and external heterogeneity is greater than internal knowledge in frugal innovation (Iqbal et al., 2025). Nevertheless, the SL–FIN connection was not moderated by EB (H7 rejected), meaning that the resource recombination skill of directors does not substantially enhance the effect of leadership on frugality results.

Thus, based on effectuation theory and UET, the study gives crucial insights into the relationship between sustainable leadership, frugal innovation, and sustainable performance. The analyses have utilised both PLS-SEM and ML to reinforce the robustness of the relationships as well as present avenues for deeper exploration. The findings of the analysis support a sustainable leadership–frugal innovation hypothesis, underscoring the importance of leaders in fostering an innovative organisational culture. This is in line with prior research, which indicates that sustainability-oriented leaders are often very much resource-conscious and also suggest that sustainable leadership enables an organisation to create an environment of frugality and creativity, where an organisation can hurdle challenges and limitations in a way that will translate such dilemmas into opportunities for creative growth.

Moreover, the findings reveal that the direct link between sustainable leadership and sustainable performance enhances the role of the leader in playing an important part in the unfolding of the organisation toward long-term success. Similar to these findings, Faraz et al. (2024) establish that leadership in sustainable performance places a vision of not only environmental and social responsibility but also values that percolate down to the organisational culture. These leaders foster a culture of sustainability that encourages teams to work toward innovative solutions that meet higher-order goals of society, which then tends to drive performance outcomes that are conducted holistically to achieve success. Torelli (2021) is of the view that the alignment between the idea of leadership and performance resource-consumingly to think of sustainability as not an add-on but rather as a fundamental characteristic of the resilient and prosperous organisation.

From the findings, it is clear that there is considerable support for the connection between frugal innovation and sustainable performance, which points to the main opportunity of frugal approaches in the transformation of organisational performance. It is in line with the findings of various research that organisations can leverage cost-effective solutions through frugal innovation in the face of addressing prevailing market issues, while working towards meeting sustainability agendas (De Marchi et al., 2022; Iqbal, Ahmad, et al., 2021b; Iqbal et al., 2022). Iqbal et al. (2022) describe that organisations that adopt frugal innovation are very agile and adaptive. Such organisations stand to be far better placed for success, particularly in dynamic markets. This ultimately unfolds to state that innovation does not have to be resource-consuming to be effective. Instead, by focusing on creativity and efficiency, organisations can attain sustainability that would achieve both economic and ecological goals (Lazaridou et al., 2020).

The present study's findings do not support the hypothesis that entrepreneurial bricolage is a moderator of the sustainable leadership–frugal innovation relationship. This means that the mere application of the approach of bricolage would not be sufficient to improve outcomes for innovation. This finding aligns with the findings of a study by Iqbal, Ahmad and Li (2021), which shows that the effect of sustainable leadership on frugal innovation did not vary for the different values of entrepreneurial bricolage. It suggests that bricolage appropriateness is conditional and dependent upon critical contextual and organisational factors, along with their underlying capabilities. For instance, H. Z. Alsharif et al. (2021) describe that successful bricolage will depend upon factors such as the availability of diversified resources, creativity from teams, and the organisational culture that encourages experimentation and risk-taking. Such critical variables might undoubtedly restrain the maximum realisation of bricolage in high magnification of sustainable leadership.

Moreover, evidence from the findings of this study for external heterogeneous knowledge sharing also underscores the impetus for co-operation with a variety of heterogeneous external partners in driving



frugal innovation (Iqbal & Piwowar-Sulej, 2023). It is through involvement with a number of stakeholders, from suppliers to customers, from research institutions and other organisations, that firms can tap into a more varied spectrum of ideas, perspectives, and resources. On the other hand, there is no evidence in the findings of this study to support the idea that internal knowledge sharing suggests that gathering knowledge within an organisation itself will not be enough to spark innovation. It is against the findings of Iqbal and Piwowar-Sulej (2023) but is in line with the research by Iqbal et al. (2024), which shows that internal knowledge sharing does not mediate the sustainability-oriented leadership–frugal ecosystem relationship. Thus, for example, fragmented departments or a lack of many channels of communication or incentives to cooperate may be a constraint on internal resource efficiency. Therefore, for organisations, it is essential to focus on tools that enhance the efficiency of external knowledge exchanges, but also to reevaluate their internal processes toward having a more integrated and collaborative environment that creates innovation from both sides.

The findings of the present study indicate that the mediatory function of frugal innovations between the concepts of sustainable leadership and sustainable performance places much emphasis on how it converts intentions of leaders into viable results (Tian & Wang, 2023). This mediation indicates that sustainable leaders encourage a resource-efficient and innovative solution conducive to the sustainability goals. From this perspective, bridging the gap between leadership and performance, frugal innovation enables organisations to achieve measurable outcomes across the dimensions of environmental, social, and economic elements (Tariq et al., 2024). Therefore, this relationship explains the fact that effective leadership is not just a matter of setting out objectives but also empowering an organisational culture where innovation becomes a catalyst for sustainable performance.

Additional findings of the machine learning analysis through an extra tree regressor model with hyperparameter tuning illustrate synergies among the relationships discussed in the present. Hence, the intricate patterns enhance our understanding of how sustainable leadership, frugal innovation, and sustainable performance interact through complex interactions identified with advanced algorithms in addition to direct correlations. This multi-dimensional analysis underlines the point that organisations need to move toward a whole-system approach consistent with these relations. It suggests that organisations can play on such synergy to unlock the full potential in their sustainability efforts and reap worthwhile sustainable performance benefits.

6. Conclusion

In conclusion, this research has contributed profound insights into the interactive model of sustainable leadership, frugal innovation, and sustainable performance. The findings emphasise the strategic role that the sustainable leader needs to play in order to contribute to the innovative organisation culture and drive frugal innovation, hence achieving sustainable performance. Based on the literature presented and findings drawn, this paper provides both theoretical as well as practical implications and avenues for further research as follows.

7. Implications

7.1 Theoretical Implications

This study significantly contributed to theoretical literature in relation to sustainable leadership, frugal innovation, and sustainable performance as it explored the relationships among these constructs. Based on the arguments above, this study adds to the theoretical knowledge of sustainable leadership by clarifying this role as an innovation performance catalyst. Bringing out the role of external networks and knowledge heterogeneity, this research finds the ways through which different collaborations enable organisational capabilities for frugal innovation (Tian & Wang, 2023).

Moreover, insights about entrepreneurial bricolage suggest more in-depth exploration of conditions under which this can be an effective or ineffective approach with sustainable leadership. Understanding such conditions will prove to be a highly valuable insight into how leaders can create contexts that are helpful for the bricolage but aligned with achieving sustainability objectives (Iqbal et al., 2024). This research, therefore, will be a basis upon which scholars can derive an even more integral framework that



combines entrepreneurial bricolage with sustainable leadership. This will result in innovation-driving and performance-driving strategies that are presumably even more effective.

The current research contributes to the literature of effectuation theory as it has shown evidence which focuses on how leaders can utilise the resources and partnerships at their disposal to guide innovation in uncertain environments. The current study also enhanced the literature about UET by validating the mediating role of frugal innovation. Collectively, the theories therefore provide a holistic framework from which to understand the complexities in the nurturing of frugal innovation and sustainable performance (Iqbal, Ahmad, et al., 2021b). In addition, the application of the ML technique not only supported those relationships that emerged using PLS-SEM but also offered a robust analytical frame within which to articulate the complex interactions within the data. Theoretically, the present study has filled the research gap in that it has confirmed that sustainable leadership and frugal innovation are significantly important in increasing sustainable performance.

7.2 Practical Implications

From the practical point of view, the study also provided various significant implications to business professionals, general managers, and policymakers. This is because practitioners and policymakers are increasingly being compelled to enhance their sustainable performance (Malik et al., 2021). So, the proposed sustainable performance framework presented in this study can be adopted for the exploitation of the least possible resources, minimisation of wastage, along with lesser CO₂ emission for better environmental performance in emerging economies. The current scientific evidence also suggests that organisations should focus on sustainable leadership development, considering frugal innovation because it can greatly enhance performance outcomes. Sustainable leadership development will ensure that the companies have leaders who can utilise strategic thinking by making resourceful choices and acting as champions of sustainability (Iqbal & Piwoswar-Sulej, 2023).

More importantly, such emphasis on partnerships external to the firm for sharing knowledge is required. In that regard, when diverse stakeholders are involved, innovative practices in line with the goals of sustainability can be galvanised (Shehzad et al., 2023). Pragmatically, this study suggests that such initiatives should be supported through targeted training, in which leaders learn appropriate competencies through which they can engage with meaningfully relevant external collaborations and apply frugal innovation principles appropriately. This would build up the leaders' skills more in networking, resource optimisation, and creative thinking and thus position any organisation to navigate challenges and capitalise on opportunities today in their ever-changing marketplace.

8. Limitations and Future Research Directions

The study has some limitations that need to be mentioned. First, by its size and context, findings may not be generalised as such to populations of other industries or regions, hence limited external validity. The second limitation is based on the fact that this study employs self-reported measures, which leads to the possibility of measurement bias, thus raising questions about whether the outcome reflects reality, impacting the validity of the relationships found. Although the study supports several relations, longitudinal studies could be used to establish causality clearly, which might have provided a better sense of dynamics through time. Although machine learning has given strong analytical power, at times it is not interpretable. Complex models such as the one used in this study might have obscured certain relations that may be hard to clarify unless managed accordingly.

Studies of sustainable leadership, frugal innovation, and performance dynamics in other industries and under different cultural environments are the directions for further studies in generalising findings. More longitudinal studies are needed to explain the temporal relationships among the variables concerned to gain a more comprehensive view of the dynamics of how such variables change over time. Future research can further test other mediating or moderating variables, such as organisational culture or even external environmental factors that may affect sustainable leadership and innovation. Ultimately, using more sophisticated machine learning techniques will reveal those hidden, complex patterns and relationships deep



down within the data. It will not only enrich the theory but also provide pragmatic insights to the organisations, which are looking for ways to enhance their approach towards sustainability.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Appendix

Measurement items

“A. Sustainable leadership

1. In our firm, leaders take a sustainable, socially responsible action.
2. In our firm, leaders take sustainable, environmentally responsible action.
3. In our firm, leaders take sustainable, ethically responsible action.
4. In our firm, leaders make decisions based on consensus.
5. In our firm, leaders are willing to correct mistakes that affect sustainability.
6. In our firm, leaders use unique innovative methods to resolve sustainability issues.
7. In our firm, leaders create wealth through sustainable efforts.
8. In our firm, leaders put purpose before profit.
9. In our firm, leaders balance sustainable social responsibility with profits.
10. In our firm, leaders demonstrate sustainability by persevering through all types of change.
11. In our firm, leaders are concerned about how sustainability affects employees.
12. In our firm, leaders communicate sustainability decisions to all involved.
13. In our firm, leaders build a culture of sustainability through their communication efforts.

B. Entrepreneurial bricolage

1. We are confident of our ability to find workable solutions to new challenges by using our existing resources.
2. We gladly take on a broader range of challenges than others with our resources would be able to.
3. We use any existing resource that appears useful to respond to a new problem or opportunity.
4. We deal with new challenges by applying a combination of our existing resources and other inexpensive resources available to us.
5. When dealing with new problems or opportunities, we take action by assuming that we will find a workable solution.
6. By combining our existing resources, we take on a surprising variety of new challenges.
7. When we face new challenges, we put together workable solutions from our existing resources.
8. We combine resources to accomplish new challenges that the resources were not originally intended to accomplish.

C. Internal heterogeneous knowledge sharing

1. The firm's technical knowledge spans many technical fields.
2. The firm makes the investment and development in other domains besides core technology.
3. Patents that the firm applied for are merged by technical knowledge in various fields.
4. The firm has technology staff with a wide range of training and educational backgrounds.

D. External heterogeneous knowledge sharing

Please evaluate the degree of variance in the field of technology between your firm and the innovative partners in a specific cooperation period:

1. The technical knowledge.
2. The field of technology investments.
3. The professional backgrounds of technology staff.
4. The producing process and conditions.
5. The classification of patent applications.

E. Frugal innovation

1. Our firm develops low-cost products/services.
2. It is easy to use our firm's product/service.
3. Our firm uses resources thriftily.



4. Our firm offers sustainable products/services.
5. Our firm introduces good-enough quality products/services.

F. Sustainable performance

Environmental performance

1. Improvements in its environmental situation.
2. Reduced waste (e.g., water and/or solid).
3. Reduced air emissions.
4. Decreased its consumption of hazardous/ harmful/toxic materials.

Economic performance

5. The cost of materials purchased is reduced.
6. The cost of energy consumption is reduced.
7. Improvement in earnings per share is achieved.
8. Improvement in return on investment is achieved.

Social performance

9. Improved its image in the eyes of its customers.
10. Increased its investments in social projects (e.g., education, culture, sports).
11. Improved its relations with community stakeholders (e.g., nongovernmental companies and community activists).
12. Improved in occupational health and safety of employees.”

