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A Comparison of Specific Nonconjugated Conductive Polymers for Application as Protective Shields against Nuclear Radiation including Radioactive Iodine

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Abstract: Nonconjugated conductive polymers have been shown to be uniquely suited to protective applications against nuclear radiation including radioactive iodine. In this report, we discuss comparative studies of four important nonconjugated conductive polymers for capturing iodine from air and water for the nuclear shielding applications. These four polymers include: cis-polyisoprene, trans-polyisoprene, poly(ß-pinene) and styrene butadiene rubber (SBR). The studies discussed here included measurements of iodine uptakes (doping) over time, consequent increases in electrical conductivities and recorded color changes. In terms of capturing iodine or radioiodine from air and water, cis-polyisoprene has the highest efficiency (fastest), followed by SBR, trans-polyisoprene and poly(ß-pinene). These differences arise from variations in molecular structure, chain packing, morphology, and availability of doping sites which impact diffusion dynamics in the formation of charge-transfer complexes. Stopping radioiodine (vapor phase) escaping from nuclear reactors and extracting radioiodine from contaminated water are both significant objectives which can be uniquely achieved by these nonconjugated conductive polymers. Nuclear reactors should be covered by such a polymer to protect against radioiodine emission / leakage to the outside.

INTRODUCTION

Radioiodine (I-131 and I-129) is among the most hazardous fission products due to its volatility, solubility in water, and strong tendency to accumulate in the human thyroid, causing the risk of thyroid cancer and other related illnesses [1-4]. Roughly 3% by weight of all fission products generated in a nuclear reactor consists of radioiodine. Since the threshold level for causing diseases is extremely low, even small releases of radioiodine can be dangerous. Past nuclear accidents, including Chernobyl and Fukushima, showed that inadequate containment of iodine isotopes can lead to widespread contamination and lasting health consequences. Moreover, even during normal operations, reactors may release traces of iodine isotopes, highlighting the need for reliable protective barriers [4]. While potassium iodide tablets provide only temporary biological protection, material-based solutions such as nonconjugated conductive polymers can physically trap iodine and chemically immobilize it [1].

Nonconjugated polymers with isolated double bonds offer distinct advantages compared to conjugated polymers which are not stable in air and water. Nonconjugated polymers are flexible, affordable, easy to process, stable in air and water, and can be activated by iodine to show significant changes in conductivity and mechanical performances [1,5]. Thakur first demonstrated that iodine doping of diene-based rubbers could induce conductivity, and subsequent studies established that such materials display unusually large nonlinear optical responses [5,6].

The characteristics of nonconjugated conductive polymers make them uniquely suited to shielding applications against radioiodine in addition to other applications in flexible electronics, photonics, and sensing technologies.

EXPERIMENTAL SECTION

Materials

Cis-polyisoprene, trans-polyisoprene, styrene-butadiene rubber (SBR), and poly(ß-pinene) were obtained in solid form from commercial suppliers. Toluene was used as the solvent to make solutions of each of these polymers. Iodine crystals with 99.8% purity were used for doping. We carefully cleaned glass slides and treated with acetone before using those as substrates for the polymer films.

Film Preparation

For each polymer, 6-8 drops of the solution were drop-cast onto separate, clean glass slides. These films were allowed to dry at room temperature for 24 hours to ensure no solvent left and surface uniformity.

Iodine Doping

Dried films were placed in sealed Petri dishes containing iodine crystals for vapor-phase doping over 3.5 hours with 30 minutes interval, ensuring consistent exposure.

Figure- 1a: Polymer films after iodine doping; initially transparent.

Photographs of iodine-doped polymer films on glass slides, showing distinct color changes corresponding to iodine uptake over a 3.5 hours time period.The samples, trans-polyisoprene, cis-polyisoprene, styrene-butadiene rubber, and poly(ß-pinene). The darker coloration of CPI and SBR indicates higher iodine intake and charge-transfer interactions, while Trans-PI and PBP exhibit lighter brown/yellow shades,meaning less iodine intake over the same doping time. These visual differences match the measured resistance changes and confirm the differing doping efficiencies among the four polymers.

Measurements

Weight and electrical resistance measurements were taken every 30 minutes throughout the doping process. Iodine uptake was monitored by recording film weight using a high-precision balance. Electrical resistance was determined via a two-probe method utilizing a digital multimeter. To ensure reproducibility, multiple samples were analyzed.

Data Analyses

Data were processed using **MATLAB** to generate plots of resistance versus weight and weight versus time, facilitating kinetic and electrical analysis of the doping process. Additionally, images of the films on glass slides were recorded to document any color changes during doping.

RESULTS

CPI

Table - 1(a)

Index	Weight (g)	Resistance (GΩ)
1	0.0008	4.5
2	0.0017	0.4
3	0.0055	0.08
4	0.0080	0.05
5	0.0084	0.016
6	0.0096	0.008

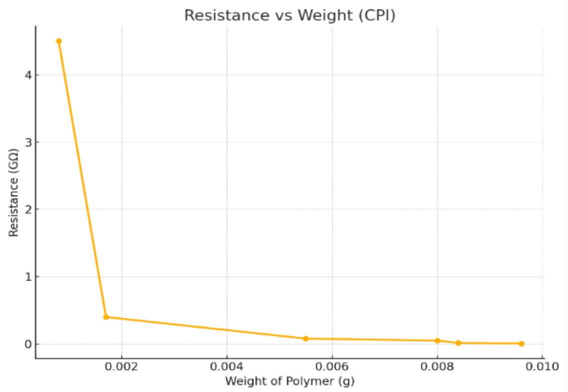

Figure - 2(a)

Table - 1(b)

Index	Time	Weight (g)
1	12:30	0.0008
2	13:12	0.0017
3	13:54	0.0055
4	14:36	0.0080
5	15:18	0.0084
6	16:00	0.0096

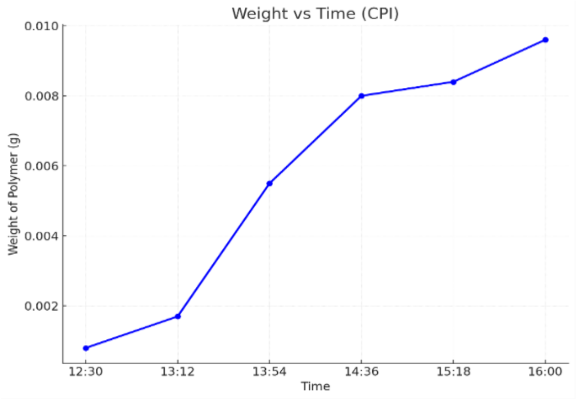

Figure - 2(b)

SBR

Table - 2(a)

Index	Weight (g)	Resistance (GΩ)
1	0.0015	2.3
2	0.0037	1.2
3	0.0092	0.8
4	0.0120	0.072
5	0.0145	0.049
6	0.0147	0.013
7	0.0147	0.0007

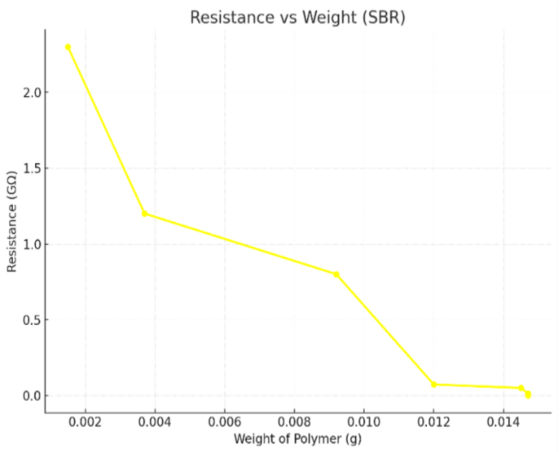

Figure - 3(a)

Table - 2(b)

Index	Time	Weight (g)
1	12:20	0.0015
2	12:53	0.0037
3	13:26	0.0092
4	13:59	0.0120
5	14:32	0.0145
6	15:05	0.0147
7	15:38	0.0147

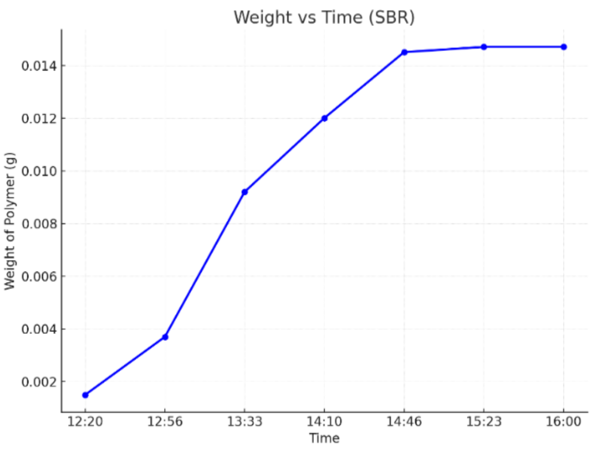

Figure - 3(b)

Poly(β-pinene)

Table - 3(a)

Index	Weight (g)	Resistance (GΩ)
1	0.0028	3.8
2	0.0031	2.5
3	0.0032	1.6
4	0.0034	1.4
5	0.0036	0.3

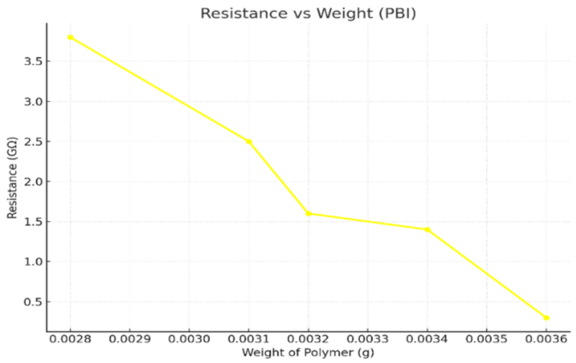

Figure - 4(a)

Table - 3(b)

Index	Time	Weight (g)
1	12:30	0.0028
2	13:15	0.0031
3	14:00	0.0032
4	14:45	0.0034
5	15:30	0.0036

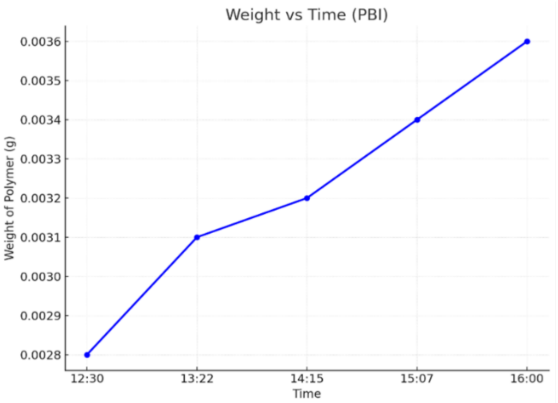

Figure - 4(b)

Trans-polyisoprene

Table - 4(a)

Index	Weight(g)	Resistance(G-O)
1	0.0002	3.4
2	0.0004	0.8
3	0.0010	0.054
4	0.0012	0.032
5	0.0013	0.010
6	0.0016	0.006
7	0.0020	0.003

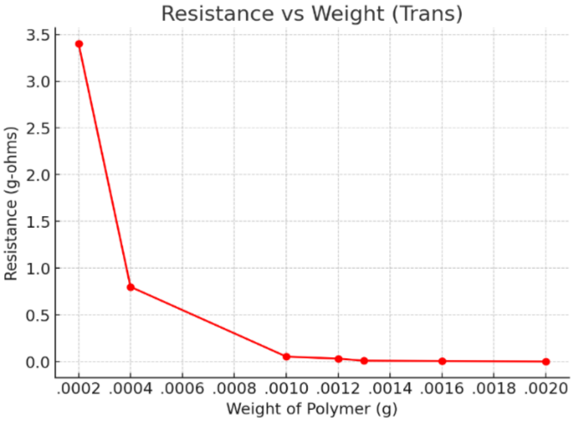

Figure - 5(a)

Table - 4(b)

Index	Weight(g)	Time
1	0.0002	12:30
2	0.0004	1:15
3	0.0010	2:00
4	0.0012	2:45
5	0.0013	3:30
6	0.0016	4:15

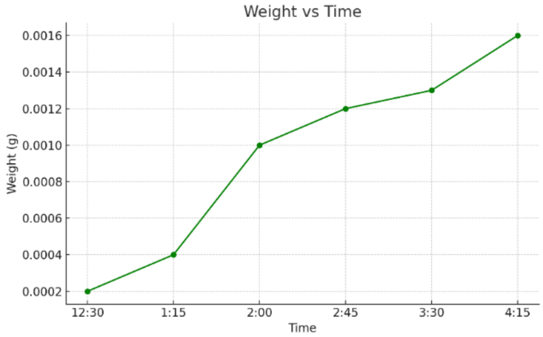

Figure - 5(b)

Conductivities after heavy doping: The final conductivities of these polymers after heavy doping which takes about 24 hours, were reported earlier [5,10,11]. The values are: about 10^{-2} to 10^{-1} S/cm for cis- and trans-polyisoprene, 0.008 S/cm for poly(β-pinene) and 0.05 S/cm for SBR.

Cis-polyisoprene (CPI) exhibited the highest iodine uptake efficiency, with electrical resistance dropping sharply from 4.5 GΩ to 0.01 GΩ as the sample weight increased from 0.0008 g to 0.0096 g over 3.5 hours. **Styrene-butadiene rubber (SBR)**

followed a similar trend, showing a gradual decrease in resistance from 2.3 GΩ to 0.01 GΩ over a broader weight range. In contrast, **poly(β-pinene)** demonstrated limited iodine absorption, with resistance declining modestly from 3.8 GΩ to 0.2 GΩ. These observations highlight the role of molecular architecture and chain dynamics in governing interaction with iodine and doping efficiency in nonconjugated polymer systems.

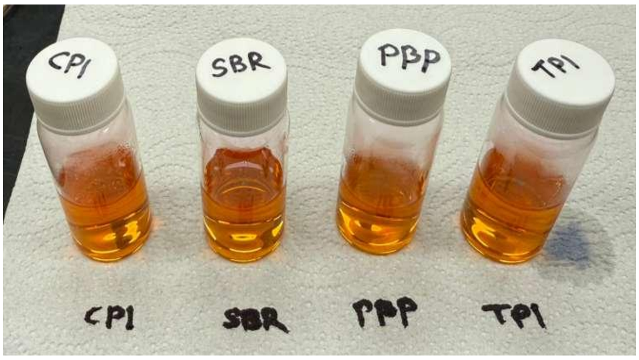

Figure – 6(a): Iodine Solution in Water

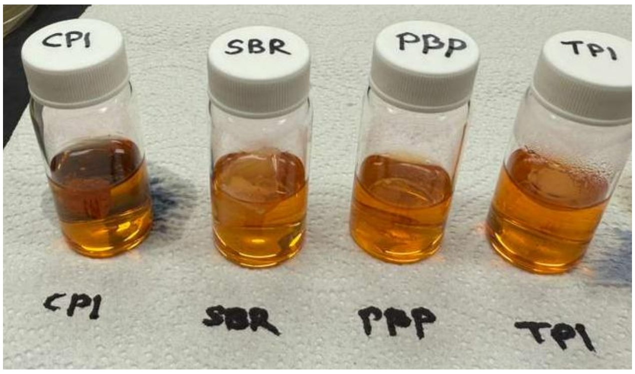

Figure - 6(b): Solution with Polymer

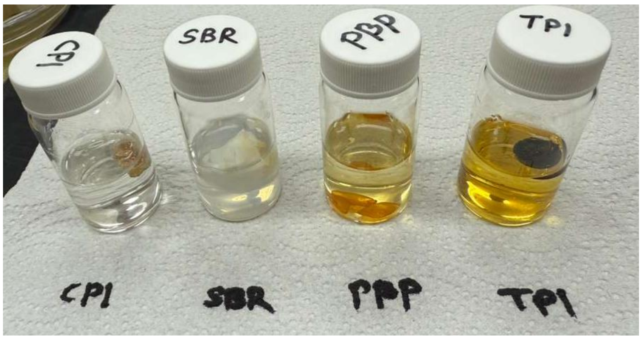

Figure-6(c): After 24hrs showing differences in iodine uptake.

When the four polymer samples—CPI, SBR, PBP, and TPI—were placed in iodine solution in water and left at room temperature for 24 hours, distinct differences were observed (Figs.6a, 6b and 6c). Initially, all solutions appeared orange-brown, showing iodine was well dissolved in water. After 24 hours, the solutions with CPI and SBR became almost clear, indicating nearly complete uptake of iodine. The PBP sample retained a faint yellow color, suggesting partial uptake, while the TPI solution remained orange-yellow, showing the less uptake. These results highlight variations in iodine (radioiodine) decontamination by these polymers. CPI and SBR demonstrated the strongest interaction, likely due to the availability of cis-double bonds and styrene–butadiene sequences that favor iodine complexation. PBP exhibited moderate binding capacity, while TPI, with its trans-configuration, showed limited interaction. Such differences emphasize the role of polymer structure in iodine uptake and suggest that CPI and SBR may be especially effective candidates for developing iodine-absorbing materials in shielding and containment applications.

DISCUSSION

Iodine doping is a process where the charge transfers from the polymer's double bonds to the iodine leading to the formation of radical cations. Importantly, this happens without changing the polymer's main structure [1, 5]. Spectroscopic data, including NMR and FTIR, consistently confirm these interactions. They show reduced double bond resonance and reduction in =C-H vibrations after doping [8,9].

Polymer-Specific Doping Behavior

The interaction of iodine vapor with each nonconjugated polymer revealed distinct doping characteristics, largely governed by their intrinsic chemical structures and morphologies.

Cis-Polyisoprene

Before Doping: Comprised of repeating isoprene units with cis double bonds ($-CH_2-C(CH_3)=CH-CH_2-$), cis-polyisoprene possesses a largely amorphous structure.

During Doping: Iodine diffused rapidly into the amorphous matrix, forming stable charge-transfer complexes with the abundant isolated double bonds. NMR studies confirmed this via a marked reduction in C=C resonance intensity [1]. Electrical conductivity increased dramatically—by up to 11 orders of magnitude [1,5]—accompanied by a significant weight gain, with iodine concentrations reaching up to 0.8 molar [1].

After Doping: The polymer backbone remained chemically stable, with excellent iodine retention and charge-transfer complexes at the double bond sites.

Trans-Polyisoprene

Before Doping: Molecular structure similar to its cis- counterpart, trans-polyisoprene features trans double bonds, leading to a more crystalline configuration.

During Doping: Although iodine formed radical cation species upon interacting with double bonds, the polymer's crystallinity restricted diffusion. Consequently, iodine uptake and conductivity enhancement were moderate relative to cis-polyisoprene.

After Doping: The polymer backbone remained intact, but iodine retention was similar.

Styrene-Butadiene Rubber (SBR)

Before Doping: SBR is a copolymer comprising styrene ($-CH(C_6H_5)-CH_2-$) and butadiene ($-CH_2-CH=CH-CH_2-$) segments [11].

During Doping: Iodine preferentially interacted with the butadiene units, forming charge-transfer complexes. Interactions with the aromatic styrene units were comparatively weaker, leading to moderate doping efficiency and corresponding conductivity enhancement.

After Doping: The polymer backbone remained stable as charge-transfer complexes were formed.

Poly(β-pinene)

Before Doping: Composed of nonconjugated bicyclic monomeric units ($-C_{10}H_{16}-$), poly(β-pinene) is structurally rigid and sterically hindered [11].

During Doping: Iodine formed only weak complexes within the limited amorphous regions, due to the absence of accessible double bonds. This resulted in comparatively less iodine uptake and the lower conductivity increase among all samples. FTIR data showed reduced =C–H vibrational modes due to doping and charge-transfer [11].

After Doping: The polymer backbone remained chemically unaltered, along with the charge-transfer sites and with negligible iodine loss.

Factors Influencing Iodine Uptake

The variation in doping efficiency and conductivity among the polymers is primarily attributed to the following structural and physical parameters:

- Double Bond Accessibility: High densities of accessible C=C bonds (as in cis- and trans-polyisoprene) ease iodine interactions and greater uptake. SBR exhibited lower uptake due to lower mobilities of the styrene units (steric hindrance) although butadiene units facilitate iodine interaction, while poly(β-pinene) showed relatively lower iodine uptake due to its rigid molecular structure (glassy).
- Crystallinity: The amorphous structure of cis-polyisoprene allowed rapid iodine intake. The crystalline regions in trans-polyisoprene have comparatively slower iodine intake. SBR's moderately amorphous matrix supported moderate uptake, whereas the structural rigidity of poly(β-pinene) counteracted its amorphous nature.
- Molecular Weight and Chain Mobility: molecular weights and chain mobility may also influence iodine intake and efficiency.
- Diffusion Kinetics Over Time: During the 3.5-hour doping period, cis-polyisoprene demonstrated the fastest iodine uptake and conductivity increase, followed by trans-polyisoprene, SBR, and poly(β-pinene).

Comparison with other Available Materials for Protection Against Radioiodine from Nuclear Reactors

Our literature review indicates that currently there is no material that is being used to protect against radioiodine emitted by nuclear reactors other than using thick concrete walls. The key point is that if radioiodine can be stopped at its source (nuclear reactor) then it cannot transport by air or water and make hazardous emission (gamma, beta decays) elsewhere. Radioiodine from Fukushima arrived at United States and was reported to have caused illnesses in children. The presently used materials to block gamma radiation are all based on heavy metals such as lead as has been the practice in local medical applications [13-16]. That is, however, not the focus of this report.

Threshold Level of Radioiodine that May Cause Illnesses

The threshold level of radioiodine that may cause illnesses is extremely low! According to the federal safety standard for radioactive iodine (in drinking water), a molar concentration of more than about 10^{-21} per day (equivalent to about 3 pCi/L) is considered hazardous. However, this lower limit is many orders of magnitude less than the saturation molar concentration (0.8) of these polymers – therefore safety can be assured when these polymers are used as shields.

Applications

Cis-polyisoprene demonstrated superior doping efficiency, significant iodine retention, and exceptional conductivity enhancement, making it the best among the three polymers for shielding applications against radioiodine. Trans-polyisoprene and SBR, with moderate performance, also make them suitable for the shielding applications considering, in particular their better thermal properties. Poly(β-pinene)'s comparatively lower iodine uptake make it less appropriate for the stated shielding application. In both capturing of iodine from air and from water the performance characteristics are best for cis-polyisoprene followed by SBR, trans-polyisoprene and poly(β-pinene). Overall, considering all other materials reported in the literature, nonconjugated conductive polymers are unique for protection against radioiodine. The nuclear reactors need to be covered using these polymers to assure protection against radioiodine.

CONCLUSIONS

In this study, we compared four nonconjugated conductive polymers—CPI (cis-polyisoprene), TPI (trans-polyisoprene), SBR (styrene-butadiene rubber), and PBP (poly(β-pinene))—for their ability to capture iodine, with applications in shielding against nuclear radiation including radioactive iodine. Experimental results, including weight gain measurements, resistance changes over time, and visual observations of color shifts in doped films, showed clear differences in performance. CPI exhibited the fastest and highest iodine uptake, with electrical resistance dropping sharply from 4.5 GΩ to 0.008 GΩ as weight increased to 0.0096 g over 3.5 hours. TPI and SBR showed moderate uptake and conductivity improvements, while PBP had the least efficiency, with resistance decreasing from 3.8 GΩ to 0.3 GΩ and limited weight gain up to 0.0036 g.

These differences arise from structural factors such as double bond accessibility, crystallinity, and chain mobility (steric hindrance) which affect iodine diffusion and charge-transfer complex formation. Data plots and tables confirm that CPI's amorphous structure enables superior doping kinetics compared to the more rigid or crystalline TPI and PBP. SBR's performance falls in between due to its mixed structure. Photographs of the films further supported these findings, with darker colors in CPI and SBR indicating stronger iodine interactions.

Overall, CPI emerges as the most efficient material for practical use in capturing radioiodine from air or water, offering unique lightweight and cost-effective protection methods. The other three also offer special attributes in higher strength and higher temperature operation. This work underscores the importance of nonconjugated polymers for applications in nuclear radiation safety and opens pathways for further advancements in flexible shielding technologies.

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