Four decades of trends in invisible gold research: a web of science-based bibliometric analysis (1985–2024)

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Abstract

Invisible gold research is essential for understanding gold mineralization, overcoming analytical limitations, and addressing the technological bottlenecks in the economic extraction of refractory gold, thereby unlocking the potential of these deposits and their tailings. To assess research trends and demand, this study analyzed 1300 records from the Web of Science database (1985–2024) using the cross-disciplinary publication index (CDPI), the co-authorship model, and the technology-economic linkage model (TELM), with visualizations generated via VOSviewer and Microsoft Excel. The analysis reveals a 65% increase in publications between 2015 and 2021, with a peak of 98 papers in 2021. Articles constitute the majority (84.6%), followed by conference proceedings (9.8%) and reviews (3.9%). Interdisciplinary contributions surged by 40% after 2015, particularly in "materials science", as indicated by a high CDPI of 0.81; while a discipline-pair co-occurrence score between "materials science and nanotechnology" reached a CDPI of 0.75. Notably, the CDPI model reveals that 68% of advancements in extraction technologies between 2015 and 2024 originated from nanoscale-oriented invisible gold research published in geoscience-focused journals employing advanced nanotechnologies. Furthermore, the TELM framework identifies that between 2021 and 2024, high gold prices—ranging from $1,798/oz to $1,940/oz—were well correlated ($R^2 = 0.89$) with publication counts, which remained consistently high at 94 to 98 papers annually. Two key methodological trends identified in this study for invisible gold research are: (1) the development of environmentally friendly extraction techniques, including biooxidation or thiosulfate leaching, and advanced pre-treatment processes; and (2) the adoption of high-precision analytical tools such as LA-ICP-MS, SIMS, and TIMA-X, which have significantly enhanced nanoscale gold detection and characterization. This methodological progress is further supported by the increase in annual research funding—from approximately $2–5 million when gold prices averaged $370/oz (1985–2000), to $10–30 million at around $700/oz (2001–2015), and up to $50–120 million as prices exceeded $1,500/oz (2016–2024)—demonstrating a strong positive association between rising gold prices and investment in invisible gold research. The findings reveal key trends in invisible gold research, demonstrating that Web of Science data, VOSviewer visualizations, and the CDPI and TELM frameworks provide a more reliable basis for identifying interdisciplinary patterns and economic drivers. They highlight not only scientific progress in mineral exploration, extraction technologies, and metallurgical methods, but also persistent challenges in the economic recovery of invisible gold. These insights offer a roadmap for future research, industrial application, and international collaboration.