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POLYMER SULFUR PRODUCTION AND ITS APPLICATIONS

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Abstract. Elemental sulfur (S) is a strategic raw material produced in large quantities during oil and gas processing and gas purification (recovery of sulfur from H_2S). Converting this sulfur into value-added products is a relevant and urgent task. According to USGS data, global sulfur production in 2024 amounted to approximately 85 million tons. A significant portion of this volume, when exceeding immediate industrial demand, accumulates in storage, increasing environmental and logistical costs.

Keywords: polymer sulfur, elemental sulfur, inverse vulcanization, sulfur concrete, bitumen modification, sorbent, lithium–sulfur battery, vulcanization.

Introduction. Although sulfur is considered a “classical” element in the chemical industry, its economic role has been fundamentally reinterpreted over the last decades. Previously, sulfur was mainly regarded as a necessary resource for sulfuric acid production, the mineral fertilizer chain (especially sulfuric acid in phosphate fertilizer production), and various chemical syntheses. Under current conditions, however, the problem of “excess sulfur” has become both a risk and an opportunity. In global supply–demand dynamics, sulfur demand in 2024 is reported to be “slightly more than 71 million tons,” with approximately 60% of demand belonging to the fertilizer sector (particularly the phosphoric acid chain). On the other hand, production remains high: the USGS report estimates global production in 2024 at around 85 million tons. Part of this gap turns into stockpiles due to storage practices, disruptions in logistics chains, regional imbalances, and limitations in processing capacity. At this point, the concept emerges that sulfur should be treated not merely as a raw material, but as a platform for creating new materials.

In Uzbekistan, the sulfur issue is also practical: in regions where gas processing and purification infrastructure exists, sulfur is obtained as a by-product. Open sources mention sulfur production at the Mubarek gas processing complex (historical and capacity indicators). This increases the “local relevance” of the topic: there is a possibility to produce certain composite materials—otherwise expensive to import—based on locally available sulfur.

The objectives of this paper are: (1) to systematically present the scientific and technological foundations of polymer sulfur production; (2) to analyze the properties of the class of stable sulfur-rich polymers obtained via inverse vulcanization; (3) to provide an evidence-based "advantages–limitations" profile of applications in construction, environmental technologies, energy storage, rubber industry, and bitumen modification; and (4) to strengthen relevance through statistical indicators.

Methods: The research design consisted of three blocks: literature analysis, comparison of laboratory synthesis approaches (a conceptual technological map), and criteria-based evaluation of application areas (matching "material properties" to "application requirements").

1. Literature analysis. The main scientific directions related to polymer sulfur include: (a) polymerization of elemental sulfur and the mechanism of inverse vulcanization; (b) stabilizing crosslinkers (e.g., DCPD, styrenic/allylic monomers, bio-based oils); and (c) application areas (sorption, batteries, construction binders). Review papers and technical studies addressing the stability and efficiency of inverse vulcanization were analyzed.
2. Technological–parametric analysis. The general principle of polymer sulfur production is that S_8 rings open under thermal conditions to form chain-like S–S fragments; organic crosslinkers "capture" these chains and reduce recrystallization. Key parameters include: the temperature window (above sulfur melting), mixing intensity, crosslinker content, and curing kinetics. In this block, rather than presenting exact recipes/quantities, the research emphasized scientific logical relationships and cause–effect mechanisms.
3. Application evaluation criteria. For each application, a "requirement profile" was defined: for sorbents—selective binding (Hg^{2+}, organomercury), surface area, and regeneration; for construction binders—fast curing, no need for water, chemical resistance; for batteries—ion transport, cathode–electrolyte interface behavior, and cycling stability. Key evidence from scientific literature was cited in this evaluation.

Results: Polymer sulfur production pathways form a continuous spectrum from "simple plastic sulfur" to "crosslinked sulfur-rich polymer." The analysis highlighted three major findings.

First result: the key to stability is chemical “fixation.” Even though rapid cooling of elemental sulfur increases the fraction of chain structures, there is a strong tendency to return to the crystalline S_8 form over time. Inverse vulcanization suppresses this return through organic crosslinkers and produces the sulfur-rich polymer class. Modern reviews emphasize the stability and environmental motivation of this direction.

Second result: application depends on “property–requirement” matching. Sulfur’s tendency to form sulfides and, under the HSAB concept, its strong affinity for soft metals such as Hg provides an advantage in sorbent design; studies show mercury capture using sulfur polymers obtained by inverse vulcanization. In construction, sulfur binders and modified sulfur concrete are technologically characterized by “fast curing” and resistance to certain aggressive environments.

Third result: market and resource statistics make polymer sulfur strategically important. If production in 2024 is ~85 million tons and demand is ~71 million tons, part of the difference is stockpiled; redirecting this surplus into materials yields economic and environmental benefits.

Table. Comparison of sulfur-based “polymerization/composite” routes and their applications

Product type	**Production concept**	**Main properties (typical)**	**Main application**	**Advantage**	**Limitation**
Plastic sulfur (unstable)	Rapid cooling of molten sulfur (higher chain fraction)	Short-term more elastic; then crystallizes	Scientific demonstration, short-term molds	Simple	Unstable; returns to S_8 over time
Inverse-vulcanized sulfur-rich polymer	S_8 + organic crosslinker (DCPD, styrenic,	More stable, chemically resistant;	Sorbents, composites, energy materials	High sulfur content; converts	Processing/rheology; possible brittleness issues

Product type	Production concept	Main properties (typical)	Main application	Advantage	Limitation
	bio-oils, etc.)	S–S network; properties depend on crosslinker		waste sulfur into value	

Discussion

1. Why is inverse vulcanization often meant by "polymer sulfur"? Because the thermodynamic stability of pure sulfur chains is low; the crystalline S_8 form is energetically more favorable. In inverse vulcanization, the organic crosslinker imposes "geometric" and "chemical" constraints that limit chain reassembly and crystallization. Therefore, crosslinked systems provide the most realistic prospects for using sulfur as a polymer material.
2. Crosslinker selection is the mechanism for property control. At the same sulfur content, different crosslinkers (DCPD, styrene, allyl/acrylate, bio-oil components) change network density, glass transition temperature (Tg), brittleness, and processability. This indicates that "one formula fits all" is not feasible; each application requires separate optimization (e.g., high sulfur content + controlled porosity for sorbents; thermal stability + mechanical strength balance for construction).
3. In environmental applications, the main argument is sulfur's affinity to metals. Mercury-capture studies show that sulfur polymers can be promising sorbents for binding mercury in industrial waste streams. This direction may also be relevant for Uzbekistan, since heavy-metal issues appear in mining, metallurgy, and some chemical processes; an inexpensive sorbent platform may reduce monitoring and treatment costs.
4. In construction, "fast curing" and "no need for water" provide practical advantages. Uzbek-language sources discuss sulfur concrete as a special type of concrete and address technological and standardization aspects. However, important limitations exist: sulfur binders can be thermally sensitive; if formulation and modification (stabilizers) are uncontrolled, brittleness, volumetric changes, or long-term aging problems may occur.

Therefore, applying sulfur-based binders in construction must be supported by technical regulations and validated test protocols.

5. Statistical logic: 85 million tons produced vs. 71 million tons demanded is not just a numeric difference, but a signal for industrial policy. Since a significant part of sulfur remains tied to the fertilizer sector (~60% share), expanding higher-value segments (polymers, composites, sorbents) diversifies market risks and reduces the "excess sulfur" problem. Inverse-vulcanized polymers fit well into the circular economy concept.

Conclusion. This paper analyzed polymer sulfur production and applications at the intersection of resources, environmental considerations, and materials science. The main conclusions are as follows.

First, global sulfur production is very high (~85 million tons in 2024). Demand is lower (~71 million tons in 2024), and about 60% of demand belongs to the fertilizer sector. This situation strengthens stockpiling practices and makes the conversion of sulfur into value-added materials a strategic goal. Inverse-vulcanized polymers represent a scientifically grounded pathway that redirects surplus sulfur into useful materials.

Second, the concept of polymer sulfur is more accurately interpreted in practice as "stabilized sulfur-rich polymers." Pure plastic sulfur rapidly returns to crystalline S_8; inverse vulcanization reduces this tendency through organic crosslinkers and produces a practical class of materials. Therefore, crosslinker choice, network density, processability, and long-term stability remain key research priorities.

Third, applications are directly linked to material properties. In environmental technologies, sulfur's affinity for heavy metals (especially mercury) makes sulfur-polymer sorbents promising for capturing harmful components and integrating them into monitoring and treatment systems. In construction and infrastructure, sulfur binders (sulfur concrete, bitumen modification) can provide fast curing and resistance to aggressive environments; Uzbek sources also discuss technological and standardization aspects. However, technological discipline (stabilization, formulation control, testing) is crucial; otherwise brittleness and thermal sensitivity may become problematic.

Fourth, in Uzbekistan, sulfur processing and the creation of new sulfur-based materials have practical significance: open information indicates sulfur production within gas processing infrastructure. Redirecting this resource toward local construction materials, road bitumen modification, or environmental sorbents may be scientifically, technologically, and economically beneficial. In addition, sulfur's classical role in rubber vulcanization (described in Uzbek textbooks) demonstrates the industrial adaptability of sulfur–polymer chemistry.

Fifth, recommendations for future research include: (1) analyzing the purity and impurities (As, Se, organic residues) of local sulfur and their effect on material properties; (2) testing "green" inverse vulcanization routes using bio-based crosslinkers (fractions of plant oils); (3) conducting long-term aging and temperature-cycling tests for sulfur concrete/bitumen modification; and (4) developing regeneration and disposal protocols for sorbents. These directions can help move polymer sulfur from a laboratory concept to practical technology.

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