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How Are Discoveries in Chemistry Made? Insight from Three Discoveries and Their Impact

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Abstract

Learning how discoveries in chemistry are made and utilized by the users of innovation in chemistry offers several benefits both to chemistry innovation practitioners and to research policy makers. We study the research and societal impact of three discoveries in chemistry reported between 2002 and 2022. The analysis confirms that, also in chemistry, science does not develop in a linear fashion, and that scientific developments continue to occur, driven by curiosity from self-determined researchers whose work is driven by intrinsic motivation relying on intellectual gratification. Companies in numerous industrial sectors, well beyond the chemical industrial sector, greatly benefit from chemistry innovation developed at public research institutes and universities. An obvious consequence is that policy makers should continue to support the work of chemistry research institutions using taxpayer money, leaving researchers free to choose research topics and the way to conduct research.

Keywords: innovation in chemistry; research impact; LimoFish; molecularly doped metals; metal–organic alloys; cocktail-type catalysis

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1. Introduction

Research in chemistry differs from research in other fundamental scientific disciplines because it has originated a huge industry providing wealth and prosperity for society in all industrialized countries for nearly two centuries [1]. Hence, the users of chemistry innovation very often are not only other researchers, but also industrial manufacturing companies in widely different sectors that go from manufacturing basic materials and basic chemicals to producers of advanced electronic devices, dyes, drugs, fertilizers, nutraceuticals, explosives, and coatings.

Accidental (serendipitous) discoveries are common across many disciplines, including chemistry. The fact that many important discoveries in chemistry were (and continue to be) serendipitous findings, recently led Rulev to conclude that the progress of chemistry is unpredictable and not the outcome of careful planning [2]. Research in the chemical sciences suffers from a decline in the number of students enrolling in chemistry university courses due to a prolonged decline in public perception of chemistry. For example, in 2017, a survey of 186 chemists from across academia and industry was carried out by a chemistry research data company owned by the world's largest academic publisher. The survey found that 76% of the respondents said there is a long-standing or growing problem in terms of attracting new talents [3]. The vast majority of respondents (80%) claimed that innovation in chemistry was being held back by overemphasis on applied research. "Chemists", commented the manager of the company commissioning the survey, "need to focus on highlighting the ways in which research is cutting-edge and innovative in order to draw more people into the field" [4].

Learning how discoveries in chemistry are made and actually utilized by the users of innovation in chemistry offers several benefits both to chemistry innovation practitioners and to research policy makers. In this study, we analyze three selected discoveries in chemistry reported between 2002 and 2022 and the translation of research to impact, including impact for society resulting from the process of research and the ability of others to find colleagues' work in a variety of circuitous paths. The discoveries are as follows: the cocktail-type reaction mechanism in catalysis [5]; the LimoFish circular economy process for the marine bioeconomy [6]; and molecularly doped metals [7]. The outcomes of the analysis are of direct relevance both to chemistry scholars engaged in the practice of research as well as in undergraduate education, and to policy makers interested in fostering innovation able to further provide wealth and prosperity for society in both industrialized and economically developing countries.

2. Methodology

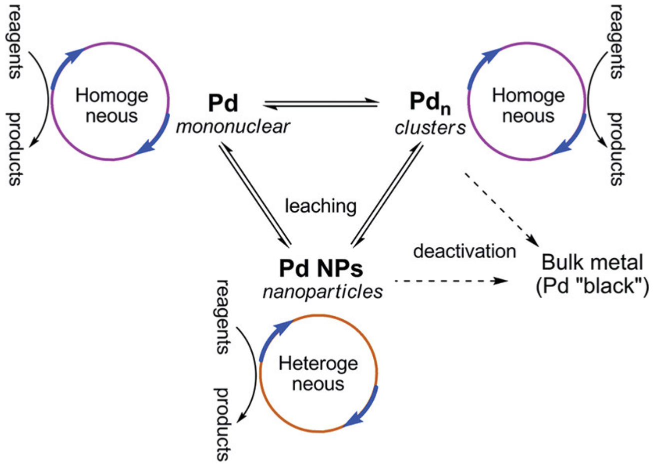
The impact and public understanding of three important discoveries in chemistry (the cocktail-type reaction mechanism in catalysis; the LimoFish process circular economy process for the marine bioeconomy; and molecularly doped metals) were investigated. As proxy for the assessment of public perception of the discovery, we used altmetrics, a social web tool measuring the societal impact of research beyond citations [8]. Research impact was assessed by citations identified by Google Scholar, a freely accessible comprehensive research database. The choice of Google Scholar in place of paywalled Web of Science or Scopus is due to the fact that the former database is freely accessible by anyone (access to Google Scholar does not even require registration), thereby increasing transparency. Furthermore, the set of citation sources indexed by Google Scholar is far wider than those indexed by Web of Science and Scopus, comprehensively including non-journal sources such as theses, books, conference papers, and unpublished material [9].

3. Results

3.1. Cocktail-Type Catalysis

In 2012, Ananikov and co-workers in two articles published nearly concomitantly by *Organometallics* provided the first experimental discovery [10], and the "cocktail-type" hypothesis to explain it [11], that a widely used palladium catalyst, long thought to be purely molecular, actually formed in solution palladium nanoparticles that played a key role in the reaction.

The Russian scholars thus suggested that metal catalysis is a dynamic phenomenon mediated by metal atoms, clusters, or nanoparticles (NPs) and a metal catalytic system would be better "described as a 'cocktail' of catalysts with varying contributions of different cycles to the product formation depending on substrate, temperature, solvent, additive, and other conditions" [11]. The latter study included a scheme that nowadays is used in catalysis and chemistry undergraduate courses worldwide (Scheme 1):



Scheme 1. Interconversion of different catalyst types in solution ("cocktail" of catalysts). [Reproduced from Ref. [11], with kind permission].

In brief, suggesting that real catalytic systems are not static but rather a dynamic mix of different catalytic species, the scholars rationalized previous findings for which it was shown that nanoparticles are readily formed during the reaction starting from mononuclear Pd complexes (or salts such as $Pd(OAc)_2$, $PdCl_2$, etc.) used as precursor, and others from heterogeneous catalysis in which leaching was shown to generate soluble metal complexes and clusters from the nanoparticle precursor. The mechanism, furthermore, explained the surprisingly high catalytic activity of Pd trace impurities (50 ppb) contained in commercial sodium carbonate base used in the cross-coupling reaction is enough to successfully mediate Suzuki–Miyaura cross-coupling reactions [12].

Providing a new meaningful bridge between homogeneous and heterogeneous transition metal catalysis, the study immediately impacted research in catalysis worldwide. In 2012, it received four citations, two of which were from PhD theses defended in Czechia and in the USA [13]. The first article to cite the study, two weeks after its publication in February, was a mechanistic investigation of Pd complexes in aryl–aryl cross-coupling catalysis that revealed homogeneous catalysis originating from heterogeneous Pd NPs formed in the reaction medium, leaching Pd atoms [14]. Albrecht and co-workers wrote therein that:

> "Heterogenization of the molecular precatalyst to palladium nanoparticles and subsequent dissolution of palladium atoms from these nanoparticles constitutes a model that accounts for all of the observations detailed above. Such a model has been suggested, although only rarely underpinned with experimental evidence [14]."

In the subsequent year, the seminal concept study [11] received 43 citations. Since then, it is regularly cited (Figure 1), having an Altmetric Attention Score (AAS) of 10 (shared 15 times in social media). Citation numbers contextualize trends (e.g., growth in publications and impact of certain subfields), with publications in fast-growing topics having a significant citation advantage compared to publications in slow-growing or declining topics [15].

The forecast for which "the main concepts should be also valid for other metals and catalytic reactions" [11] turned out to be true. Since 2012, many other systems based on various transition metals—including platinum, rhodium, nickel, and copper—were shown to follow similar behavior [5].

As mentioned above, the dynamic reaction mechanism in which overly active atomic or cluster species are responsible for catalysis explains why small contamination with Pd of reactants or even stir bars is enough to catalyze cross-coupling reactions. This was shown by Ananikov's team in 2019 reporting in *ACS Catalysis* how metal adsorbed on the surface of used magnetic stir bars was largely enough to catalyze the reaction [16].

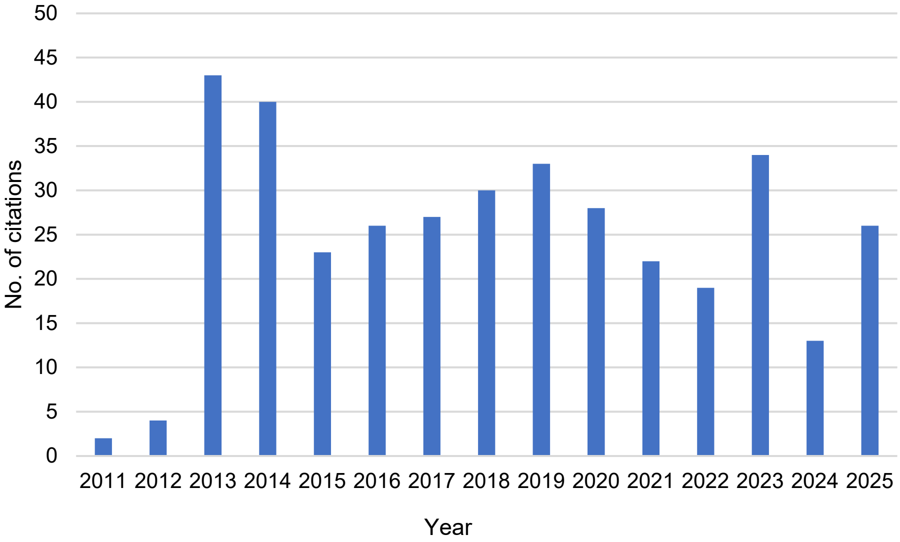


Figure 1. Citations for "Toward the ideal catalyst: from atomic centers to a "cocktail" of catalysts" between 2011 and late 2025. [Plot based on data sourced from Google Scholar, 2025].

In detail, the team collected 60 used stir bars and analyzed the stains via electron microscopy and X-ray spectroscopy which clearly unveiled the presence of metal nanoparticles or microparticles comprising different metals, including Pd, Au, Cr, Pt, Co, and Fe, entrapped within the polytetrafluoroethylene (PFTE) coating polymer filaments contained in cracks at the bar's surfaces.

The team found that, whereas running the Suzuki–Miyaura reaction in the absence of a palladium catalyst with a new stir bar gave no coupling products, employing a used stir bar catalyzed the reaction, affording a significant amount of the coupling product. In one experiment, the contaminated stir bar alone afforded the same amount (17%) of the coupling product of that obtained in the presence of Pd/C catalyst.

The study attracted broad interest on the Social Web and in the specialized press. Besides 287 tweets mentioning the article, the study is discussed in seven news outlets, including popular science journals and chemistry magazines such as *Chemistry World*, *ChemistryViews*, and *Education in Chemistry*, but also on websites of chemistry and process chemistry training companies such as Scientific Update. The AAS of the study (262, to date) makes it one of the most discussed articles in chemistry published in 2019.

As noted in the proceedings of the conference "New Horizons of Catalysis and Organic Chemistry" held in 2025 at the same Institute of the Russian Academy of the Sciences where the discovery was made in the early 2010s,

> "The "Cocktail"-type catalysis gives rise to a new way of thinking. Rather than fighting complexity, it embraces it. This approach is helping chemists design better, more flexible catalytic systems—ones that work under challenging conditions, require less metal, and offer greater control over reactivity and selectivity. It is a dynamic, cooperative view of catalysis that opens the door to next-generation technologies in sustainable chemistry and industrial applications [17]".

3.2. *The LimoFish Process*

Consumption of *n*-3 (omega-3) polyunsaturated fatty acids contained in triglyceride form in oily fish or fish oil, in eicosapentaenoic acid (EPA, C20:5*n*-3) and docosahexenoic acid (DHA, C22:6*n*-3) form, is critical for both physical and mental health of adults and infants [17]. In most world's countries, and especially in western countries, during the past century the dietary content of *n*-6 PUFA, such as linoleic acid, γ-linolenic acid, and arachidonic acid, mostly abundant in most vegetable oils, pork, lard, and turkey meat raised the ω-6/ω-3 fatty acid ratio from 1:1 in 1900 to today's 20:1 (15:1 in Europe and 25:1 in the United States of America) creating the conditions of chronic inflammation due to continuous production of pro-inflammatory lipid mediators [18].

These polyunsaturated fats are key hormone precursors and moderate the propensity for arachidonic acid cascade overreactions when ω-6 (*n*-6, first double bond from the ω end between 6th and 7th carbon atom) lipids dominate, defending tissue against inflammation [19]. The ideal ratio should be 1:1 [18], whereas today, less than 20% of the world's population meets the minimum recommended dietary intake of 250 mg seafood omega-3 per day [20]. Accordingly, global access to uncontaminated omega-3 lipids is a public health and environmental challenge requiring collective action [21].

Supplying a 250 mg/day daily dosage to 6.5 billion people would require a daily production of 1625 tonnes of EPA and DHA (>593,000 t/a), not including the demand of fatty acids by hatcheries. Estimates of EPA and DHA current production are around 160,000 tonnes/year, with more than 90% of this coming from fishery and aquaculture resources [22].

This unbalance between supply and demand explains why omega-3 PUFAs need to be sourced by algae, land-based plants, and from fish processing waste and no longer from fish [23]. Today, nearly half (47%) of the whole yearly fish oil output is chiefly sourced from small pelagic fisheries [24] and anchovies in particular.

Not surprisingly, fish oil, highly refined and generally made available as concentrate of marine omega-3 lipids in ethyl ester form, has become one of the most popular dietary supplements in the world, particularly in Europe and North America, with the EPA and DHA omega-3 finished product market size reaching $52.4 billion in 2023 [25].

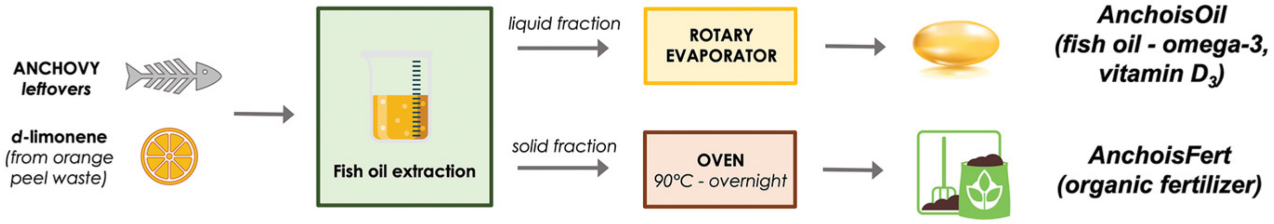
In brief, the production and refinement of fish oil and omega-3 concentrates need to be made sustainable, replacing wild capture with processing waste, reducing the energy required, and affording omega-3 concentrates directly in bioavailable triglyceride form, and not as ethyl esters [26]. In 2019 the discovery that a new valued fish oil in integral (triglyceride) form could be cold extracted from milled anchovy filet leftovers using *d*-limonene as extraction solvent was reported in paywalled journal *ChemistrySelect* [27], after having been made openly accessible by posting its preprint at Preprints.org.

A few months later, further work unveiled that all vitamin D in the anchovy oil dubbed "AnchoisOil" extracted with biobased and health-beneficial solvent limonene is present in its most bioavailable form (vitamin D_3) in 81.5 µg/kg high content [28].

In 2020, Pagliaro's team in Italy, in collaboration with that of Chemat in France, reported in *ACS Omega*, an open access (OA) chemistry journal, that the method could be readily extended to shrimp processing waste, obtaining a marine only rich in both omega-3 lipids and astaxanthin, with limonene identified computationally as ideally suited solvent for these lipids [29].

Two years later, in collaboration with agronomists led by Muscolo, the team reported in OA journal *Global Challenges* the discovery that the solid residue comprising milled anchovy leftovers after fish oil extraction with biobased limonene is a powerful organic fertilizer [30]. Named "AnchoisFert", the fertilizer turned out to largely be superior to commonly used organic (manure) and chemical (nitrogen phosphorous potassium) fertilizers. Rich in essential amino acids [31], organic carbon, flavonoids, magnesium, potassium, phosphate, and sulfate, and devoid of antibiotics and antibiotic resistance genes, the new organic fertilizer can replace both conventional organic and inorganic fertilizers.

The latter discovery closes the fishing material cycle for the most fished species across the seas (anchovy), opening the route to a new class of high-quality fish oils and organic fertilizers derived from abundant biowaste via the LimoFish circular economy process (Scheme 2).



Scheme 2. The LimoFish process on a laboratory scale. [Reproduced from Ref. [6], Commons License CC-BY].

Both articles reporting the discovery of the new marine oil and that of the organic fertilizer were (and are) highly read and frequently cited (Figure 2).

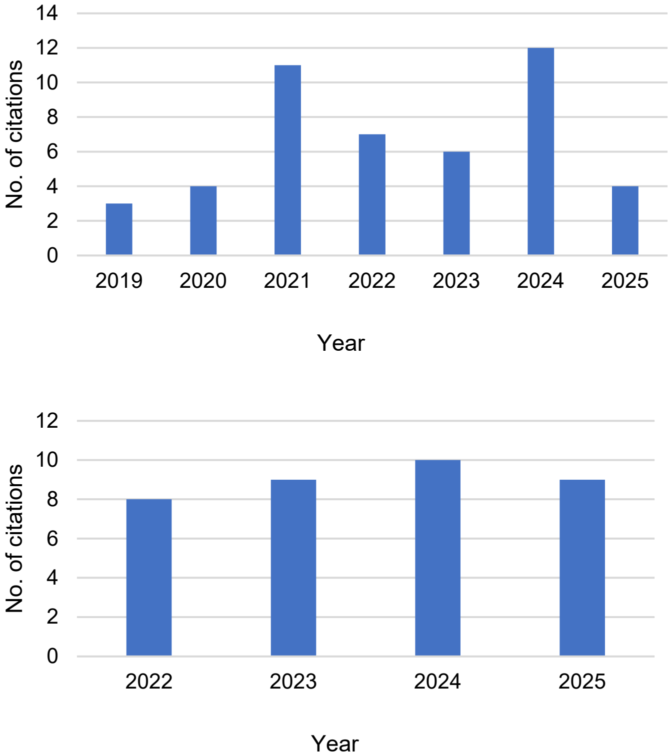


Figure 2. Citations for "A circular economy approach to fish oil extraction" between 2019 and late 2025 (***top***), and for "AnchoisFert: a new organic fertilizer from fish processing waste for sustainable agriculture" between 2022 and late 2025 (***bottom***). [Plots based on data sourced from Google Scholar, 2025].

Aware of the practical relevance of the discovery, the teams of Chemat and Pagliaro in 2019 published the first chemical, environmental, and economic assessment of fish oil extraction from anchovy filet leftovers via the LimoFish process in *ACS Omega*, an OA cross-disciplinary chemistry journal [32].

Citing the aforementioned article, in early 2021, researchers in Spain reported that limonene can be successfully used for the extraction of monkfish liver oil [33]. Extraction yield was slightly lower (37% vs. 39% w/w) than in the case of extraction conducted with conventional extraction solvent mixture (Folch reagent, chloroform-methanol in a 1:2 v/v ratio). The team ascribed the slightly lower yield to "the harsh conditions used to recover the oil from the solution (90 °C/0.3 mbar), which could help the evaporation of part of the more volatile compounds present in the fish oil" [33]. Compared to green solvent 2-methyltetrahydrofuran (2-MeTHF), limonene was found to have better environmental profile (measured via life cycle assessment) and nearly half the cost (on laboratory scale): EUR 23.4/L for limonene vs. EUR 60.8/L for 2-MeTHF [33].

Scheme 2 illustrates the LimoFish process on a laboratory scale applied to anchovy filet leftovers. The process, however, is general and can be applied to any fishery biowaste including shrimp and other small (sardine, makerel, etc.) and large (tuna) fish processing waste. In 2024, indeed, experiments conducted at the University of Reggio Calabria expanded the method to the leftovers of European sardine (*Sardina pilchardus*) [6]. The joint team furthermore demonstrated full reproducibility of the process with the composition of the AnchoisOil extracted in Calabria found to be nearly identical to that reported in 2019 for AnchoisOil extracted in Sicily [6].

Subsequent work reported in 2024 in a OA journal showed evidence of high stability of the AnchoisOil stored at −20 °C under N_2 for more than four years, unveiling high concentrations of lipid-soluble vitamin Q (coenzyme Q10, 1015 mg/100 g of oil) and vitamin A (retinol, 113.4 mg/100 g) retained in the oil along with transparency and deep orange color [34].

In the same year, researchers in Indonesia reported in another OA cross-disciplinary journal that the LimoFish method, combined with ultrasound assisting the extraction, can be successfully applied to milkfish leftovers [35]. Collected milkfish leftovers from five different areas of the country were cleaned and dried using a cabinet dryer at 55 °C until water content reached 10%. The dried samples were milled using an electric blender and used for extraction. Optimization study showed that, as expected, sonication time and temperature had a significant influence on yield of extracted oil.

The optimal extraction conditions were 68 min, 84 °C, with a solvent-to-solid ratio of 3:1 mL/g, resulting in high oil recovery (21.95%) containing omega-3 PUFAs (12.50%) in triglyceride form. Characterization of the oil in terms of its quality parameters (acid, peroxide, anisidine-total oxidation, and iodine values) showed that newly extracted milkfish oil met the criteria of the IFOS (International Fish Oil Standards) for the best fish oils [36], leading the authors to conclude that the method is "applicable for industrial oil production" [35].

In detail, the free fatty acid value varied between 1.59 and 1.63 mg KOH/g, which is substantially lower than the threshold (3 mg KOH/g) of free fatty acids of the IFOS standard, whereas the peroxide value (PV) and anisidine value varied between 3.85 and 4.40 meq O_2/kg for PV and 12.42 and 14.18 meq O_2/kg for anisidine value, which is lower than the maximum PV and anisidine value for best fish oils according to the IFOS standard (5 meq O_2/kg for PV and 20.0 meq O_2/kg for anisidine value).

Launched in Canada as Nutrasource Diagnostics inaugural certification program in 2002, the IFOS standard ensures (no other certification program tests fish oils by individual lot number) that the quality of commercially available fish oil products exceeds international standards established by the Council for Responsible Nutrition and the World Health Organization, allowing marine oil companies to test and certify their omega-3 supplement products based on the highest quality, safety, and purity standards [36].

On an industrial scale, the zero-waste LimoFish circular economy process requires only a relatively low energy input in the form of heat and electricity to separate limonene from the marine oil via distillation under reduced pressure [37]. Small amounts of limonene residual in the oil are highly beneficial because limonene (generally in the form of orange oil) is an effective preservative (antioxidant and antimicrobial) already added to many fish oil omega-3 dietary supplements [38] to prevent oxidation [39], eliminating, at the same time, the fishy aftertaste.

Considering that the process can be employed to leftovers of the world's most fished species, the anchovy, as well as to world's most commercially valuable fish (tuna) chiefly commercialized in the form of canned filets [40], the process has the versatility and low capital and operating expenditure costs required for industrial uptake in all countries hosting large fisheries and fish processing companies. Eventually, this will result in the cost-efficient and effective recovery and transfer of key marine essential nutrients (including vitamin D_3, astaxanthin, and vitamin Q) to human and animal food chains, diverting fish oil and organic fertilizer production from wild capture to fish processing waste.

3.3. Molecularly Doped Metals

Invented by Avnir in 2002 when the Israeli scientist Behar-Levy reported in *Chemistry of Materials* the first ever entrapment of three dyes (Congo red, Safranin-O, and thionine) in metallic silver [41], molecularly doped metals are readily from a metal salt precursor via a single reduction process of the metal cation (M^{n+}) with a reductant conducted in the presence of an organic species in the same solution followed by entrapment, aggregation, and precipitation (Equation (1)):

$$M^{n+} + \text{organics} \xrightarrow{\text{reductant}} \text{organics@M} \tag{1}$$

For example, the first synthetic process reported used the aqueous reduction of silver cations with sodium hypophosphite in the presence of water-soluble Congo red, Safranin-O, or thionine [41]. The resulting material generally consists of an aggregate of metal crystallites with typical particle sizes on the order of 100 µm, and interstitial porosity, with much of the dopant molecules residing in closed interstitial pores formed by the metal crystallite aggregation where they are available to the access of external reactants [41].

The discovery opened the completely new field of metal–organic alloys (MORALs), merging the chemistry of metals with organic chemistry [42]. Indeed, subsequent research will demonstrate the possibility to successfully entrap in metals such as Ag, Au, Ga, Fe, Cu, Pd, Pt, and many others, not only small, water-soluble molecules but also enzymes, metal complexes, polymers, and even the graphene moiety. Advantageous applications of MORALs were demonstrated in polymer chemistry, heterogeneous catalysis, electrochemistry corrosion resistance, induction of chirality, tailoring unconventional properties to metals, and more [42].

In 2011, the weekly magazine of the American Chemical Society highlighted the discovery [43] that a simple electrical circuit can be made in which the two electrodes are made of the same metal (silver): one of pure silver and the other of silver doped with Congo red organic dye [44].

Given the broad scope of applications and the ease of MORAL preparation route, one would expect that the materials science community to rapidly build on this major advance in chemistry and materials science. A Boolean search with the query "molecularly doped metals" conducted in late 2025, however, returned only 55 results in Google Scholar and 91 results in Scopus [45]. Furthermore, on the same date, the original paper reporting the discovery [41] had been viewed on the publisher's website only 698 times. Cited in the scientific literature to date 74 times, the study received the highest number of annual citations (7) in 2009 when Avnir's team reported a number of key advances in the field (Figure 3).

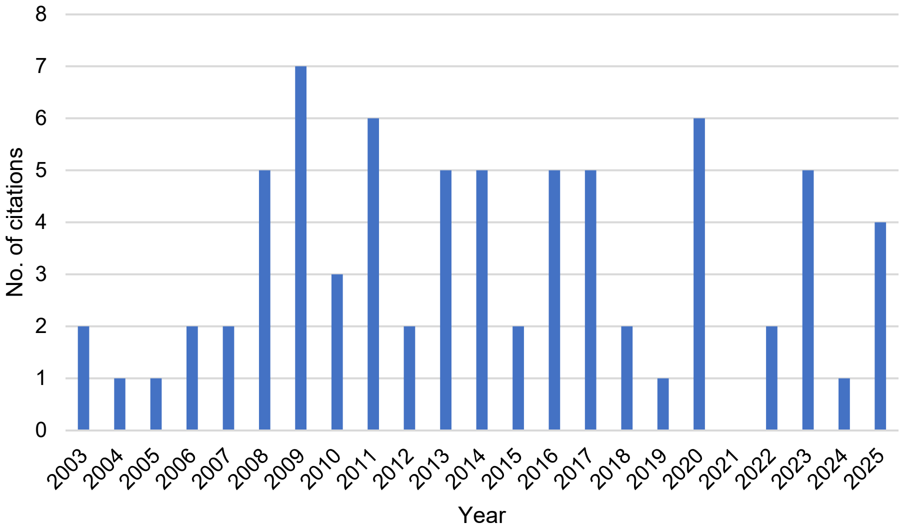


Figure 3. Citations for "Entrapment of organic molecules within metals: dyes in silver" between 2003 and late 2025. [Plot based on data sourced from Google Scholar, 2025].

Reporting in 2021 on the formation of an ionomer-Ag composite comprising a polymer entrapped in silver for creating an electrode material for electrochemical oxygen reduction reaction synergistically combining ionic conductivity, electronic conductivity, and electrocatalytic activity, Herring and co-workers wrote that,

> "The study of molecularly doped metals is a relatively new area of materials science, where metals may be used to entrap soft matter, such as polymers. . . During molecular doping, molecules may be encapsulated within a metal, creating a dopant-metal structure with far stronger interactions than metal with adsorbed polymer. . . [46]".

As noted by Lévy-Leblond, science does not develop in a linear fashion. On the contrary, many scientific developments often remain shelved and forgotten until rediscovery occurs, giving place to "surprising events of historical hysteresis" [47] with scientific developments dating back years or even decades rediscovered. Indeed, more than two decades after the MORAL discovery, new works ranging from copper of enhanced conductivity due to doping with graphene [48] to exceptionally stable hydrogenation catalysts for the synthesis of aniline under ultramild conditions [49] describe societally relevant advances based on the original discovery of metal–organic alloys dating back to 2002.

4. Discussion

An outcome common to all three innovations investigated is that innovation originated from self-determined researchers whose work is driven by intrinsic motivation, relying on intellectual gratification. The academic researchers who developed said innovations did not experience the "overemphasis on applied research" [3] that holds back innovation in chemistry according to a pool of academic and industrial chemists surveyed in 2017.

Psychologists have ascribed such self-determination ability to feelings of autonomy (not feeling controlled or compelled by others), competence (feeling that one can be effective in the activity), and relatedness (feeling of connectedness and belonging with others) [50].

Manufacturing companies well beyond the chemical industry may thus greatly benefit from chemistry innovation developed at public research institutes and universities. Indeed, investment in research and development (R&D) and not in digital technologies continues to be the most reliable predictor of innovation performance in companies [51]. By using innovation independently developed at public research institutes, companies will save huge financial resources.

An obvious consequence is that policy makers should continue to support the unconstrained work of chemistry researchers at public institutions using taxpayer money, without requiring research chemists to focus on applied research, but rather leaving them free to self-determine in their work, freely choosing the topics of their investigations and the way to conduct research.

Innovation in chemistry is relatively cheap, namely, it does not require large budgets as it happens in Big Science research, namely, highly organized, collaborative research projects involving large-scale common experimental facilities developed over time [52].

Two out of three (the molecularly doped metals and the LimoFish process) innovations analyzed in this study did not originate from research projects funded by an external agency. Funding for the discovery of molecularly doped metals project was even denied by a public research agency. The third one (the discovery of the cocktail-type catalysis mechanism) was funded by the Russian Foundation for Basic Research.

The fact that the innovation was nonetheless developed shows further evidence that Uskoković was right in advocating "the philosophy of poverty" for the practice of scientific research, highlighting the benefits that emerge from lack of financial resources [53], as scientists start acting in many creative ways to compensate for this lack of resources [54]. Research funding, for example, in the form of instruments and devices available in a laboratory, may accelerate research, easing the testing of new ideas, but external funding shortage is far more beneficial for generating new ideas because it forces fund-deprived but talented researchers to identify new avenues (new products and new processes in Chemistry) using the few resources available.

5. Conclusions

In conclusion, the study of the research and societal impact of three discoveries in chemistry reported between 2002 and 2022 offers insight into how discoveries in chemistry are made and benefit the users of chemistry innovation.

The analysis further confirms that in chemistry too, science does not develop in a linear fashion and that scientific developments continue to occur driven by curiosity from researchers. In other words, researchers based at public research and education institutions working free from external pressure to develop profitable innovations, as well as from the need to attract external funds to develop the innovation, eventually developed innovations of large applicative potential.

This is the case of the "cocktail-type" mechanism explaining metal-based catalysis (the first discovery studied), the LimoFish process (the second innovation analyzed), and molecularly doped metals (the third discovery scrutinized).

Users of said chemistry innovations will likely include chemical companies manufacturing metal catalysts and those using ubiquitous supported metal catalysts in chemical productions; bioeconomy companies that will source integral marine oil and organic fertilizer from widely different fishery processing waste via the LimoFish process; and advanced materials companies that will use molecularly doped metals in a wide range of applications, ranging from electricity and electronics to biomedicine.

In conclusion, the analysis unveils that creativity remains the key driver of chemistry innovation. Hence, chemistry scholars engaged in undergraduate education should focus on pedagogic approaches able to foster student creativity. The case studies analyzed in this study may be useful to further inform said education.

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