(양식 1)

【 고분자학회 학회상 포상 지원서 】

[표지]

공모분야	신진학술상				
지원자 인적사항	성 명	한 글	여 현 욱	영 문	HYEONUK YEO
		한 자	**呂 鉉 旭**		
	소속기관	기관명	경북대학교		
		부서명 (학과명)	화학교육과	직위/직급	부교수
		주 소	대구광역시 북구 대학로80 경북대학교 화학관		
업적요지	○ **(주요연구분야) 합성적 측면에서의 기능성 고분자 개발**에 관한 것으로, 2017년 박사학위 취득 후 독립 연구자로서 '**액정의 자기조립 현상에 기반한 기능성 열경화성/비트리머 수지의 설계 및 합성에 관한 연구**'를 수행하고 있습니다. - 열경화성 수지 분야에서 새로운 기능성 물질 합성 방면의 신진 연구자로 다양한 원천 소재 물질을 개발하여 현재까지 **Macromolecular Research 7편, Polymer-Korea 1편 포함 73편의 국제 학술 논문을 출판**하였고, 44건의 국내외 등록 특허를 보유하고 있습니다. 기능성 부여를 위한 고분자 수지에 대한 분자 설계를 시작으로 실제 물질의 유기 합성, 고분자화 반응 및 가공법, 개발품의 응용에 걸친 것으로, 전반적 연구 업적은 기능성 고분자 분야의 학문 발전에 미력하나마 기여를 하고 있는 것으로 생각합니다. ○ **(대표업적) 친환경성과 기능성을 겸비한 열경화성 수지에 관한 원천 소재 물질 및 기술** 연구에 관한 것으로 *Adv. Mater.*, *ACS Macro Lett.*, *Chem. Eng. J.* 등 고분자과학/공학 분야의 우수 학술지에 논문을 출판하였습니다. 이를 통해 전기전자, 기계소재, 우주항공 등 첨단 산업에 널리 활용되는 열경화성 수지의 열적, 전기적, 기계적 특성의 강화에 연결되는 핵심적인 개발 전략을 제시하였습니다. 특히, 영구적 화학 결합으로 인해 재활용이 곤란한 열경화성 수지에 동적 화학 결합을 도입하는 것으로 재가공 및 재활용이 가능한 분자 설계 사례를 다수 제시하여 **국가연구개발 우수성과 100선에 선정**되는 등 새로운 친환경성-기능성 양립 방법론을 선도하였습니다. ○ **(학회 활동)** 2013년부터 정회원으로 정기총회/지부/부문위원회 등에서 **5건의 초청 발표 및 30건 이상의 지도학생 발표**를 진행하였고, 2019춘계/2022추계 세션 오가나이저, 2025년부터는 운영이사 및 학술운영위원으로 활동하고 있습니다. ○ **(요약)** 기능성 유기 소재 분야의 유망 신진연구자로, 친환경성-기능성 양립 소재 개발 전략 제시를 통해 국내 소재 원천기술 발전에 기여하였습니다. 이에 한층 진보된 연구를 통해 고분자과학/공학/재료 분야에 학술적 기여를 하고, 우리 학회 발전에 도움이 되는 신진연구자가 될 수 있도록 절차탁마하고자 합니다.				

상기와 같이 고분자학회 학회상 포상을 지원합니다.

2025. 7. 15.

기관명 : 경북대학교
직 위 : 부교수
지원자 : 여 현 욱 (직인)

(양식 2)

1. 인적사항

가. 학력사항 (대학교 이상만 기재)

기 간	학 교 명	전공 및 학위, 지도교수
2016.11~2017.03	Kyoto University	Polymer Chemistry, 박사, Yoshiki Chujo
2011.04~2013.03	Kyoto University	Polymer Chemistry, 석사, Yoshiki Chujo
2007.04.~2011.03	Kyoto University	Industrial Chemistry, 학사, Yoshiki Chujo

나. 경력사항 (5개 이내 기재)

기 간	기관명(직위, 직책 등)
2017.09~현재	경북대학교(조교수, 부교수)
2013.04~2017.08	한국과학기술연구원(연구원)

다. 수상경력 (최근 3년 이내)

※ 정부 포상, 민간 포상 등 연구개발 업적 관련 수상경력 모두 기재

일 자	수 상 내 용	시 상 기 관
2024년 11월 29일	학술연구지원사업 우수성과 50선	교육부
2025년 1월 23일	국가연구개발우수성과 100선	과학기술정보통신부

2. 수상후보자 추천인단 명부

성 명	전 공 분 야	세부전공 분야	소 속	비고
구본철	고분자화학	고분자복합재료	한국과학기술연구원	별도 송부
김병수	고분자화학	고분자합성	연세대학교	별도 송부
박치영	고분자화학	기능성고분자	대구경북과학기술원	별도 송부

3. 대표논문의 연구업적 요약서

ㅇ **(대표논문)** Trinh, T. E.; Ku, K.; Yeo, H.*, "Reprocessable and Chemically Recyclable Hard Vitrimers Based on Liquid-Crystalline Epoxides" Adv. Mater., 2023, 35, 2209912.

ㅇ **(성과 요약)**
- 에폭시 수지는 우수한 물성으로 다양한 산업에 활용되지만, 비가역적 가교 구조로 인해 재가공 및 재활용이 어려워 환경 문제를 야기함. 이를 해결하기 위해 본 연구는 자기조립형 액정 분자를 도입하고, 에스터 및 이민 기반의 동적공유결합을 활용한 새로운 비트리머 수지를 설계함. 개발된 수지는 경화 후 130℃에서 재가공이 가능하며, 범용 에폭시 수지 대비 3배 이상의 열전도도를 나타냄. 또한, 수계 조건에서 화학 분해를 통해 원료 회수 및 재경화가 가능하고, 재활용 후 일부 물성이 오히려 향상됨. 본 성과는 친환경성과 고기능성을 동시에 갖춘 고분자 소재의 가능성을 보여주며, 산업계에서의 실용성이 높은 것으로 판단됨.

ㅇ **(우수성):** 비트리머는 기존 열경화성 수지의 재가공 및 재활용 한계를 극복할 수 있는 차세대 고분자 소재로 학계와 산업계의 큰 관심을 받고 있음. 하지만 대부분의 기존 연구는 연질 고분자에 기반하거나 상용 단량체 사용에 한정되어 기능성과 친환경성의 양립이라는 핵심 문제를 해결하지 못하고 있음. 본 성과는 아래와 같은 우수성을 바탕으로, 고기능성과 친환경성을 동시에 구현한 경질 비트리머를 선도적으로 개발하는 것에 성공함.
- 단량체 설계부터 재활용까지 완전한 유기소재 개발 프로세스 시연: 기존 비트리머 연구 대부분이 상용 단량체에 의존하는 반면, 본 연구는 액정 구조를 갖는 새로운 단량체를 유기합성하여 분자 수준에서 기능성과 친환경성을 동시에 구현 가능하도록 설계함. 단량체 합성 → 경화 시스템 구축 → 재가공 및 화학적 분해 → 재경화(재활용)까지 소재 개발의 전 주기를 아우르는 실험 기반 연구로, 기존 문헌과 명확히 구분됨.
- 정밀한 화학 구조 분석으로 신뢰성 있는 검증 확보: 일반적인 비트리머 연구가 간접적 점탄성 측정이나 FT-IR 분석에 그치는 것과 달리, 본 연구는 NMR, MS, FT-IR, NIR 등 정량적이고 직접적인 분광학적 분석법을 체계적으로 병행하여 가교 구조 변화의 정확한 확인을 수행함. 이는 비트리머 분야에서 사실상 표준화되지 않은 분석 체계를 새롭게 제시한 사례로, 후속 연구에도 큰 참고가 될 수 있음.
- 연질 중심 기존 연구와 달리, 산업적 수준의 경질 소재 구현: 기존 자기수복 고분자 등은 대부분 연질로 구성되어 산업 적용이 어려운 반면, 본 연구는 기계적 물성이 뛰어난 경질 수지를 기반으로 재가공 및 재활용을 성공적으로 시연함. 경질 비트리머 연구는 극히 드문 분야이며, 특히 재활용 시 유리전이온도(Tg)가 60℃ 향상되는 등 기성품보다 성능이 강화되는 사례는 학술적으로도 매우 희귀함.
- 세계 최고 수준의 열전도도 확보(고기능성): 열전도도는 유기물의 구조적 한계로 인해 향상에 큰 제약이 있으나, 본 연구는 포논 산란 억제에 유리한 액정 구조를 분자 수준에서 도입하여, 0.64 W/m·K의 등방성 열전도도를 확보함. 이는 벌크 고분자 기준 세계 최고 수준의 90% 달성, 상용 에폭시 대비 3배 이상 우수한 성능임. 이와 동시에 내열성, 경도, 재활용성 등도 모두 확보하여, 고기능성과 지속 가능성이라는 상반된 요구를 동시 충족함.
- 산업 수요에 최적화: 개발된 소재는 열전도도와 내열성 모두에서 반도체 및 디스플레이 산업이 요구하는 방열 수지 스펙을 상회함. 경질 기반으로 기계적 내구성 또한 확보되어 실제 제품 응용이 가능하며, 재가공·재활용 특성으로 인해 탄소 중립 및 자원 순환 정책과의 정합성도 매우 우수함.

ㅇ **(의의)**
- 본 성과는 극히 드문 기능성과 친환경성을 동시에 겸비한 열경화성 고분자 소재 개발에 대한 것으로 두 상반특성 부여를 위한 화학적 소재 설계에서 시작하여 개발, 분석에 이르기까지 새로운 물질 개발의 관점뿐만 아니라 해당 소재의 응용을 제시한 점에서 과학기술적 의의가 높음.
- 특히, 액정 구조의 자기조립 특성을 바탕으로 방열성과 내열성, 기계적 특성을 확보하였으며, 이 대표 기능성을 바탕으로 반도체, 디스플레이 등 첨단 전자산업 군에 적용이 가능한 소재 원천 기술을 확보하였음.
- 또한, 대다수의 친환경성 고분자가 기초적 물성 부족 또는 기능성 부재로 인해 산업적 적용이 어려운 반면, 본 성과물은 대표적인 열경화성 수지인 에폭시 수지의 물리/화학적 우수성을 그대로 가지면서 고기능성을 가질 뿐만 아니라 추가적인 재가공과 재활용 등 친환경성을 가지는 열경화성 소재와 그 개발 원천기술에 대한 것이므로, 산업계의 지속가능 전략에도 부합하여 적극적인 대응이 가능할 것으로 기대함.

4. 연구개발 실적

(1) 업적 총괄 (단위:건)

논문	SCIE 등재 학술지				h-index		
	제1저자	공동저자	교신저자	소계	Web of Science	Google Scholar	SCOPUS
	14	35	24	73	23	25	24
특허	국내		국외		기술이전	연구 보고서	저서
	등록		등록				
	32		12		2	9	0

*h-index 증빙자료(화면캡처본) 제출.

(2) 대표논문 목록 (5편), 신진학술상의 경우 3편

제 목	발표지명	Impactor factor (JCR2024)	발표 년도	역할(저자)	저자수 (명)	피인용 횟수
Reprocessable and Chemically Recyclable Hard Vitrimers Based on Liquid-Crystalline Epoxides	Advanced materials	26.8	2023	교신	3	40
Design and Evaluation of a Reprocessable Bismaleimide Thermoset: Enhancing Functionality and Sustainability Compatibility	ACS Macro Letters	5.2	2024	교신	3	1
Solvent-free and one-step fast fabrication of a side-chain liquid crystalline network	Chemical Engineering Journal	13.2	2025	교신	3	-

*제목 및 저자를 확인할 수 있는 증빙자료 제출.

(3) 총괄연구업적 목록

□ 학술지 논문 - SCIE 등재지에 한함

제 목	발표지명	Impactor factor (JCR2024)	발표 년도	역할(저자)	저자수 (명)	피인용 횟수
High-temperature insulating polyimide aerogels with a hierarchical porous hyper-cross-linked structure derived from aqueous polymerization of mesostructured silica-grafted Poly(amic acid) salt	Polymer Testing	6.0	202506	공동	6	-
Effect of Alkyl Chain Tail on Thermal Conductivity and Physical Properties of Side-Chain Liquid Crystalline Polymers	Macromolecular Chemistry and Physics	2.7	202506	교신	5	-
Solvent-free and one-step fast fabrication of a side-chain liquid crystalline network	Chemical Engineering Journal	13.2	202504	교신	3	-
Thermal Conductivity in Side-Chain Liquid-Crystal Epoxy Polymers: Influence of Mesogen Structure	Macromolecular Rapid Communications	4.3	202504	교신	3	1
Molecular Orientation and Thermal Conductivity in Liquid Crystalline Epoxy Resins by Anionic Ring Opening Polymerization	Industrial & Engineering Chemistry Research	3.9	202411	교신	2	2
Effect of Flexible Chains on Thermal Conductivity of Liquid Crystalline Epoxy Resins	ACS Applied Polymer Materials	4.7	202411	교신	2	4
Curing Kinetics of Ultra-High-Temperature Thermosetting Polyimides Based on Phenylethynyl-Terminated Imide Oligomers with Different Backbone Conformations	ACS Applied Polymer Materials	4.7	202411	공동	8	–
Dependence of Thermal Conductivity and Reprocessability on Polymerization System for Liquid Crystalline Epoxy Vitrimers	ACS Applied Polymer Materials	4.7	202411	교신	3	2
Phenylethynyl-Terminated Imide Oligomer-Based Thermoset Resins	Polymers	4.9	202410	공동	8	1

Consideration of molecular weight-dependent high thermal resistance of end-capped-oligoimide based thermoset resins	Polymer Testing	6.0	202411	교신	10	-
Design and Evaluation of a Reprocessable Bismaleimide Thermoset: Enhancing Functionality and Sustainability Compatibility	ACS Macro Letters	5.2	202410	교신	3	1
Exploring Novel Quorum Quenching Strain: Enhanced Disrupting Autoinducer-2 Bacterial Communication to Combat Biofouling in Membrane Bioreactor for Wastewater Treatment	Chemical Engineering Journal	13.2	202404	공동	9	5
Structural Effect of Cyclic Olefin Cross-linker on Long-wave Infra-red Transmitting Sulfur Polymers	Macromolecules	5.2	202403	공동	6	6
Enhancement of Thermal Conducting Properties in Epoxy Thermoset Systems Using an Aligned Liquid-Crystalline Mesophase	Materials Advances	4.7	202402	교신	2	8
Long-wave infrared transparent sulfur polymers enabled by symmetric thiol cross-linker	Nature Communications	15.7	202305	공동	7	41
Reprocessable and Chemically Recyclable Hard Vitrimers Based on Liquid-Crystalline Epoxides	Advanced Materials	26.8	202303	교신	3	40
Phase-controllable topochemical polymerization of liquid crystalline epoxy according to spacer length	Polymer Chemistry	3.9	202302	교신	2	10
Catalytic performance of tridentate versus bidentate Co(ii) complexes supported by Schiff base ligands in vinyl addition polymerization of norbornene	RSC Advances	4.6	202212	공동	7	7
Norbornene and methyl methacrylate polymerizations catalyzed by palladium(II) complexes bearing aminomethylpyridine and aminomethylquinoline derivatives	Journal of Molecular Structure	4.7	202209	공동	5	-

Vinyl-addition polymerizations of norbornene and methyl methacrylate by the palladium(II) complexes ligated by 2-iminomethylquinoline and 2-iminomethylpyridine derivatives	Inorganica Chimica Acta	3.2	202209	공동	6	6
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Reprocessable and Chemically Recyclable Hard Vitrimers Based on Liquid-Crystalline Epoxides

*Thi En Trinh, Kyosun Ku, and Hyeonuk Yeo**

The rapid increase in demand for recyclable and reusable thermosets has necessitated the development of materials with chemical structures that exhibit these features. Thus, functional mesogenic epoxide monomers bearing both ester and imine groups that can be vitrimerized and recycled are reported herein. The compounds show mesophase characteristics at 100–200 °C and can be converted into hard epoxides by a common curing reaction. The obtained hard epoxides have high isotropic thermal conductivity (≈0.64 W m^{-1} K^{-1}), which is derived from their highly ordered microstructures. The cured products can be easily reprocessed through imine metathesis and transesterification, and decomposed products can be obtained through imine hydrolysis under acidic or basic conditions and subsequently be re-cured. Surprisingly, recycled materials can be repeatedly reprocessed or chemically decomposed. The reprocessed materials retain the properties of their pristine counterparts, and the recycled products preserve the advantages of the hard thermosets without alteration to any of their unique properties. A dehydration reaction occurs between the residual hydroxyl groups during the re-hardening, which dramatically increases the glass transition temperature by ≈60 °C. These reprocessable and recyclable vitrimers demonstrate the effectiveness and environmental friendliness of the molecular design strategy reported herein.

1. Introduction

Thermosetting resins such as epoxy resins exhibit several excellent properties, facilitate the fabrication of composite materials, and are extensively used in a diverse range of materials ranging from daily-use substances to aerospace materials.[1–3] However, unlike thermoplastic resins, most thermosetting resins are insoluble and infusible after curing, which hinders their reprocessing and recycling, thereby leading to environmental problems.[4–6] To solve this reuse-related issue, numerous studies have recently been conducted on thermosetting resins that behave as thermoplastic resins when their crosslinked structure dissociates under certain conditions owing to their dynamic crosslinking covalent bonds.[7–9] These new-class polymers, which were named vitrimers in 2011, have monomers that contain two or more polymerizable functional groups, one of which comprises reactive functional groups capable of reversibly crosslinking and dissociating under certain conditions.[10–12] Alternatively, vitrimers can be designed by introducing a dynamic crosslinking functional group to thermoplastic polymers.[13–16] Commonly used dynamic crosslinking functional groups include esters,[17,18] carbonates,[19] urethanes,[20] and disulfides.[21] Additionally, the topological freezing temperature (T_v), which is the temperature at which the melt viscosity reaches 10^{12} Pa s, can be tuned depending on the system design parameters, such as the chemical structure and the presence or absence of a catalyst.[22,23] Vitrimers possess the mechanical durability of thermosetting resins at temperatures below T_v and have potential utility as environmentally friendly, innovative materials because of their processability and recyclability at temperatures above T_v.[24,25]

However, existing cutting-edge materials typically exhibit a trade-off relationship between their environmental friendliness and functionality. Therefore, materials such as vitrimers, which have been found to show limitations in fundamental investigations, require enhancements in their electrical, optical, and thermal properties.[26,27] Vitrimers essentially inherit the characteristics of the base thermosetting resin, because of which they exhibit properties such as adhesion and excellent insulation in the case of epoxy resin systems, as well as transparency and heat resistance in the case of acrylic resin systems.[3,28] Additionally, most vitrimers including urethane resin systems can serve as advanced stimulus-responsive materials owing to their elasticity.[29,30] From the viewpoint of applying plastics in promising industries, vitrimers can facilitate the development of advanced electronic products. In this regard, the development of vitrimers for composite materials and improvement of their properties are underway, with their heat dissipation characteristics, in particular, requiring enhancements for use in small and

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Letter

Design and Evaluation of a Reprocessable Bismaleimide Thermoset: Enhancing Functionality and Sustainability Compatibility

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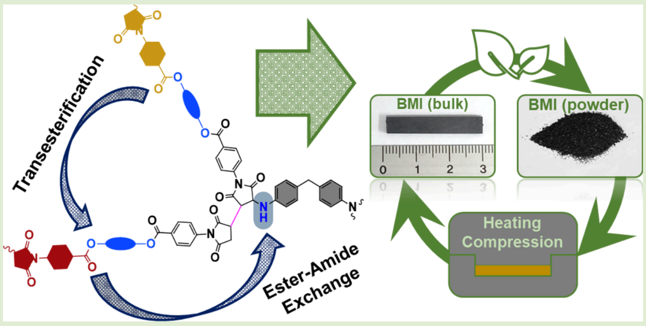
ABSTRACT: Bismaleimide (BMI) resins are high-performance thermosets that are primarily used in aerospace because of their exceptional heat resistance and physical properties. However, their growing demand has led to significant environmentally unfriendly waste. To address this, our research proposes a reprocessable BMI system using a newly synthesized BMI vitrimer (BMIV) with functional groups that form covalent adaptable networks (CANs). To enhance the properties, a symmetrical BMI with two ester groups introduced into the rigid rod molecule was designed as a CAN component. After confirming the structure using various spectroscopic techniques, BMIV was coupled with aromatic diamines via an additional aza-Michael reaction to obtain the cured resins. Subsequently, the mechanical properties and reprocessing behavior of the thermally stable and optimized thermosetting material with the best performance were evaluated, and the evidence, mechanism, and activation energy of the topology rearrangement are reported in detail.



Thermosets are a family of polymers categorized by their profound thermal and mechanical durability, which makes them favorable for use in intense working environments.[1,2] These characteristics stem from the irreversible and stable three-dimensional networks formed through covalent bonds as cross-links between linear polymer chains.[3] Thermosets include epoxies, bismaleimides (BMIs), unsaturated polyesters, and polyurethane. Among these, BMI resins have been recognized as a high-performance material that possesses properties strictly required for aerospace and aeronautic applications.[4] These properties include high glass transition temperatures, high thermal and oxidative stability, excellent mechanical properties, a relatively low dielectric constant, and low moisture absorption.[5−9]

In addition to these advantages, the irreversibility of the chemical structure of thermosetting polymers, particularly BMI resins, renders them incapable of being reprocessed or reshaped once cured, which results in cross-links.[10] Consequently, even the smallest mistake during the shaping process or the spoilage of thermoset pieces causes these materials to become a permanent waste burden on the ecosystem.[11,12] Generally, covalent adaptable networks (CANs) are incorporated to overcome the challenge of producing sustainable thermosets without sacrificing their most desirable properties.[13−19] These networks feature dynamic linkages that can be exchanged under external stimuli, such as heat and pressure, making it possible for thermoset pieces such as vitrimers to be reprocessed and reused multiple times. Since their initial introduction by Leibler et al. over two decades ago,[20] vitrimers have been extensively researched, and various methods of designing CANs have been explored. Vitrimers can undergo several chemistries, including transesterification, transalkylation, disulfide metathesis, transamination, transcarbamoylation, and imine exchange, with or without the use of a catalyst.[21−24]

To date, researchers have reported numerous thermosetting materials that exhibit vitrimer-like behavior and leverage the advantages of CANs to demonstrate reprocessability, remoldability, reconfigurability, and self-healing ability.[25−28] However, in the field of BMI resins, reports on BMI resins remain very limited even though there are many reports on utilizing maleimide as a component in Diels−Alder chemistry.[29,30] Shibata's group developed reprocessable and self-healable BMI thermosets that contain disulfide bonds capable of undergoing thermally induced disulfide metathesis.[31,32] Additionally, Ning et al. introduced synthetic curing agents for triple-shape memory BMI thermosets that can be remolded based on transesterification.[33] Their reports demonstrate reprocessability derived from curing systems designed for commercial BMIs. The issue is that the reported BMI systems face challenges,

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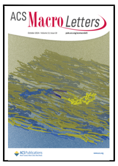

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Solvent-free and one-step fast fabrication of a side-chain liquid crystalline network

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ABSTRACT

Liquid crystal networks (LCNs) are advanced materials with applications in medical devices and aerospace owing to their reversible adhesion, shape memory, and self-healing properties. Traditional LCN synthesis involves acrylate-based liquid crystal (LC) monomers and photopolymerization; however, it has limitations such as oxygen sensitivity, shrinkage, and thickness constraints. Epoxy-based LCNs using anionic ring-opening polymerization overcome some of these issues but still face challenges such as the need for high-purity solvents and reduced thermal and mechanical properties due to short-chain polymers. Here, we present a solvent-free, one-step, fast-curing method for synthesizing LCNs via heat compression in an atmospheric environment. This process incorporates LC diepoxide (D), acting as a chain extender and crosslinker, with LC monoepoxide (M), forming the side-chain linear polymer. Imidazole initiates the curing reaction at LC temperatures, ensuring fast curing and optimized crystallinity, which successfully induces LCN formation. Increasing the D content improves chain extension or crosslinking, forming LCN networks with varying crosslinking densities. All samples exhibit thermal conductivity over 0.55 $Wm^{-1}K^{-1}$. Samples with a higher D content demonstrate superior mechanical properties and thermal stability. Notably, samples with a balanced epoxide ratio exhibit crystalline structures and the highest thermal conductivity. This method efficiently enables the cost-effective production of epoxy-based LCNs with customizable properties.

1. Introduction

Liquid crystalline networks (LCNs), which include liquid crystalline elastomers (LCEs) and liquid crystalline thermosets (LCTs), represent polymer classes with significant potential for advanced functional materials. These materials exhibit exceptional properties owing to their anisotropic shapes, making them suitable for applications in soft robotics, responsive surfaces, and photonics [1–4]. LCEs have a low crosslinking density, enabling high deformation, whereas LCTs exhibit greater rigidity due to higher crosslinking, thereby limiting their deformation. LC epoxy resins enhance properties such as fracture toughness, thermal stability, and moisture resistance [5–11].

LCNs can be produced using different starting materials and through different polymerization techniques. There are two primary methods commonly employed: one involves crosslinking liquid crystal side-chain linear polymers, while the other utilizes reactive LC monomers with polymerizable groups such as acrylates. The former results in elastomeric properties, which are beneficial for actuators and sensors [12,13], whereas the latter produces highly crosslinked networks suitable for optical applications and soft robotics [14–19]. Photopolymerization, a frequently used technique in LCN production, encounters challenges such as light penetration issues, shrinkage, and sensitivity to oxygen [20]. To overcome these challenges, LC monomers containing epoxide groups are preferred over traditional acrylates due to their advantages such as reduced shrinkage, enhanced alignment, and the ability to undergo post-curing [21–26]. However, polymerizing reactive LC monomers through cationic ring-opening and ionic coordination pathways may lead to low yields and the formation of side products [27–31]. Anionic ring-opening polymerization using *t*-BuOK and 18-crown-6 can enhance control but still results in low yield and limitations in molecular weight [31–37]. Recent advancements have been made using LC epoxy monomers with short spacer chain lengths and low temperatures,

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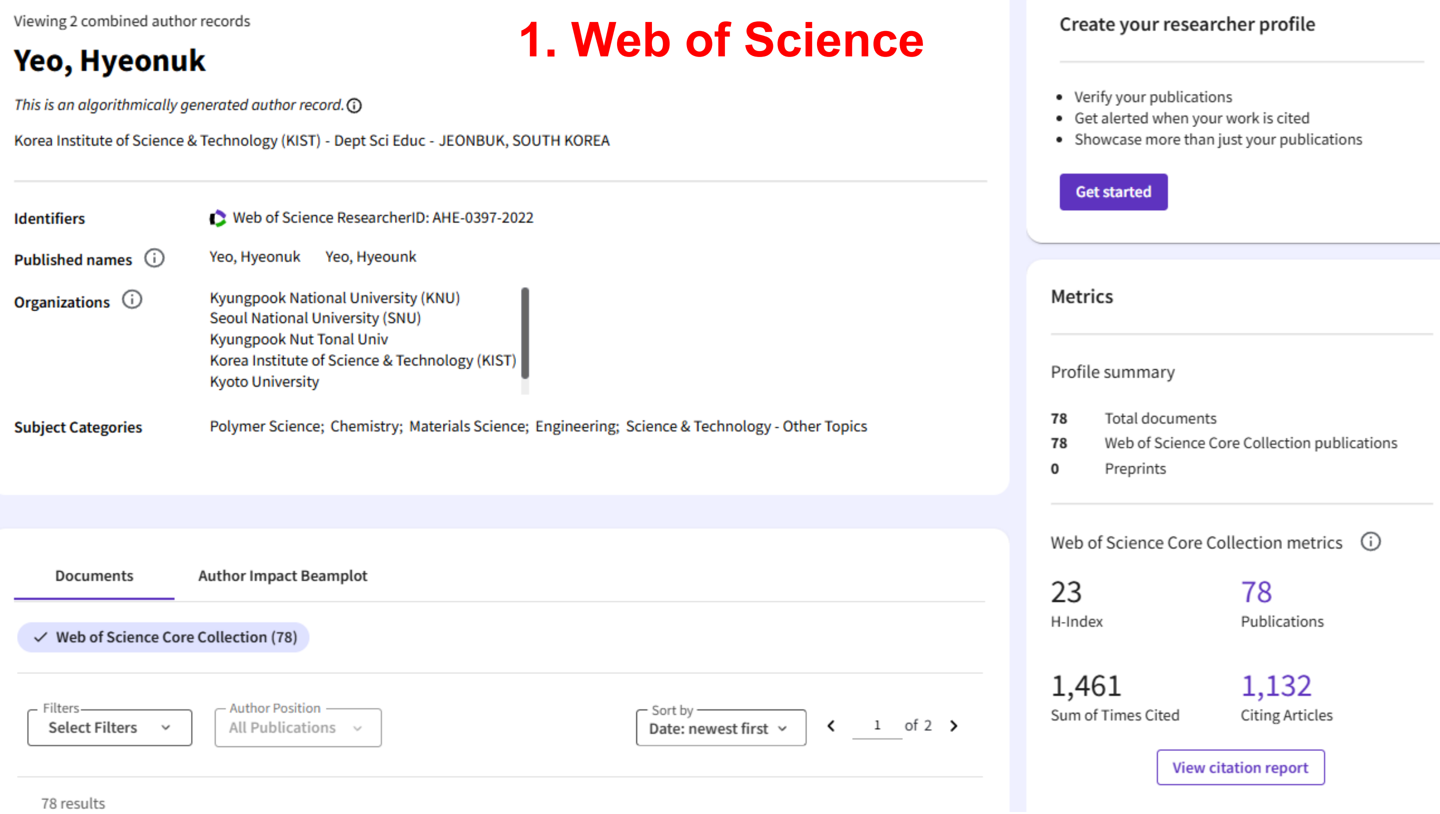

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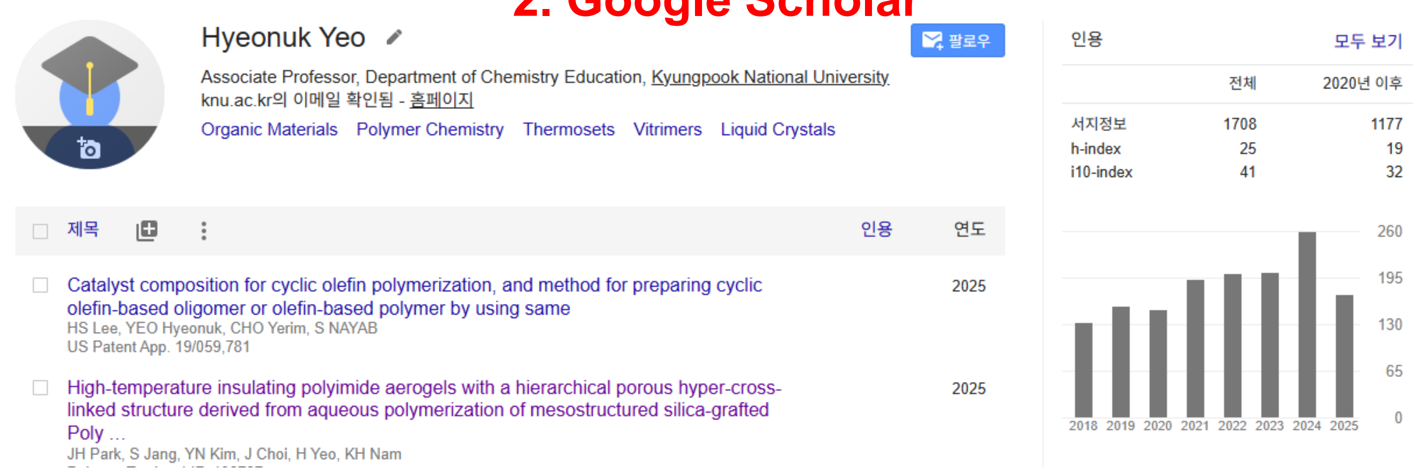

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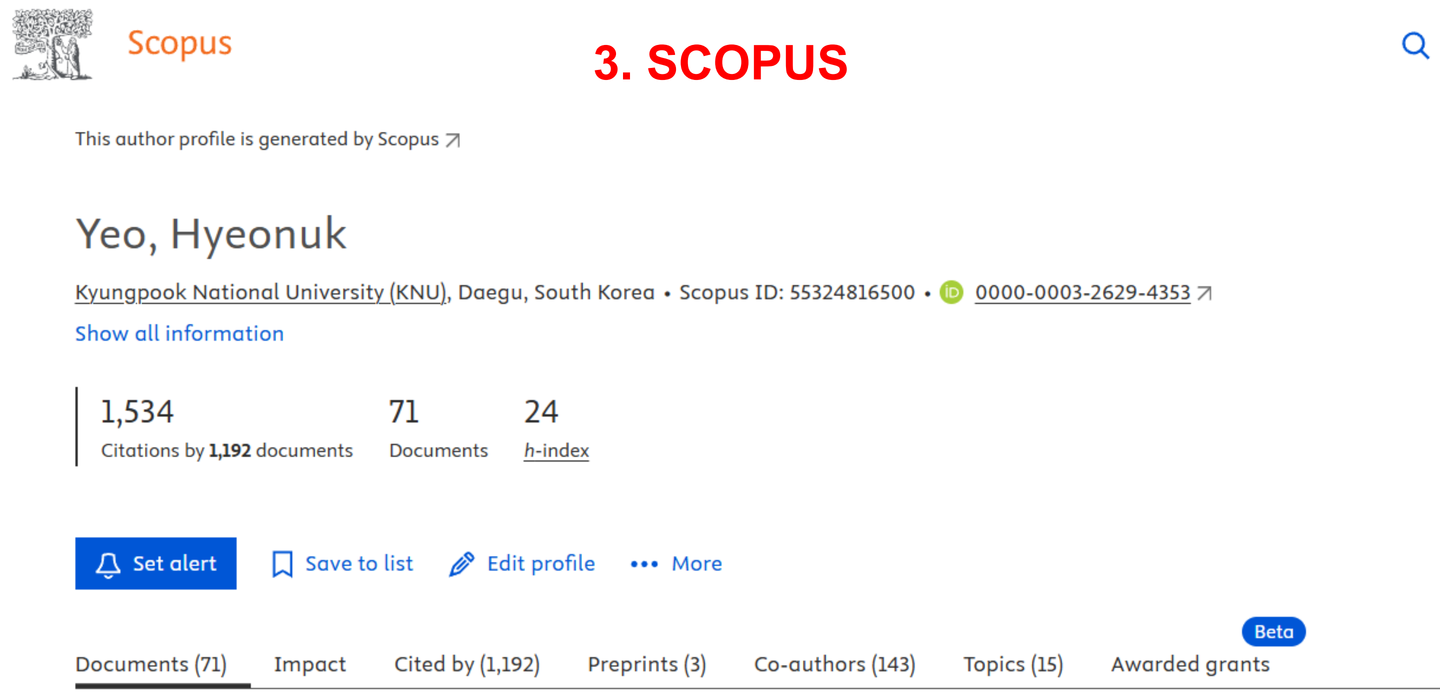

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