

Sustainable production of Carbon Black pigment from waste Tire Pyrolysis for Printing Ink Applications

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Abstract

The increasing demand for sustainable and cost-effective materials has intensified interest in alternative sources of carbon black derived from waste resources and environmentally friendly processes. This study investigates the production of recovered carbon black (rCB) from the pyrolysis of scrap rubber tires and its application in nitrocellulose-based flexographic printing inks. The rCB was obtained through pyrolysis of waste tires at temperatures ranging from 350–600°C and subsequently processed into pigment concentrates using optimized dispersion techniques. The performance of the developed rCB pigment was benchmarked against commercial PRINTEX®35 carbon black manufactured by Orion Engineered Carbons GmbH. The pigment concentrates were prepared using a controlled formulation and dispersed through bead milling to achieve a uniform particle size distribution. The developed inks were evaluated in terms of shade, rheological behavior, gloss, pH stability, tint strength, opacity, tonal value, and adhesion performance. Experimental results demonstrated that the recovered carbon black exhibited performance comparable to commercial carbon black while offering significant cost and sustainability advantages. The findings highlight the potential of waste tire-derived carbon black as an environmentally sustainable, economically viable, and circular alternative for industrial flexographic printing ink applications.

Keywords: Carbon black, Sustainable recycling, Pyrolysis, Printing inks, Waste valorization, Sustainable materials

1. Introduction

The sustainable management and disposal of scrap rubber tires have become major environmental concerns due to their contribution to environmental degradation and potential human health hazards [2]. Approximately 1–1.5 billion tires reach the end of their useful life annually worldwide, with nearly 4 billion end-of-life tires currently accumulated in landfills and stockpiles globally. This figure is projected to increase to 5 billion by 2030, while nearly 250 million ELTs are generated annually in the United States [3,4]. However, there is growing interest in adopting alternative and sustainable waste tire management approaches instead of conventional disposal methods such as landfilling, tire-derived fuel combustion in cement kilns, power plants, industrial boilers, retreading, devulcanization, [2,5] and incineration. These conventional practices can release toxic emissions, create fire

hazards, and contribute to soil and water contamination [3,7]. In addition, improperly managed waste tire stockpiles provide breeding grounds for insects and rodents responsible for the transmission of various diseases [7,11,14]. After evaluating the limitations of conventional waste tire management methods, pyrolysis has emerged as a promising and sustainable alternative for tire recycling [5,6,14], with increasing attention in recent years. Pyrolysis involves the thermal decomposition of materials at elevated temperatures (typically 300–600 °C) under inert conditions, converting end-of-life tires into valuable products such as gases, liquid fuels (pyrolytic oil), and solid carbonaceous residue [1,14]. These products can be further utilized in various industries including chemicals, energy, and transportation, thereby reducing environmental and health impacts [10,16].

The primary gases generated during waste tire pyrolysis include

H₂, light hydrocarbons (C₁–C₄), CO, CO₂, and H₂S [16,10,18]. Pyrolytic oil can be upgraded for use as a feedstock for chemical production, including polymers and industrial additives [12,15]. The solid char fraction can be processed into recovered carbon black (rCB), which is widely used as a black pigment in printing inks, coatings, and plastics, or further activated to produce adsorbents for the removal of heavy metals from contaminated water.

The conversion of end-of-life tires into carbon black provides a sustainable alternative to conventional carbon black production [1,17,18], which is heavily dependent on fossil fuel-based processes and associated with significant environmental burdens and high production costs. In contrast, waste tire-derived carbon black offers both environmental and economic advantages, making it a promising material [18] for sustainable printing ink applications. This study focuses on the reprocessing of carbonaceous residue [19] obtained from waste tire pyrolysis into printing ink-grade carbon black, a valuable feedstock for the production of inks, coatings, paints, and toners. The objective is to demonstrate the feasibility of this approach at the laboratory scale, particularly by evaluating whether carbon black derived from waste tire pyrolysis exhibits comparable properties to conventional furnace carbon black produced from petroleum-based feedstocks.

Pyrolysis-derived carbon black (rCB) typically exhibits several limitations, such as elevated ash content, poor dispersion characteristics, and non-uniform particle morphology. Therefore, this study systematically investigates these challenges through optimized formulation strategies and improved dispersion techniques. In addition, the performance of the developed rCB is evaluated and compared with commercial PRINTEX® 35 carbon black, supplied by Orion Engineered Carbons GmbH, which is used as the reference standard.

2. Experimental Procedure

2.1 Materials

- Pyrolysis carbon residue from scrap tire processing
- Nitrocellulose solution
- Polyurethane Resin
- Wax and Plasticizers additives
- Adhesion Promoter
- Alcohol (Ethanol and Isopropanol)
- Ethyl Acetate
- PRINTEX® 35 Commercial carbon black (reference): Orion Engineered Carbons GmbH

2.2 Equipment and Instruments

- IKA Eurostar Disperser -6000rpm
- Eiger Mini Motor mill / Dyno Mill
- Sheen Gloss meter
- X-Rite Spectro densitometer
- HANNA pH meter
- RK Printing proofer
- Brookfield viscometer

2.3 Preparation of Pigment Concentrate and finished printing black ink

The ink was prepared by using the carbon black (ref) as well as rCB as per below formulation.

Component	Composition (wt. %)
Carbon Black -Ref	18 %
Nitrocellulose Solution	12 %
Polyurethane Resin	15 %
Adhesion Promoter	1%
Dispersant	0.5 %
Wax	0.5 %
Ethanol	33 %
Ethyl Acetate	15 %
Methoxy Propanol	5 %

Table 1. Ink Formulation Component Composition by Weight

The pigment concentrate processing involved the following steps:

- Pre-Mix (Solvent + dispersant + resin), Components were mixed at 1000 rpm for 35 mins
- Pigment Dispersion (Added carbon black slowly)
- Grinding (Eiger Mini Motor mill / Dyno Mill to reduce particle size: < 5 microns) because milling ensured, reduction of particle size, improved dispersion and enhanced homogeneity
- Let-down Stage (added remaining resin, solvents, and additives), the semi-finished pigment concentrate was further diluted and adjusted using solvent systems to obtain the final printing ink with suitable viscosity and application properties.
- Filtration (used 10–25 micron filter to remove large size particles and impurities)

2.4 Characterization Methods

2.4.1 Shade Analysis

The recovered carbon black (rCB)-based ink was evaluated both visually and instrumentally using a X-Rite Spectro densitometer and compared in parallel with PRINTEX® 35 commercial carbon black. The inks were applied onto low-density polyethylene (LDPE) films subjected to corona treatment (>38 dynes/cm). Color performance was assessed by measuring ΔE and Lab* values under standard D50 illumination conditions.

2.4.2 Rheological Properties

Rheological properties describe the flow and deformation behavior of a material when subjected to an applied force or stress. Rheology is essential for understanding how liquids, semi-solids, pastes, and suspensions behave during processing operations such as mixing, pumping, coating, printing, and application. The rheological behavior of the inks was described using Newton's law of viscosity: $\tau = \eta \dot{\gamma}$ where:

- τ = shear stress (Pa)
- η = viscosity (Pa·s)
- $\dot{\gamma}$ = shear rate (s⁻¹)

For experimental analysis, 100 g of each ink sample was taken in a glass beaker, and their rheological behavior was evaluated using a rheometer under controlled conditions.

2.4.3 Gloss Measurement

Gloss measurement is an important analytical technique used to

evaluate the surface characteristics of coatings, inks, plastics, and paint films. In flexible packaging applications, the gloss of solvent-based inks is typically measured at a 60° angle to assess surface smoothness, pigment dispersion quality, and binder leveling performance. Higher gloss values generally indicate improved carbon black dispersion, reduced surface roughness, and enhanced film formation. Gloss values can be interpreted as follows:

- 0–10 GU → Matte / very low gloss
- 10–70 GU → Semi-gloss / satin finish
- 70–100+ GU → High gloss

To evaluate the gloss performance of carbon black (rCB)-based ink against PRINTEX® 35 commercial carbon black ink, print drawdowns were prepared on plastic films. The gloss values were measured and compared using a calibrated Sheen gloss meter under standard conditions.

2.4.4 pH Measurement

For pH analysis, 100 g of each ink sample (rCB-based ink and PRINTEX® 35-based ink) was transferred into separate 100 mL beakers and allowed to equilibrate at room temperature for 30 minutes. Prior to measurement, the pH meter was calibrated using standard buffer solutions. The pH of both ink samples was then measured as per ASTM D1208 and recorded to evaluate any variation between the recovered carbon black (rCB) and commercial carbon black formulations.

2.4.5 Opacity

Opacity refers to the ability of an ink or coating to conceal the underlying substrate and is also known as hiding power or contrast ratio (CR). It can be measured using an X-Rite Spectro densitometer based on the contrast ratio method. A CR value close to 1.0 indicates high opacity, which is associated with better pigment dispersion, finer particle size, and improved substrate coverage, making it ideal for black ink applications. In contrast, CR values below 0.9 indicate lower opacity. For comparative evaluation, ink drawdowns were prepared using an RK Print proofer to assess the opacity of both the standard commercial pigment and the recovered carbon black derived from the pyrolysis process.

2.4.6 Adhesion Tape Test

The tape test is a simple and widely used method to evaluate how strongly a coating (paint, ink, varnish, etc.) is bonded to a substrate like metal, plastic, or paper according to ASTM D3359 below ratings;

- | | |
|----------------------------|-------------------------|
| No ink removed - Excellent | <5% removed – Very good |
| 5-15% removed – Good | 15-35% removed – Fair |
| 35-65% removed – Poor | >65 % Removed – Failure |

In this test, a grid pattern is cut into the printed ink layer, and an adhesive tape is applied and then removed rapidly to assess the amount of coating detachment. The test provides a direct indication of the bonding strength between the ink film and the substrate. A cross-adhesion test was performed to assess bonding strength on the transparent corona treated substrate with >38 dynes/cm.

3. Results and Discussion

The conversion of scrap tires into recovered carbon black (rCB) through the pyrolysis process demonstrates strong potential for

sustainable utilization in printing ink applications. The recovered carbon black exhibits acceptable particle size distribution, surface characteristics, and fine powder morphology when compared with the reference carbon black pigment PRINTEX® 35, produced from fossil fuel-based processes by Orion Engineered Carbons. Characterization results indicate that key performance parameters, including dispersion behavior and rheological properties—both critical for high-performance printing inks—are comparable to those of the commercial reference material. As shown in Fig. 1, the color difference between rCB and PRINTEX® 35 is manageable and can be further minimized through additional purification and surface upgrading treatments.

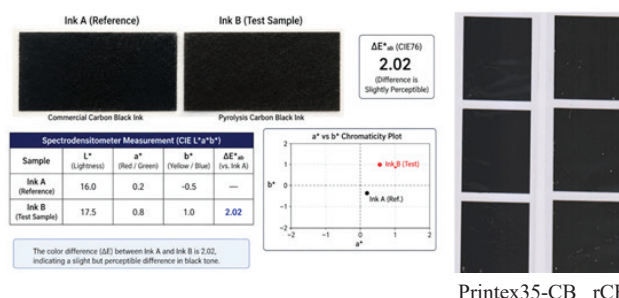


Fig.1 Delta E (ΔE) measurement for color difference between two carbon inks on white low density polyethylene film with spectrodensitometer (Ink A-Printex35 and Ink B-Carbon derived from scrap tires)

The measurement of the Delta E (ΔE) is an important test that helps to evaluate color accuracy in printing, inks and coating application. Fig 1, showed that color difference between derived carbon black inks from pyrolysis of scrap tire against the standard printex35 carbon black. The drawdown of inks were prepared on white low density polyethylene film and measured with X-Rite spectrodensitometer. The mentioned CIEL*a*b value explained that the derived carbon black color shade is slightly lighter, greenish with bluish resulting Delta E (ΔE) 2.02 which is observable with instrument but not visually distinguishable to the naked eye. The result showed that with this color difference, pyrolytic carbon black can be used as a replacement of the Printex35 imported pigment. The Delta E (ΔE) 2.02 can be improved by adding a small %age of magenta to that will bring the pyrolysis carbon ink closer to the standard reference ink with Delta E (ΔE) <1.00.

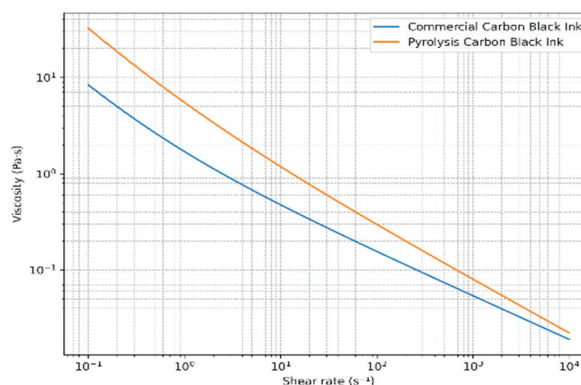


Fig.2 The rheological behavior curve between two black formulated with Printex35 and Carbon black derived from scrap tires through the process of the pyrolysis in oxygen free environment at 400-700°C

The rheological evaluation is a critical parameter that indicates ink viscosity stability, ink flow behavior, printability and uniformity in ink transfer during the printing operations. A comparative evaluation for rheological behavior for both formulated ink with reference- Printex35 black pigment and recovered carbon black from scrap tires were tested using rotational rheometer under

varying shear rate conditions to determine the viscosity behavior and ink flow characteristics. The fig.2 illustrated the ink viscosity versus shear rate that showed both inks exhibited a significant decrease in viscosity with increasing shear rate, indicating typical shear-thinning or pseudoplastic behavior commonly required for high-performance printing ink applications. At lower shear rates, recovered carbon black ink from scrap tires demonstrated higher viscosity compared to the reference Printex35 carbon black ink that may be attributed due to irregular particles morphology, higher surface activity and stronger internal particles-particles interactions. The graph also showed that as shear rate increased, viscosity of the both inks gradually decreased and closer that improving flowability and ink transfer. The analysis from the graph curve also confirms that carbon black recovered from scrap tires can effectively function as sustainable alternative black pigment in the printing ink formulation maintaining desirable printing results and more predictable printing behavior due to narrow particle size distribution, better dispersion and fewer aggregates while pyrolysis carbon black ink showed steeper drop in viscosity with shear due to broader particle size distribution, higher ash, stronger tendency of agglomeration.

The gloss comparative evaluation of the carbon black inks at angle 60° illustrated a clear variations in surface optical properties between inks formulated with reference printex-35 carbon black and pyrolysis carbon black.

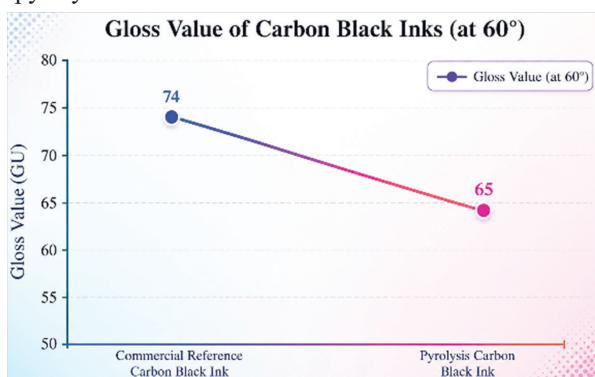


Fig.3 Comparative Gloss Analysis between two black formulated with Printex35 and Carbon black derived from scrap tires at angle 60.

As per Fig.3, commercial reference ink exhibited a gloss value of 74 GU, while the pyrolysis carbon black ink showed a gloss value of 65 GU, representing a reduction of 9 GU about 12.2% in gloss performance. The higher gloss 74 GU of reference carbon black indicates the formation of a smoother and more uniform ink film capable of reflecting a greater amount of incident light in the specular direction. In contrast, the comparatively lower gloss 65 GU value of the pyrolysis carbon black ink suggests a slightly rougher surface morphology and lower light reflectivity. This behavior may be associated with the intrinsic characteristics of pyrolysis-derived carbon black, including irregular particle structure, higher ash content, broader particle size distribution, and the presence of residual inorganic impurities generated during the tire pyrolysis process. These factors can adversely affect pigment dispersion and film smoothness, ultimately reducing gloss development. Despite the reduction in gloss value from 74 GU to 65 GU, the pyrolysis carbon black ink still exhibited a relatively high gloss level suitable for various printing and coating applications. Generally, gloss values above 60 GU at a 60° geometry are considered indicative of good surface reflectivity and acceptable visual appearance in many commercial printing ink systems. Therefore, the obtained value of 65 GU confirms that pyrolysis carbon black possesses promising potential as a

sustainable and economically viable alternative to conventional commercial carbon black. The comparatively small gloss difference of only 9 GU further highlights the capability of pyrolysis-derived carbon black to produce inks with competitive optical properties while simultaneously supporting waste tire recycling and circular economy initiatives.

The pH analysis graph revealed that both ink formulations based on derived carbon black from scrap tires and commercial Printex35 carbon black exhibited mildly acidic properties with measurable differences.

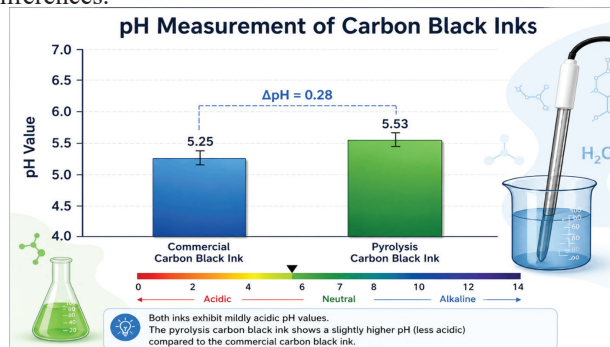


Fig.4 pH Behavior of Pyrolysis derived carbon black ink and Commercial Printex-35 Carbon Black Ink

Fig.4, demonstrated that commercial carbon black (PRINTEX®35) ink possesses pH value of 5.25, whereas the pyrolysis carbon black (rCB) ink showed a slightly higher pH value of 5.53. The calculated pH difference (ΔpH) between the two ink systems was 0.28 units, indicating that the pyrolysis-derived ink was comparatively less acidic. So the pyrolysis carbon black ink exhibited approximately 5.3% higher pH than the PRINTEX®35 ink that showed increase in pH suggests a modification in the surface chemistry and chemical composition of the pyrolysis-derived carbon black particles. The slightly elevated pH value may be attributed to the presence of residual inorganic minerals, metal oxides, or alkaline ash components generated during the waste tire pyrolysis process. The acidic behavior of both inks, with pH values ranging between 5.25 and 5.53, is considered acceptable for many printing ink applications, particularly in formulations where controlled acidity contributes to pigment stability, dispersion quality and substrate compatibility. The relatively narrow pH variation of only 0.28 units also indicates that the incorporation of pyrolysis carbon black did not significantly disturb the chemical balance of the ink system.

These findings demonstrate that pyrolysis carbon black (rCB) can serve as a promising sustainable alternative to PRINTEX®35 without causing major changes in ink acidity. The comparable pH performance highlights the feasibility of utilizing waste tire-derived carbon black in environmentally friendly ink formulations while maintaining acceptable physicochemical properties required for industrial printing applications.

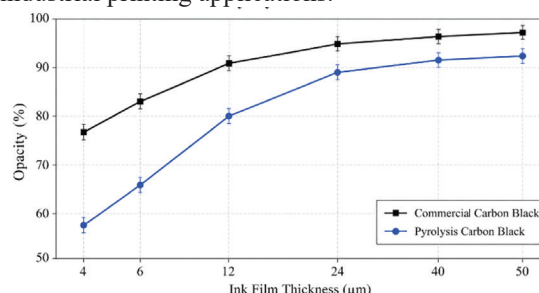


Fig.5 Opacity behavior illustration between derived carbon black ink and Commercial Printex-35 Carbon Black Ink at different film thickness

Fig.5 demonstrates that the opacity performance of the prepared inks was strongly influenced by ink film thickness, with both the PRINTEX®35 ink and the pyrolysis carbon black (rCB) ink exhibiting progressive increases in opacity as the coating thickness increased from 4 to 50 μm. The commercial Printex-35 carbon black ink consistently demonstrated superior opacity across all thickness levels, achieving values of approximately 76.5%, 83.0%, 90.8%, 94.8%, 96.3%, and 97.1% at film thicknesses of 4, 6, 12, 24, 40, and 50 μm, respectively. In comparison, the pyrolysis carbon black ink exhibited opacity values of approximately 57.5%, 66.0%, 80.0%, 89.0%, 91.5%, and 92.3% at the corresponding thicknesses.

The graph also showed that at film thickness 4 μm, the opacity difference between the two inks was approx. 19.0 %, indicating that the commercial carbon black possessed significantly stronger light-blocking capability under thin-film conditions. As film thickness increased, the opacity gap progressively decreased. At 12 μm film thickness, the difference reduced to nearly 10.8 percentage points, at 50 μm the difference further narrowed to only about 4.8 percentage points. This trend suggests that the pyrolysis carbon black ink achieved improved optical coverage at higher pigment deposition levels, approaching the performance of the commercial reference ink.

The opacity enhancement with increasing film thickness observed can be attributed to greater pigment concentration per unit area, which increases light absorption and scattering efficiency within the ink layer. The lower opacity values of the pyrolysis carbon black ink may be associated with differences in particle morphology, lower tinting strength, residual ash content, and less uniform particle dispersion compared to the highly engineered commercial carbon black. These characteristics can reduce the efficiency of light absorption and lead to slightly lower hiding power, particularly at lower coating thicknesses.

Despite these differences, the pyrolysis-derived carbon black (rCB) demonstrated substantial opacity improvement, increasing from 57.5% at 4 μm to 92.3% at 50 μm, corresponding to an overall opacity enhancement of approximately 34.8 %. In comparison, the commercial carbon black ink showed an increase of about 20.6% over the same thickness range. The greater rate of improvement observed for the pyrolysis carbon black indicates its strong responsiveness to increased film build-up and suggests that optimized formulation strategies could further enhance its optical performance.

Importantly, the pyrolysis carbon black ink achieved opacity values exceeding 89% at thicknesses above 24 μm, which is generally considered suitable for many industrial printing and coating applications requiring high hiding power. These findings demonstrate that waste tire-derived pyrolysis carbon black possesses considerable potential as a sustainable alternative pigment material capable of delivering competitive opacity performance while simultaneously supporting waste valorization and circular economy initiatives.

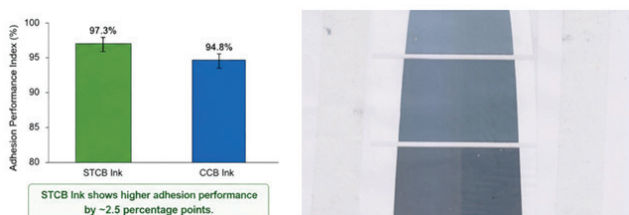


Fig.6 Adhesion evaluation of waste tire-derived and commercial carbon black ink films using 3M tape Test”

The tape test (cross-hatch adhesion test) is a widely used method to evaluate the adhesion strength of printing inks and coatings on a substrate surface. In printing ink applications, the tape test plays a critical role in determining print durability, coating integrity, and resistance to peeling or flaking during handling, transportation, and end-use conditions. Strong adhesion indicates effective interaction between the pigment, binder, and substrate, leading to improved scratch resistance and long-term print stability. Conversely, poor adhesion results in ink removal, reduced print quality, and higher product rejection rates. Therefore, tape test analysis is an essential quality-control parameter for evaluating the industrial suitability and performance reliability of printing ink formulations.

Fig.6, demonstrates that the carbon black derived from scrap tire (rCB) ink exhibited superior substrate bonding characteristics compared to the commercial carbon black (CCB) reference ink. As presented in the adhesion performance index results, the STCB ink achieved an adhesion value of 97.3%, whereas the CCB ink showed 94.8% adhesion efficiency, indicating an improvement of approximately 2.5 percentage points for the sustainable tire-derived carbon black formulation. The lower standard deviation observed for the STCB ink also suggests improved coating uniformity and enhanced interfacial interaction between the pigment particles and binder matrix. Cross-hatch adhesion observations further confirmed the excellent film integrity of the STCB ink, with minimal coating detachment after tape testing, demonstrating strong cohesive and adhesive forces within the printed layer.

The enhanced adhesion behavior of the STCB ink can be attributed to the optimized surface morphology and functionalized carbon structure obtained during tire pyrolysis and post-treatment processing. The presence of active surface groups and improved particle dispersion likely promoted stronger mechanical interlocking and physicochemical interactions with the substrate surface. From an industrial printing perspective, this improvement is highly significant because even a small increase in adhesion performance can substantially enhance print durability, abrasion resistance, and long-term coating stability during handling and packaging operations. The results clearly indicate that sustainable tire-derived carbon black can successfully compete with commercial carbon black pigments while simultaneously offering environmental benefits through waste tire valorization and circular material utilization.

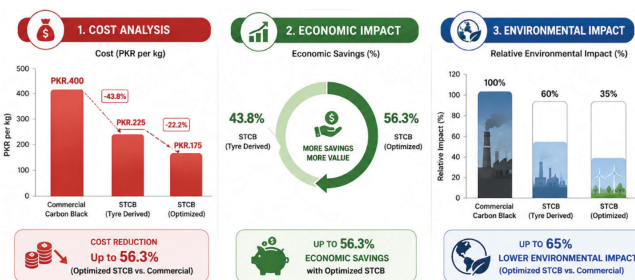


Fig.7 Comparative cost, economic and environmental impact analysis of scrap tire derived carbon black with commercial Printex-35 carbon black”

After consideration of cost, economic and environmental impact, the Fig.7, revealed that scrap tire derived carbon black ink provides significant economic and environmental advantages over conventional commercial carbon black with substantial reduction in raw material cost from PKR 400/KG for commercial carbon ink to PKR 225/kg for scrap tire derived carbon black, saving about PKR 175/kg approx. 43.2% reduction. Such a decrease in production cost can greatly improve industrial profitability and commercial competitiveness in large-scale printing operations. These findings indicate that the use of waste tire-derived

carbon black can effectively lower material expenditure without compromising functional ink performance.

In addition to economic benefits, the environmental impact analysis highlighted remarkable sustainability improvements. Taking the environmental impact of commercial carbon black as the baseline (100%), the STCB ink reduced the relative environmental impact to 60%, whereas the optimized STCB ink further reduced it to only 35%, corresponding to an overall 65% reduction in environmental impact.

The substantial environmental improvement is mainly attributed to the valorization of waste tires, reduced dependence on fossil-based carbon black production, lower energy consumption, and minimized greenhouse gas emissions. Overall, the results strongly demonstrate that optimized STCB ink offers a triple advantage of lower cost, higher economic savings, and significantly reduced environmental impact, establishing sustainable tire-derived carbon black as a promising eco-friendly and industrially viable alternative for next-generation printing ink applications.

4. Conclusion

The present study establishes a compelling pathway for the sustainable production of high-performance carbon black through pyrolysis of scrap tires over production from fossil fuels, demonstrating both technical viability and industrial competitiveness for printing ink applications. Beyond performance and substantial raw material cost reduction advantages, the environmental implications of this work are particularly significant. The valorization of end-of-life tires into functional carbon materials not only mitigates solid waste accumulation but also reduces dependency on fossil-derived feedstock traditionally used in carbon black manufacturing. Collectively, these results highlight a synergistic integration of sustainability, process efficiency, and product performance, reinforcing the potential of pyrolysis carbon black as a next-generation material for the printing ink industry and advancing the transition toward a circular and resource-efficient manufacturing paradigm.

Conflict of Interests

The authors declare no conflict of interests.

Ethics Statement

“This study did not involve human participants, animals, or clinical data. Therefore, ethical approval was not required.”

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