ABSTRACT

The present study emphasized the major limitations in the conventional indigo dye production process, and an attempt has been made to develop a sustainable process by evaluating its economics, improvising the traditional dye production technique, and valorizing the waste based on its characteristics.

Life cycle cost (LCC) analysis was performed to assess the economics of the existing indigo dye production process by considering the small-scale rural indigo industries of India. The system boundary of this study included the cultivation of *Indigofera* biomass, production, and processing of indigo dye from the plant biomass, and the cost involved in each step. From LCC analysis, the total cost of natural indigo ($ 48.74/kg) was observed to be five times higher than the commercial synthetic indigo dye ($ 9.1/kg). However, the benefits of natural dye products towards the environment believed to surpass its economic barrier. Further, LCC analysis also estimated the stabilization of the rural economy by the employment of rural farmers and laborers for 1,96,250 man-days/year and 12,50,000 man-days/year, respectively, for an annual dye production of 1000 tons. Utilization of the by-products/bio-wastes generated from these dye industries predicted a cost reduction of approximately 22% of the total cost structure of the natural indigo dye.

The selection of suitable parameter(s) for monitoring the indigo dye formation in the conventional indigo dye production process is crucial to avoid the variability of dye quantity by manual observation. The adequate oxidation required for indigo dye formation was investigated by performing batch experiments based on two assumptions: (i) evaluating the effect of process parameters i.e. dissolved oxygen (DO), oxidation-reduction potential (ORP), and pH on indigo dye formation by installing an aerator system, and (ii) assessing the role of indigo particle size measurement concerning to indigo dye formation irrespective of any external aeration system. The results indicated that oxidation parameters (DO, ORP, and pH) insignificantly co-related with the indigo dye yield. Whereas the particle size analysis substantiated the indigo dye formation, with a minimum indigo particle agglomeration size ≥ 100 μm.

The potential of two by-products (waste biomass and liquid waste) generated from the indigo dye production process was explored by detailed biomass characterization and nutrient analysis. High mineral content (P = 1513.47 and K = 5672.63 ppm) and C/N ratio (19.66) makes

the waste biomass a suitable raw material for composting. Additionally, the ultimate analysis (C = 44.23%, H = 6.62%, N = 2.25%, and O = 37.94%) and lignocellulosic composition (cellulose = 41.15%, hemicellulose = 28.9%) of waste biomass indicated its theoretical potential towards methane (498.94 L/kg VS) and ethanol (281.9 L/ton) production, respectively. Finally, an integrated approach was suggested to enhance the eco-sustainability of the existing dye production process by substituting the current energy and fertilizer need in *Indigofera* biomass cultivation and indigo dye production processes. In addition to that, the phytochemical potential of waste biomass was also explored.

The waste biomass was utilized with microbial inoculum (Jeevamrutha and cow dung) at various ratios to produce stable compost for its possible re-use in *Indigofera* cultivation process. Among seven compost combinations (C1-C7), C4 with 8% Jeevamrutha showed the highest microbial activity, biomass degradation capacity (51%), and plant germination index (GI) >125%. Additionally, the nutrient-enriched liquid waste (chemical oxygen demand (COD) -18887.5 mg/L, nitrate-nitrogen (NO_3^--N)-18.22 mg/L, total ammoniacal nitrogen (TAN)-117.36 mg/L, and total dissolved phosphorus (TDP)- 99.70 mg/L) was treated using various microorganisms (bacteria, algal consortia, and indigenous microorganism) for its re-use in the dye production process. As compared to others, nutrients uptake by indigenous micro-organisms was observed to be much effective and feasible, with a removal efficiency of 79, 82, 86, and 86% for COD, NO_3^--N, TAN, and TDP, respectively. Hence, the incorporation of suitable waste management strategies in the natural indigo dye production process could help in establishing a zero-waste approach.