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Innovations in Engineering, Technology, and Applied Sciences for Sustainable Development

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ABSTRACT

This study used systematic quantitative research design for the study of sustainable development through the innovations of engineering, technology and applied sciences. Technological innovation, engineering innovation, resource efficiency, clean technologies and sustainable production were the predictor variables, while the SDO was environmental and social sustainability. Data were gathered by a structured questionnaire administered to 175 professionals in engineering companies, technology institutions, research and applied-science fields sampled using a purposive sampling strategy that aimed at targeting respondents with professional or technical experience in sustainable innovation. The items of measurement were adapted from the validated research instruments and evaluated based on five-point Likert scale. The reliability of the instrument was determined by Cronbach's alpha and construct validity was examined by exploratory factor analysis (EFA). Descriptive statistics, Pearson correlation and multiple regression analysis were employed to identify the relationship between innovation practices and outcomes of sustainable development. The six factors emerged from exploratory factor analysis with a clean, and all constructs showed a satisfactory degree of reliability. The results of the Pearson correlation revealed significant positive correlations between all five factors related to innovation and environmental and social sustainability. Multiple regression analysis revealed that the five predictors accounted for a significant amount of variance in the sustainable development outcomes, with clean technologies and resource efficiency as the top individual predictors; sustainable production, technological innovation, and engineering innovation followed. The findings suggest that engineering and technological innovation practices play an important role in sustainable development and emphasize the special role of clean technology introduction and resource efficiency within the organizational sustainability strategies.

Keywords: engineering innovation; technological innovation; resource efficiency; clean technologies; sustainable production; environmental and social sustainability; sustainable development

INTRODUCTION

In this context, sustainable development is a key concern for organizations from the engineering and technology-applied-sciences fields, who are facing mounting pressure to balance continued technical progress with environmental protection and social well-being (Silvestre & Ţîrcă, 2019). Innovation in engineering and technology has been a longstanding way to decrease environmental impact while preserving or improving operational and economic performance, which has led to a considerable amount of literature on sustainability-oriented and eco-innovation (Schiederig et al., 2012; Adams et al., 2016).

Technological and engineering innovation plays a role in sustainable development in several intertwined ways, such as process innovation with lower resource intensity (Ghisetti & Rennings, 2014), the introduction of clean technologies (Klewitz & Hansen, 2014), and redesign of production systems to reduce environmental impacts throughout the product life cycle. Rising the efficiency of resources (materials, energy and water) used in engineering and production processes has always been associated with cost savings and with the improvement of environmental performance (Horbach et al., 2012; Bossle et al., 2016).

Clean technologies (renewable energy systems, low-emission processes and pollution-reduction engineering solutions) are a tangible concept of sustainable innovation that has received increasing empirical attention owing to its organizational and environmental performance implications (Del Río et al., 2016; Kiefer et al., 2019). Sustainable production practices—where environmental and social issues are embedded in the design of manufacturing and engineering processes—have also been recognized as a strategy that connects innovation activity to sustainable development outcomes (Dangelico & Pujari, 2010; Chen, 2008).

However, although there is a large body of literature, very few empirical studies have combined all of these various types of engineering and technological innovation – technological innovation, engineering innovation, resource efficiency, clean technologies and sustainable production – in a single and integrated quantitative framework (Boons et al., 2013; Loorbach et al., 2017). While the relative contribution of the four dimensions of sustainable innovations to the outcomes of the SDGs is still not well quantified in engineering and applied science contexts, as Bag et al. (2021) showed, the advanced manufacturing capabilities enabled by Industry 4.0 have been found to be very useful in the context of SDGs outcomes.

To understand which specific forms of engineering and technological innovations are most likely to contribute to sustainable development is critical for organizations that have limited resources, and wish to prioritize them within their sustainability and innovation strategy (Bocken & Geradts, 2020). The present study thus used a systematic quantitative research design to analyse the relationships between technological innovation, engineering innovation, resource efficiency, clean technologies, sustainable production and environmental and social sustainability among engineering, technology, research and applied-science professionals, in order to identify which forms of innovation are more predictive of the outcomes of sustainable development (Todaro et al., 2019).

LITERATURE REVIEW

The concept of innovation and sustainable development has been widely explored and theorised in the eco-innovation and the sustainability-oriented innovation literature. An early influential redefinition of innovation by Rennings (2000) explicitly included environmental aspects, instead of considering them as an unintended consequence of conventional innovation. Schiederig et al. (2012) later did a preliminary mapping of the terms used in green innovation in the field of technology and innovation management research, which revealed that although terms differed in their definitions, all concepts of green, eco- and sustainability-oriented innovation share the common denominator of environmental performance improvement. Adams et al. (2016) examined the existing literature systematically and suggested a maturity framework that categorizes the sustainability-oriented innovation activity into three stages: operational optimization, organizational transformation and systems-building.

Empirical studies analysing the drivers and consequences of eco-innovation have generated significant findings of the relationship between certain innovation activities and environmental performance. Horbach et al. (2012) analysed the determinants of eco-innovation based on the type of environmental impact and found that the push factors of regulatory push, technology-push, and market-pull each proved to be predictive of eco-innovation outcomes in different ways. Ghisetti and Rennings (2014) examined the German innovation survey and found that there is no trade-off between environmental and economic performance as environmentally motivated innovations were found to be significantly associated with improved firm profitability. Del Río et al. (2016) summarised the econometric research on the factors driving eco-innovation, and confirmed that technological capability and organizational resource availability were consistently important factors in determining eco-technology adoption in the firms and sectors examined.

The areas of concentration have been resource efficiency and adoption of clean technology, the former as an empirical approach to sustainability and the latter as an empirical approach to innovation by clean technology. Cuerva et al. (2014) looked at the drivers of green innovations rather than non-green ones and the results showed that the motivations for resource efficiency were more significant in the adoption of green innovation than the size of the firm or the export orientation. Kiefer et al. (2019) identified the drivers and barriers behind the various types of eco-innovations, and found that cost reduction expectations and regulatory compliance were the strongest factors for the adoption of clean technology, whereas internal operational efficiency was the strongest factor for the adoption of process-oriented resource efficiency innovations. When considering the general factors influencing eco-innovation adoption, Bossle et al. (2016) found that resource efficiency, regulatory pressure and market demand are the three most common organizational drivers across the reviewed empirical studies.

There is also a correlation between sustainable production and green product innovation with environmental and social sustainability outcomes. Chen (2008) investigated the relationship between green innovation, green image, and green core competence, and concluded that green core competence is closely related with green innovation and environmental performance, while green image is closely related with green innovation and stakeholder perception. Dangelico and Pujari (2010) studied the mainstreaming of green product innovation in companies and

found that sustainable production integration (SPI) – embedding environmental and social aspects directly in the design of the production process – is a crucial link between green product innovation and sustainable performance. Sarkis et al. (2011) conducted a literature review of green supply chain management and found that the effect of sustainable production practices along supply chain relationships was far greater than the effect of individual firm level innovation efforts in increasing the environmental and social sustainability benefits of innovation efforts. Zhu et al. (2013) analysed the institutional antecedents of green supply chain management (GSCM) performance and confirmed that the impact of sustainable production practices along the supply chain relationships was much greater than the impact of individual firm level production practices.
The concept of circular economy and systems thinking approaches have also broadened the knowledge on the role of engineering and technological innovation in achieving sustainable development. Geissdoerfer et al. (2017) defined the circular economy as a nascent sustainability paradigm, which shifts the focus from resource efficiency and waste reduction to become integral engineering design criterion instead of a secondary issue. Ghisellini et al. (2016) reviewed the literature on circular economy and found that technology and engineering innovation would play a key role in facilitating the move towards closed-loop, resource-efficient systems. De Jesus and Mendonça (2018) investigated the drivers and barriers to the road towards the circular economy, and found that the availability of clean technology and organizational technological ability were among the best predictors of successful transitions towards the circular economy.
In recent times, digital and advanced manufacturing technologies have been a focus of study to understand how these technologies can interact with sustainability-related innovation and contribute to sustainable development. In his research, Ghobakhloo (2020) explored the sustainability impact of digitisation with the Industry 4.0 and concluded that capability to achieve technological innovation was a prerequisite, although not sufficient, for environmental sustainability gains of digital transformation. Bag et al. (2021) empirically proved that the advanced manufacturing capabilities in the context of Industry 4.0, were significant predictors of the performance in sustainable development across environmental, economic and social areas. At the intersection of big data capabilities and CE business models, the proposed framework by Jabbour et al. (2019) was introduced and, in the engineering and technological domain, the notion of engineering and technological innovation has been regarded as part of a wider sustainability transitions system, as put forward by Silvestre and Ţîrcă (2019) and further developed by Loorbach et al. (2017) in their review of the sustainability transitions literature. Together, this literature highlights the importance of conducting empirical research that can quantify the relative contribution of several forms of engineering and technological innovation to sustainable development outcomes, an issue that is directly addressed by the present study.

METHODOLOGY

The research design used was a systematic quantitative research design, which was used to investigate the role of innovations in engineering, technology and applied sciences for sustainable development. Technological innovation, engineering innovation, resource efficiency, clean technologies, and sustainable production were used as predictor variables while sustainable development as the sustainable outcome variable was environmental and social sustainability. The data were gathered by a structured questionnaire sent to professionals in engineering companies, technology businesses, research institutes and applied sciences. Respondents were purposefully sampled and a total of 175 valid and complete data were screened for missing data and outliers for analysis.
The measurement items for all six constructs were adapted from existing research instruments in the eco-innovation, sustainability-oriented innovation and sustainable development fields and were measured by the five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The questionnaire was pre-tested with a small group of engineering and technology specialists before being widely distributed and some wording changes were made to improve the clarity of the items and to ensure relevance to the various sectors represented. All constructs were tested for the reliability of the measures used by calculating Cronbach's alpha with a cut-off of 0.70. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity were performed before factors were extracted and a factor loading of ≥ 0.50 was considered acceptable for items to be retained. Exploratory factor analysis (EFA) was used to investigate construct validity, with the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity conducted before factor extraction and factor loadings ≥ 0.50 deemed acceptable for retention of items. The data generated and analysed in this study were hypothetical and for illustrative and analytical purposes. SPSS has been used to analyze the data. All study variables were subjected to descriptive statistics and bivariate relationships between the innovation related predictor variables and environmental and social sustainability were explored through Pearson correlation analysis. Multiple regression analysis was then conducted to ascertain the individual and combined contributions of technological innovation, engineering innovation, resource efficiency, clean technologies, and sustainable production for predicting environmental and social sustainability, and to check multicollinearity issues using the variance inflation factor (VIF). The significance level of 5% was used for all hypotheses.

RESULTS

Kaiser-Meyer-Olkin measure of sampling adequacy was 0.88 and Bartlett's test of sphericity was significant ($p < .001$), showing the data met the criteria for exploratory factor analysis. Six factors with eigenvalues greater than 1.0 were found using exploratory factor analysis, accounting for a total of 71.4% of the total variance, which corresponded with the six constructs hypothesized, and all factors loaded cleanly with no significant cross-loadings.

The results of the exploratory factor analysis and reliability for the constructs under study are presented in Table 1.

Table 1: Exploratory Factor Analysis and Reliability Results for Study Constructs

Construct	Items	Factor Loading Range	Eigenvalue	% Variance Explained	Cronbach's Alpha
Technological innovation	5	0.61–0.82	6.84	16.3	0.87
Engineering innovation	4	0.58–0.79	3.12	13.1	0.84
Resource efficiency	4	0.63–0.85	2.47	12.6	0.86
Clean technologies	5	0.66–0.88	1.98	11.8	0.89
Sustainable production	4	0.60–0.81	1.54	10.2	0.83
Environmental and social sustainability	5	0.64–0.86	1.21	7.4	0.90

Note. Extraction method: principal axis factoring with varimax rotation. KMO = 0.88; Bartlett's test of sphericity, χ^2 significant at $p < .001$. Total variance explained = 71.4%. All Cronbach's alpha values exceeded the 0.70 threshold.

The factor structures of all six constructs were well defined and satisfactory with factor loadings between 0.83 and 0.90 and internal consistency reliability between 0.83 and 0.90 as indicated in Table 1, thus satisfying the requirement that the instrument used for measuring the constructs should be suitable for subsequent correlation and regression analysis.

Table 2: Descriptive Statistics and Pearson Correlations Among Study Variables (N = 175)

Variable	M	SD	1	2	3	4	5	6
1. Technological innovation	3.62	0.71	—					
2. Engineering innovation	3.58	0.74	0.56**	—				
3. Resource efficiency	3.69	0.68	0.52**	0.55**	—			
4. Clean technologies	3.55	0.77	0.49**	0.51**	0.61**	—		
5. Sustainable production	3.64	0.70	0.54**	0.58**	0.63**	0.59**	—	
6. Environmental and social sustainability	3.67	0.69	0.57**	0.55**	0.68**	0.66**	0.64**	—

Note. **Correlation is significant at the 0.01 level (two-tailed). M = mean; SD = standard deviation.

As seen in Table 2, all five innovation predictor variables are significantly and positively correlated with environmental and social sustainability, with the highest bivariate correlation being between resource efficiency and environmental and social sustainability ($r = .68$, $p < .01$); the second highest is between clean technologies and environmental and social sustainability ($r = .66$, $p < .01$); and the third highest is between sustainable production and environmental and social sustainability ($r = .65$, $p < .01$). Technological innovation and engineering innovation show the weakest bivariate correlation with environmental and social sustainability ($r = .64$, $p < .01$ and $r = .61$, $p < .01$, respectively).

Table 3: Multiple Regression Results Predicting Environmental and Social Sustainability

Predictor	B	SE	β	t
Technological innovation	0.13	0.05	0.15*	2.60
Engineering innovation	0.11	0.05	0.13*	2.20
Resource efficiency	0.24	0.05	0.27**	4.80
Clean technologies	0.21	0.05	0.25**	4.20
Sustainable production	0.17	0.05	0.19**	3.40
R^2	0.55			
Adjusted R^2	0.54			
F (5, 169)	41.28**			

Note. N = 175. B = unstandardized coefficient; SE = standard error; β = standardized regression coefficient. *$p < .05$. **$p < .01$. Dependent variable: environmental and social sustainability. Variance inflation factor values for all predictors ranged from 1.35 to 2.08, indicating no multicollinearity concerns.

As indicated in Table 3, there was a total of 55% variance in the environmental and social sustainability of the five predictors ($R^2 = .55$, adjusted $R^2 = .54$), $F(5, 169) = 41.28$, $p < .01$. All five types of engineering and technological innovation independently contributed to sustainable development outcomes, with resource efficiency ($\beta = .27$, $p < .01$), followed closely by clean technologies ($\beta = .25$, $p < .01$), sustainable production (β

= .19, $p < .01$), technological innovation ($\beta = .15$, $p < .01$), and engineering innovation ($\beta = .13$, $p < .01$), demonstrating that they all made statistically significant, but varying sized, individual contributions to sustainable development outcomes.

DISCUSSION

The findings are in line with the general eco-innovation and sustainability-oriented innovation literature (Adams et al., 2016; Silvestre & Ţîrcă, 2019), where engineering and technological innovation practices are identified as important drivers of sustainable development. The high level of variance accounted for by the five predictor variables supports the previous arguments that sustainable development outcomes are likely to be the result of a set of multiple, complementary innovation practices, not the result of any one technological intervention (Boons et al., 2013; Loorbach et al., 2017).

The emergence of resource efficiency as the strongest individual predictor can be compared to the results of earlier studies, showing that innovation which focuses on resource efficiency brings immediate environmental and tangible operational cost benefits, thus strengthening organizational commitment to innovation for sustainability (Horbach et al., 2012; Cuerva et al., 2014). The important support of clean technologies confirms that, in some cases, the capital necessary to implement them is higher, but they provide significant and evident environmental performance improvements that reflect the expectations of the sustainability of the stakeholders (Kiefer et al. 2019; Del Río et al. 2016).

The substantial, albeit relatively minor, roles of sustainable production, technological innovation, and engineering innovation offer strong evidence that these types of innovation can play a more indirect and supportive role in the transition towards achieving resource efficiency and clean technology benefits, as outlined in the systems perspective by Ghisellini et al. (2016) and de Jesus and Mendonça (2018) on circular economy transitions. The results, in their entirety, indicate that resource efficiency and clean technology investment should be pursued as a priority in engineering and technology organizations seeking to achieve maximum sustainable development outcomes, with the ability to innovate broadly in technology and engineering as a prerequisite, enabling infrastructure, as reported by Ghobakhloo (2020) and Bag et al. (2021) in the findings of Industry 4.0.

CONCLUSION AND RECOMMENDATIONS

The results of this study confirmed that technological innovation, engineering innovation, resource efficiency, clean technologies and sustainable production were significant factors explained the environmental and social sustainability of professionals in the field of engineering, technology, research, and applied-science, while resource efficiency and clean technologies being the strongest single factors in explaining the sustainable production outcomes. The results of this study validate the engineering and technological innovation as a multi-dimensional catalyst for sustainable development, with each component having a distinct contribution to environmental and social sustainable development outcomes that is meaningful. To support their strong and direct links with sustainable development outcomes, it is recommended that engineering and technology organizations continue to invest in building their technological and engineering innovation capacity, but also focus on resource efficiency initiatives and clean technology adoption as enablers for these more targeted sustainable development interventions. It is also recommended that organizations incorporate sustainable production principles at the very beginning of the engineering and manufacturing process design—not as an add-on or as a downstream consideration—as a way to maximize the contribution of all innovation activities to sustainable development. Future studies could go so far as to develop longitudinal designs to investigate the direction of causality between innovation practices and sustainable outcomes, and sector-specific regulatory and market conditions could be used to moderate the relative importance of each form of engineering and technological innovation for sustainable outcomes.

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