

## ABSTRACT

This study performs a comparative sustainability analysis of bioenergy systems in Germany and Pakistan, utilizing a multi-methodological framework—Analytic Hierarchy Process with Simple Multi-Attribute Rating Technique Exploiting Ranks (AHP SMARTER), Life Cycle Costing (LCC), Life Cycle Assessment (LCA), and Multi-Criteria Analysis (MCA) to assess environmental, economic, and social performance across biogas and biofuel production pathways. Results indicate substantial discrepancies: Germany's bioenergy systems have exceptional technological efficiency (95% feedstock conversion rates) and policy-driven scalability, attaining 60–70% reductions in greenhouse gas (GHG) emissions through sophisticated digestate management and grid-integrated biomethane. Nevertheless, dependence on monoculture feedstocks (e.g., maize) presents biodiversity trade-offs. Conversely, Pakistan's decentralized biogas models exhibit cost-effectiveness, with payback periods of 1.25 years in agro-industrial systems, and reduce open-field burning emissions by 1.5 tons CO<sub>2</sub>eq annually per plant. However, they encounter systemic inefficiencies, such as 30% feedstock spoilage, 15–20% methane leakage, and fragmented governance that restricts social equity and scalability. Germany's biogas facilities attain economic sustainability within 7–10 years due to elevated energy tariffs (€0.15/kWh) and subsidies, whereas Pakistan's dependence on donor-funded experimental projects extends payback periods to over 15 years. A techno-economic analysis of biofuels reveals Germany's cost-competitiveness, with breakeven prices 15% lower than fossil fuels, attributed to automated blending infrastructure. In contrast, Pakistan faces a 30% cost premium due to antiquated technologies and informal supply channels. The research promotes context-specific methods, such as legislative changes (e.g., feed-in tariffs, risk-sharing guarantees) and hybrid feedstock models (e.g., animal waste combined with crop residues) in Pakistan, as well as biodiversity-aware feedstock diversification in Germany. Cross-border technology transfer, including the adaptation of modular German digesters for Pakistani cattle dung, might decrease capital expenditures by 30%, while the replication of Germany's "Biofuel Corridors" along Pakistan's freight routes may lower logistics costs by 20%. This research highlights the possibility of synchronizing Pakistan's draft Bioenergy Policy with Germany's Renewable Energy Act (EEG), thereby aligning sustainability indicators, bolstering

investor trust, and furthering global climate objectives (SDG 7, 13). The results highlight the need for customized, integrative strategies to enhance bioenergy's contribution to equitable, low-carbon energy transitions in both industrialized and developing nations.