RSC Sustainability

ROYAL SOCIETY OF CHEMISTRY

PAPER

View Article Online
View Journal | View Issue

Check for updates

Cite this: *RSC Sustainability*, 2026, **4**, 1986

RECOMPENSE: a student-led open science initiative for sustainable polystyrene waste upcycling in academic labs

Victoria Lageard,[a] YuHan Yan,[a] Jiayin Liu,†[a] Yueze Gong,†[a] Shuoxi Liu,†[a] Bob C. Schroeder [a] and David Palomas *[ab]

Plastic waste is a global challenge, with polystyrene (PS) among the least recycled polymers despite its widespread use in laboratories. Conventional recycling routes for PS remain economically and technically limited, creating an urgent need for accessible, sustainable alternatives. Here, we introduce RECOMPENSE, a student-led open science initiative designed to upcycle PS waste into polystyrene sulfonic acid (u-PSSA), a heterogeneous catalyst for green organic synthesis. Developed through MSc research projects at UCL, RECOMPENSE combines technical innovation with educational engagement, offering detailed protocols and video resources freely available online. We report a reproducible method for sulfonating expanded PS under simple laboratory conditions, yielding u-PSSA with up to 45% sulfonation. Its catalytic performance was validated in Friedel–Crafts reactions using biobased substrates, achieving quantitative yields of a biofuel precursor under mild conditions. Comparative studies with commercial PSSA confirmed the viability of waste-derived catalysts, while additional tests with aromatic aldehydes demonstrated broad applicability. Beyond experimental results, RECOMPENSE exemplifies co-creation in sustainable chemistry education. By involving students in research and resource development, the project fosters practical skills, systems thinking, and global collaboration. Demonstrating how academic labs can transform plastic waste into valuable resources while preparing future scientists to lead sustainability transitions.

Received 18th December 2025
Accepted 17th March 2026

DOI: 10.1039/d5su00927h

rsc.li/rscsus

Open Access Article. Published on 19 March 2026. Downloaded on 5/2/2026 10:32:42 AM.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Sustainability spotlight

Polystyrene waste is among the least recycled plastics, contributing to mounting environmental challenges and resource inefficiency. Addressing this issue is critical to reducing plastic pollution and advancing circular economy principles. This work introduces RECOMPENSE, a student-led open science initiative that transforms single-use PS waste from academic laboratories into polystyrene sulfonic acid (u-PSSA), a reusable catalyst for green organic synthesis. By providing accessible protocols and educational resources, RECOMPENSE promotes sustainable laboratory practices and empowers future scientists through co-creation. This approach aligns with UN Sustainable Development Goals SDG 12 (Responsible Consumption and Production) and SDG 4 (Quality Education), demonstrating how collaborative innovation can simultaneously tackle waste management and embed sustainability into chemical education.

Introduction

Plastics are integral to the modern global economy, offering adaptable and cost-efficient solutions across sectors such as packaging, automotive, electronics, and healthcare. However, the environmental impact of plastic waste has escalated dramatically. In the early 2000s, the volume of plastic waste generated in just one decade exceeded that of the previous 40 years. Since 2020, global plastic production has surpassed 367 million tonnes annually,[1,2] with projections estimating that primary plastic production could reach 1100 million tonnes by 2050.[3] Due to their resistance to degradation, plastics can persist in the environment for hundreds of years, making waste management a major global concern. Alarmingly, around 13 million tonnes of plastic are estimated to enter the oceans each year.[1,2] Whether found in aquatic or terrestrial ecosystems, plastic waste remains environmentally persistent.[3] Despite growing awareness, less than 10% of the plastic waste generated worldwide is currently recycled.[3]

A significant portion of plastic products are designed for single use, contributing heavily to waste streams. Laboratories alone generate approximately 5.5 million tonnes of single-use plastic waste annually, accounting for roughly 2% of the global total.[4] Common polymers used in labware include polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polymethyl methacrylate (PMMA), and polystyrene (PS).

[a]*Department of Chemistry, University College London, 20 Gordon Street, London WC1H 0AJ, UK. E-mail: d.palomas@ucl.ac.uk*

[b]*Manufacturing Futures Lab, Marshgate Building, 7 Sidings Street, London, E20 2AE, UK*

† Equal contribution.

© 2026 The Author(s). Published by the Royal Society of Chemistry

Open Access Article. Published on 19 March 2026. Downloaded on 5/2/2026 10:32:42 AM. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

PS is frequently found in items such as filtration units, microwell plates, tissue culture dishes, and serological pipettes.[5] While recycling rates for PET and PE stand at 19% and 10% respectively, PS lags significantly behind at just 1%.[6] Recycling PS presents unique challenges, primarily due to its low density, which increases transportation costs and makes closed-loop recycling economically unattractive. Consequently, producing new PS is often more cost-effective than collecting and reprocessing waste material.[7] Mechanical recycling, currently the most widespread method, involves reprocessing plastics without altering their chemical structure. However, this approach is often limited by contamination and the diversity of plastic types in waste streams. Moreover, mechanically recycled plastics tend to be downcycled into lower-value products and degrade over time due to exposure to heat, light, and mechanical stress.[8] Recent innovations in chemical recycling and biodegradation have improved the sustainability of PS waste treatment, but significant technical hurdles remain.[9] These include energy-intensive pyrolysis with inconsistent product yields, high solvent costs for chemical structure control, scalability issues in advanced oxidation processes, slow microbial degradation rates, and operational unpredictability in insect-gut microbiota-based methods.

An alternative approach to traditional recycling is upcycling, transforming waste into higher-value products. Recent chemical upcycling strategies for PS include hydrogen-atom transfer (HAT) and degradation–upcycling (Deg–Up).[10,11] HAT approaches activate PS through selective hydrogen abstraction, typically under photocatalytic or oxidative conditions, to generate reactive polymer radicals that undergo controlled β-scission and oxidation, forming aromatic carbonyl compounds such as benzoic acid. Although powerful, HAT methods often require specialised photocatalysts, tuned wavelengths of light, and careful control of oxygen and solvent environments, making them challenging to implement in routine or teaching laboratories. Deg–Up, in contrast, follows a tandem sequence in which PS is first chemically degraded into platform intermediates such as styrene or benzene before these intermediates undergo further upgrading to high-value fine chemicals, including UV-absorbers and pharmaceutical precursors. While Deg–Up offers excellent selectivity and product diversity, it frequently relies on multistep workflows, Lewis-acid catalysts, or specific reaction atmospheres that can limit scalability and accessibility.

In contrast to these emerging yet technically demanding methods, sulfonation of PS provides a comparatively simple and practical upcycling route, yielding polystyrene sulfonic acid resins with established applications in ion exchange[12–16] and catalysis.[17–21] However, sulfonation protocols in the literature are often insufficiently detailed or require specialised equipment, limiting their accessibility in resource-constrained or educational lab settings. This creates a barrier for broader adoption of sustainable practices in academic environments and represents a missed opportunity to integrate green chemistry into teaching and research.

In response to these challenges, we present RECOMPENSE,[22] an open science initiative developed through MSc research projects in the MSc Sustainable Chemistry programme at University College London (UCL),[23] co-created with UCL chemistry undergraduate students. This platform aims to make PS upcycling more accessible by providing detailed, user-friendly protocols and educational resources. We share preliminary findings that led to the creation of the platform, along with the materials currently available *via* our website[22] and YouTube channel.[24] These include written and video-recorded procedures for converting PS waste from UCL East teaching labs into polystyrene sulfonic acid, and its application as a catalyst in the synthesis of a biodiesel precursor.

Experimental

Materials

Poly(sodium 4-styrenesulfonate) (PSSNa) with a weight average molecular weight of 1000 kg mol^{-1}, Amberlyst®-15, aromatic aldehydes, butanal, acetone, furfural, and 2-methylfuran were purchased from Sigma-Aldrich. Concentrated sulfuric acid (95–98%) was obtained from Fisher Scientific. Expanded polystyrene waste was sourced from packaging materials received in the teaching wet laboratories at UCL East and had not been contaminated with any reagents prior to sulfonation.

Preparation of c-PSSA

A 50 mL solution of PSSNa (25 wt%) was added to a mixture of 60 g of ground Amberlyst®-15 and 250 mL of deionised water. The mixture was stirred at room temperature overnight and then filtered to separate Amberlyst®-15 from the c-PSSA solution. The filtrate was evaporated to dryness at 60 °C to recover c-PSSA. The recovered c-PSSA was ground into small pieces and dried for an additional 24 h at 80 °C in an oven to minimise water content. To determine the number of acidic sites, 20 mg of c-PSSA were dissolved in 10 mL of deionised water and titrated against a 0.01 M NaOH solution using phenolphthalein as an indicator. The maximum theoretical number of acidic sites is 5.4 mmol H^+ per g of resin. The titration results showed an acidity of 4.86 mmol H^+ per g, indicating a 90% degree of sulfonation measured as mmol H^+ per g.

Synthesis of u-PSSA

1 g of expanded polystyrene (PS) waste was dissolved in a minimum amount of ethyl acetate (~5 mL) in a beaker under stirring. The resulting solution was transferred to a round-bottom flask, and the solvent evaporated using a rotary evaporator with a water bath set at 35 °C. The flask with the recovered PS was clamped to a stand, and 10 mL of concentrated sulfuric acid (95–98%) was added along with a Teflon-coated magnetic stirring bar. The reaction mixture was heated at 100 °C for 1.5 h using a heating block. After completion, the mixture was cooled in an ice-water bath, and 100 mL of ice-cold water was slowly added. A rubbery solid precipitate formed, which was filtered under vacuum and washed thoroughly with deionised water until the filtrate reached pH 7. The recovered solid was dried overnight in an oven at 70 °C, yielding a yellowish-white product. The resulting u-PSSA was insoluble in deuterated solvents and characterised by FTIR spectroscopy, TGA and DSC.

© 2026 The Author(s). Published by the Royal Society of Chemistry

Open Access Article. Published on 19 March 2026. Downloaded on 5/2/2026 10:32:42 AM. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

The number of acidic sites was determined by titration against a standard 0.01 M NaOH solution using phenolphthalein as an indicator. Typical yields ranged from 0.9 to 1.2 g of u-PSSA, with degrees of sulfonation between 30% and 45%.

Standard Friedel–Crafts reaction of aldehydes with 2-methylfuran

A 9 mL pressure tube was charged with 0.5 mL of 2-methylfuran (used as both solvent and reactant), aldehyde (0.5 mmol), and catalyst (0.025 mmol based on acidic sites, 5 mol%). The reaction mixture was stirred at 70 °C for 2 h and monitored by TLC (hexane : ethyl acetate). Upon completion, the mixture was filtered under vacuum to recover the catalyst. The filtrate was transferred to a round-bottom flask, diluted with 10 mL of ethyl acetate, and concentrated using a rotary evaporator. The crude product was purified by column chromatography using hexane : ethyl acetate as the eluent. Fractions containing the product were collected, transferred to a tared round-bottom flask, and the solvent removed. The flask was then placed on a Schlenk line for further drying. The product was analysed by FTIR and NMR spectroscopy.

Results and discussion

Background and preliminary results

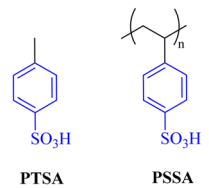
We have recently launched a new MSc Sustainable Chemistry programme at the Department of Chemistry at University College London (UCL).[23] As part of this initiative, several student-led research projects have investigated the use of recyclable solid acid catalysts for the synthesis of chemical products of interest derived from biobased and platform chemicals originating from lignocellulosic biomass.

p-Toluenesulfonic acid (PTSA) is a well-known organic sulfonic acid widely used in organic synthesis and catalysis.[25] Polystyrene sulfonic acid (PSSA) resins are polymeric materials whose repeating units share the same core structure as PTSA (Scheme 1). While PTSA is typically employed as a homogeneous catalyst and is rarely recycled, PSSA resins are insoluble in most organic solvents commonly used in synthesis, making them suitable candidates for heterogeneous catalysis.

We hypothesised that commercially available PSSA (c-PSSA) resins could replicate the catalytic behaviour of PTSA in synthetic transformations. To test this, we focused on the synthesis of biofuel precursor molecule **3a**, which can be obtained *via* a Friedel–Crafts reaction between biobased starting materials furfural (**1a**) and 2-methylfuran (**2**) (Table 1). A structurally similar biofuel precursor **3b** has previously been synthesised from 5-methylfurfural (**1b**) by Corma and collaborators using PTSA,[26] while precursor **3a** was prepared by Li and colleagues using sulfamic acid, another sulfonic acid-based catalyst.[27] In both protocols, 2-methylfuran (**2**) was used as both the reactant and solvent, with catalyst loadings of 5 mol% and 10 mol%, respectively (Table 1).

For our initial screening, we adopted conditions similar to those used by Corma, employing 5 mol% of c-PSSA resin. After conditioning, the resin exhibited a degree of sulfonation (measured as H^+ per g of resin) of 90%. The reaction catalysed by PTSA reportedly yields 93% of the structurally related biofuel precursor **3b**, while the sulfamic acid catalysed reaction yields 46% of precursor **3a.** Under our conditions, using c-PSSA resin, we achieved a quantitative isolated yield of precursor **3a** after 2 hours at 70 °C, thereby validating our initial hypothesis.

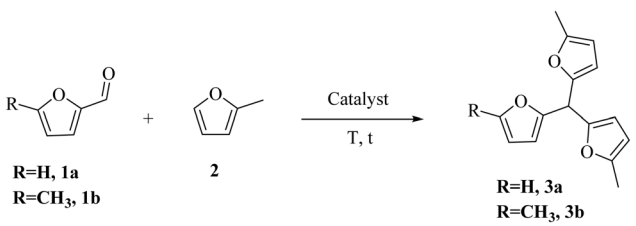
With our optimised conditions, we extended the scope of the c-PSSA catalysed Friedel–Crafts reaction to 2-methylfuran with various α-aryl aldehydes (Table 2). The reaction performed exceptionally well, delivering very high to quantitative yields in



PTSA PSSA

Scheme 1 Structures of PTSA and PSSA resin sharing the same core structure (highlighted in blue).

Table 1 Comparison of methodologies for the synthesis of biofuel precursors **3a** and **3b**



R=H, 1a
R=CH3, 1b

2

R=H, 3a
R=CH3, 3b

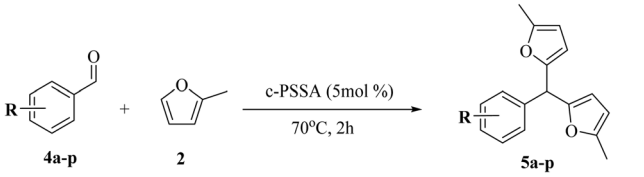
Entry	Catalyst	*T* (°C)	*t* (h)	Product	Yield[b] (%)	Reference
1	PTSA (5 mol%)	50	6	**3b**	93	Corma[26]
2	Sulfamic acid (10 mol%)	70	4	**3a**	46	Li[27]
3[a]	c-PSSA (5 mol%)	70	2	**3a**	>99	This work

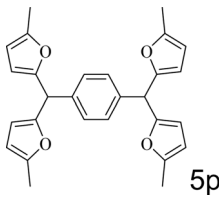
[a] Reaction conditions: furfural, **1a** (0.5 mmol), 2-methylfuran, **2**, 0.5 mL, catalyst c-PSSA (5 mg). [b] Isolated yield.

© 2026 The Author(s). Published by the Royal Society of Chemistry

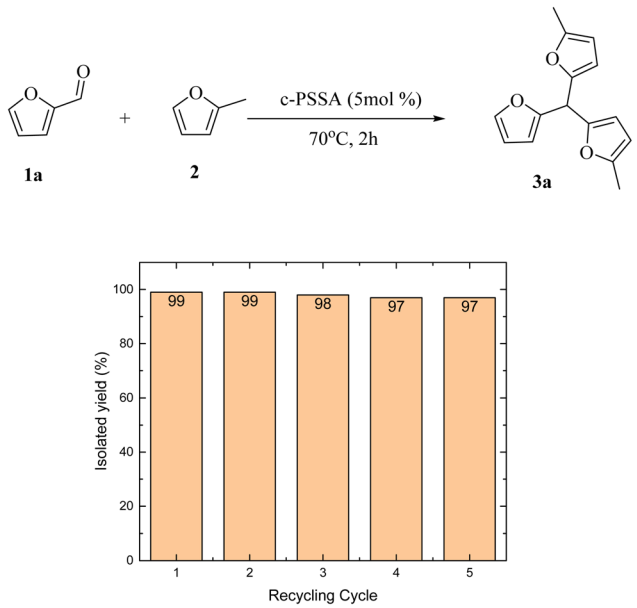
Open Access Article. Published on 19 March 2026. Downloaded on 5/2/2026 10:32:42 AM. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Table 2 Scope of the reaction of 2-methylfuran with α-aryl aldehydes catalysed by c-PSSA



Entry	R	Yield[a,b] (%)	Product
1	H, **4a**	>99	**5a**
2	*p*-CH_3, **4b**	94	**5b**
3	*o*-CH_3, **4c**	>99	**5c**
4	*m*-CH_3, **4d**	>99	**5d**
5	*p*-OCH_3, **4e**	>99	**5e**[c]
6	3-CH_3 4-CH_3, **4f**	>99	**5f**
7	*p*-F, **4g**	>99	**5g**
8	*p*-Cl, **4g**	>99	**5h**
9	*p*-Br, **4i**	>99	**5i**
10	*o*-Br, **4j**	>99	**5j**
11	*m*-Br, **4k**	83	**5k**
12	*p*-NO_2, **4l**	94	**5l**
13	*m*-CF_3, **4m**	>99	**5m**
14	3-CF_3 5-CF_3, **4n**	>99	**5n**
15	2-Cl 5-CF_3, **4o**	93	**5o**
16	*p*-CHO, **4p**	>99	 5p

[a] Reaction conditions: α-aryl aldehyde (0.5 mmol), 2-methylfuran 0.5 mL, catalyst c-PSSA (5 mg). [b] Isolated yield. [c] 3.5 h.



Scheme 2 c-PSSA recycle study for the synthesis of biofuel precursor **3a**. Reaction conditions: furfural, **1a** (0.5 mmol), 2-methylfuran, **2**, 0.5 mL, catalyst c-PSSA (5 mg). Yields obtained after purification *via* column chromatography.

most cases, regardless of the substitution pattern or the nature of the substituents on the aromatic ring. Substrates bearing electron-donating groups (entries 2–6) or electron withdrawing groups (entries 7–16) showed little influence on the reaction outcome. Only *m*-bromobenzaldehyde (**4k**, entry 11) exhibited a noticeable effect, giving a lower yield of 83% for product **5k** compared to the other examples. When using anisaldehyde (**4e**, entry 5), the reaction required slightly longer times, 3.5 h *versus* the standard 2 h, to achieve full conversion. Interestingly, terephthalaldehyde (**4p**, entry 16), which contains two aldehyde groups, also reached complete conversion to product **5p** within the same timeframe.

Importantly, the insolubility of c-PSSA in 2-methylfuran enabled straightforward recovery of the catalyst *via* filtration. c-PSSA was successfully reused in five consecutive catalytic cycles for the synthesis of **3a** without any observable loss in activity (Scheme 2), demonstrating its potential for sustainable and efficient catalysis in biomass-derived chemical synthesis.

We also explored the Friedel–Crafts reaction of 2-methylfuran (**2**) with aliphatic substrates (Table 3). Compared to α-aryl aldehydes, these substrates required longer reaction times and generally afforded moderate to good yields. Butanal (**6a**, entry 1) produced **7a** in 71% after 6 hours at 60 °C. Under similar conditions, acetone (**6b**, entry 2) gave **7b** with a yield of 67% yield. Aldehyde **6c** (entry 3), formed *in situ* from 2-methylfuran in the presence of water, yielded **7c** in 82% after 24 hours of reaction.

These results indicate that while c-PSSA is highly effective for aromatic aldehydes, its performance with aliphatic substrates is more limited, likely due to reduced electrophilicity. Nonetheless, the ability to catalyse these transformations under mild conditions further demonstrates the versatility of c-PSSA as a heterogeneous acid catalyst.

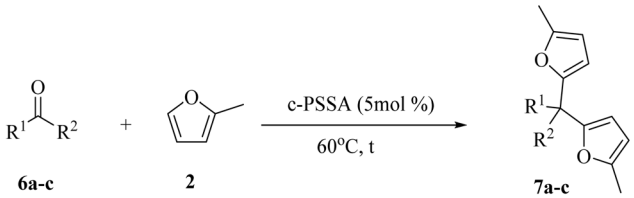
Student–staff partnership model of the RECOMPENSE project

Embedding sustainability into chemical education requires more than the delivery of technical content, it calls for active collaboration between educators and students. Co-creation offers a powerful way to achieve this, enabling students to move from passive recipients of knowledge to partners in designing solutions for real-world challenges.[28] By involving students in research and resource development, educators foster ownership, creativity, and systems-thinking skills that are essential for addressing global sustainability issues. This approach not only strengthens engagement and confidence but also aligns with the principles of green chemistry and open science, ensuring that educational activities deliver both academic and societal impact.

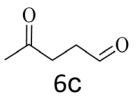
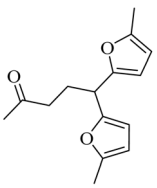
The RECOMPENSE project exemplifies this philosophy. Originating from the research projects in our MSc Sustainable Chemistry, the initiative explored whether polystyrene (PS), a material with an extremely low recycling rate, could be

Open Access Article. Published on 19 March 2026. Downloaded on 5/2/2026 10:32:42 AM. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Table 3 Reaction of 2-methylfuran with aliphatic substrates butanal (**6a**), acetone (**6b**), and **6c**



6a-c **2** **7a-c**

Entry	R^1	R^2	Substrate	t (h)	Yield[d] (%)	Product
1[a]	CH_3–CH_2–CH_2	H	**6a**	6	71	**7a**
2[b]	CH_3	CH_3	**6b**	6	67	**7b**
3[c]	CH_3–C(O)–CH_2–CH_2	H	 6c	24	82	 7c

[a] Reaction conditions: 2-methylfuran, **2** (0.5 mL), butanal, **6a** (0.17 mL), c-PSSA (10 mg). [b] Reaction conditions: 2-methylfuran, **2** (0.5 mL), acetone, **6b** (0.14 mL), c-PSSA (10 mg). [c] Reaction conditions: 2-methylfuran (0.5 mL), c-PSSA (0.5 mL, 18 wt% solution in H_2O). [d] Isolated yield.

upcycled into polystyrene sulfonic acid (u-PSSA) and replicate the catalytic performance of PTSA in organic synthesis, as demonstrated in our preliminary work with c-PSSA. This question ultimately led to the creation of RECOMPENSE, which stands for REcyclable Catalysts frOM PolystyrENe waStE, and was co-developed with our undergraduate chemistry students under the support of an RSC Sustainable Laboratories Grant.[29]

The overarching goal of RECOMPENSE is to provide an accessible and practical approach to upcycling PS waste in laboratories, while raising awareness and promoting sustainable practices within chemistry education and research. More specifically, the project aims to:

- Develop robust, user-friendly, and cost-effective protocols for sulfonating single-use PS waste generated in laboratories.
- Evaluate the catalytic performance of u-PSSA resins derived from PS waste in organic synthesis.
- Produce detailed protocols and characterisation data for all products and processes developed.
- Create a comprehensive database of u-PSSA applications to inspire new uses.
- Establish a free Open Science platform to share project findings and enable community contributions to expand the scope of u-PSSA applications from PS waste.

The project was developed through a combination of the preliminary results of postgraduate students' research projects from our MSc Sustainable Chemistry[23] and funded undergraduate summer internships from the Department of Chemistry at UCL and the RSC Sustainable Laboratories Grant.[29] Undergrad students were recruited through a formal application and interview process with selection criteria prioritising skills in video production, science communication, and digital/media literacy, skills the supervising academic did not possess, and which were essential for the open-science dissemination goals of the project. Successful applicants were employed full time over an 8 week funded summer internship and worked in partnership with the academic supervisor and MSc researchers. Their primary responsibilities included: (1) validating experimental results generated by MSc students, (2) producing written and video-recorded protocols, and designing, developing, and (3) maintaining the project website and YouTube channel.

A dedicated academic supervisor provided scientific oversight and led weekly progress meetings. However, day-to-day decisions in content development, communication strategy, video production, and platform design were driven by the students. This structure intentionally diverged from a traditional hierarchical supervision model and promoted partnership-led decision making. In this way, the project logistics were designed to support co-creation, not merely student assistance within an existing research programme.

To ensure that the initiative provided meaningful educational value to the partner undergrad students, clearly defined learning outcomes were established from the beginning of the project. Students were expected to develop both technical competencies and broader transferable skills aligned with the training of sustainability-focused chemists. Learning outcomes included the ability to:

- Develop technical skills in polymer handling, sulfonation chemistry, heterogeneous catalysis, and analytical characterisation.

- Apply systems thinking to understand the environmental implications of laboratory plastic waste and the life cycle of materials.

© 2026 The Author(s). Published by the Royal Society of Chemistry

Open Access Article. Published on 19 March 2026. Downloaded on 5/2/2026 10:32:42 AM. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Table 4 Comparison of traditional research supervision *vs.* RECOMPENSE's co-creation partnership model

	Traditional research supervision	Co-creation partnership model
Role of students	Assistants executing predefined experimental tasks	Co-developers shaping scientific, educational, and digital outputs
Project direction	Determined largely by supervisor. Students follow instructions	Developed collaboratively. Students influence research, communication, and dissemination
Nature of work	Focused on laboratory-based experimental tasks	Integration of laboratory work with open-science communication, media production, and resource development
Decision-making	Hierarchical, supervisor-led	Shared leadership. Student autonomy in creative and digital domains
Skill development focus	Experimental technique, data collection, lab routines	Systems thinking, communication, digital content creation, open science practices, alongside experimental research
Output ownership	Outputs typically remain within research group or academic publications	Outputs intentionally public-facing: website content, instructional videos, digital resources
Expertise contribution	Students contribute novice scientific labour	Students contribute expertise in communication, design, and media complementing scientific guidance
Educational philosophy	Apprenticeship: learning by following	Partnership: learning through co-creation and shared responsibility

- Engage with sustainability principles related to waste valorisation, resource efficiency, and green chemistry.

- Practise open science and science communication, including transparent documentation, protocol writing, video production, blogging, and social-media engagement for global audiences.

- Build professional identity by contributing to openly accessible resources, collaborating across levels of expertise, and working within an authentic research environment.

These outcomes exceed the scope of conventional undergraduate research placements, which typically emphasise laboratory technique or data generation but rarely integrate open-science practices, multi-modal communication, or sustainability-focused systems thinking.

The RECOMPENSE project diverges significantly from standard undergraduate research experiences. Rather than acting as assistants carrying out predefined tasks, students functioned as co-developers of the scientific, educational, and digital outputs central to the project. This required them to integrate laboratory research with the creation of public-facing resources, an expectation that is rarely present in traditional research roles. The supervisory relationship was also reconfigured: instead of a hierarchical model in which the academic directs all stages of the work, students and supervisor collaborated as equal partners, each contributing complementary forms of expertise. While the academic provided scientific oversight, the students led on communication strategy, video production, media design, and user-experience decisions. As a result, students held significant autonomy over the creative, digital, and dissemination components of the project, exemplifying a genuine shared-leadership model rather than a conventional research placement structure. A summary comparing traditional research supervision with the RECOMPENSE co-creation model is provided in Table 4.

Through this partnership model, the RECOMPENSE project demonstrates how an educational initiative can simultaneously advance sustainability research and support transformative student learning. Through collaboration between MSc students, undergraduate partners, and academic staff, the team has already developed a process for upcycling waste expanded PS from our wet teaching laboratories and demonstrated an application of u-PSSA for the synthesis of biofuel precursor **3a**, as described in the following sections. All associated educational resources, including written protocols, videos, and open-access materials, were created entirely by undergraduate partners and are freely available *via* our website[22] and YouTube channel[24] (see SI).

Preparation of u-PSSA from waste PS

The sulfonation of PS to produce PSSA has been widely reported in the literature.[12–21,30–33] However, many published protocols lack sufficient detail, and the isolation or purification of u-PSSA often requires specialised equipment that is not readily available in standard laboratory settings. Consequently, upcycling single-use PS waste into u-PSSA can be challenging in practice.

One of the first obstacles we faced was our limited experience working with polymers. We selected waste expanded PS as the starting material and evaluated several sulfonation procedures before identifying reproducible conditions that allowed us to isolate u-PSSA effectively. Working with expanded PS presents unexpected practical difficulties. A small mass occupies a disproportionately large volume, and cutting it into smaller pieces generates static charge, causing fragments to cling to surfaces and create considerable mess. These practical issues are rarely discussed in the literature. By first dissolving PS in ethyl acetate and then evaporating the solvent, the PS occupies a significantly smaller volume, making it much easier to handle.

Our optimised sulfonation conditions involve reacting 1 g of PS with 10 mL of concentrated sulfuric acid at 100 °C for 1.5

Open Access Article. Published on 19 March 2026. Downloaded on 5/2/2026 10:32:42 AM.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

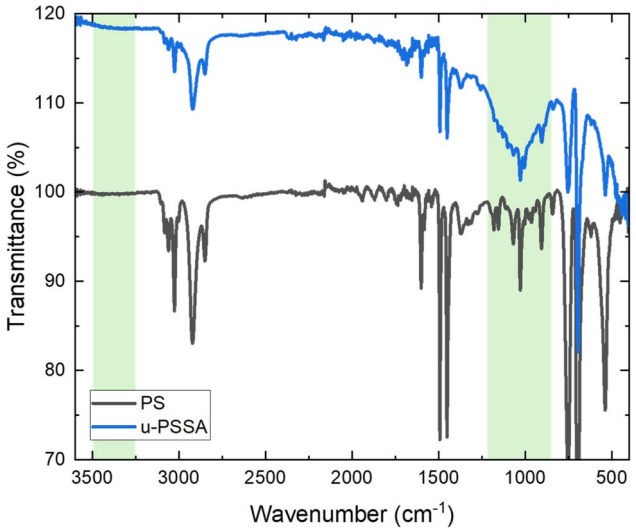


Fig. 1 Spectra of a waste expanded PS and u-PSSA showing a new O–H stretching band at 3370 cm^{-1} from the sulfonic acid functional group and sulfonate stretch bands between 950 and 1200 cm^{-1}. The new bands are highlighted in green. Note that the u-PSSA spectrum was offset by 20% on the *y*-axis for clarity.

hours. Extending the reaction to 2 hours increases the degree of sulfonation and homogeneity but complicates isolation for example through the use of dialysis membranes or other specialised techniques, which are not feasible in most teaching or research labs. In contrast, the RECOMPENSE project prioritises simplicity, affordability, and reproducibility.

Using our optimised conditions (see SI), we obtained u-PSSA samples with a degree of sulfonation ranging from 30% to 45%, measured as H^+ per gram of resin. Once the procedure was standardised, results became highly reproducible. Variability typically arose from incomplete contact between the PS and sulfuric acid.

To isolate the synthesised u-PSSA, the reaction mixture was carefully diluted with water in an ice bath, precipitating the u-PSSA as an insoluble solid. The material was filtered and washed repeatedly with water until the filtrate reached pH 7. After drying in an oven at 70 °C for 24 hours, a yellowish-white powder was recovered. The resulting u-PSSA was characterised by Fourier transform infrared spectroscopy (FTIR), nuclear magnetic resonance (NMR), and acid–base titration (see SI).

FTIR analysis (Fig. 1) of u-PSSA confirmed the successful sulfonation as evidenced by the broad band at 3370 cm^{-1}, corresponding to the O–H stretching vibrations of sulfonic acid (–SO_3H) groups, and distinctive bands in the 950–1200 cm^{-1} region, characteristic of sulfonate stretching vibrations. These features are absent in the original PS sample, consistent with previous reports.[12,34]

Despite the limited solubility of u-PSSA, it was possible to obtain ^{1}H-NMR and ^{13}C-NMR spectra in DMSO-d_6 (see SI), which further support the partial sulfonation of the starting waste PS material, consistent with previous reports in the literature.[18,21,35] Fig. 2A shows the ^{1}H-NMR spectrum, which features broad signals at 1.25, 1.50, and 1.80 ppm,

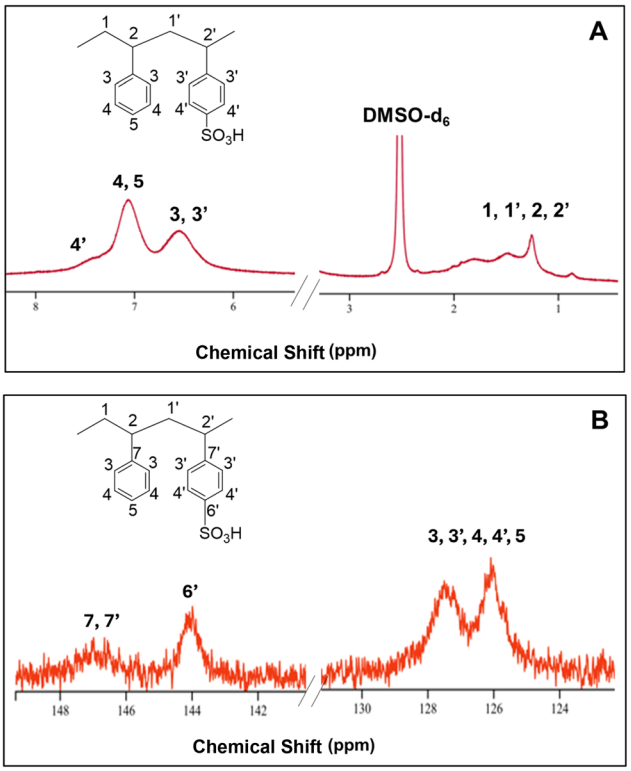


Fig. 2 (A) ^{1}H-NMR spectrum of u-PSSA in DMSO-d_6 showing the characteristic aliphatic and aromatic proton signals. (B) ^{13}C-NMR spectrum of u-PSSA in DMSO-d_6 highlighting the aromatic carbon signals. The aliphatic carbon peaks are not shown, as they are obscured by the residual DMSO-d_6 peak at around 40 ppm.

corresponding to aliphatic protons 1, 1′, 2, and 2′, as well as broad peaks in the aromatic region at 6.55, 7.07, and 7.47 ppm, assigned to protons 3, 3′, 4, 4′, and 5. Fig. 2B displays the corresponding ^{13}C-NMR spectrum, which shows aromatic carbon signals at 126.1, 127.5, 143.9, and 146.9 ppm, corresponding to carbon atoms 3, 3′, 4, 4′, 5, 6′, 7, and 7′. The aliphatic carbon signals are expected to appear around 40 ppm,[35] but their low intensity causes them to be obscured by the residual DMSO-d_6 peak.

It is important to note that u-PSSA obtained from post-consumer expanded polystyrene is unlikely to be structurally uniform. Under the strong sulfonation conditions employed, the resulting material may contain partially sulfonated domains, regions of variable crosslinking, residual unsulfonated polystyrene, and low-molecular-weight sulfonated fragments. Consequently, the FTIR spectra presented here should be interpreted as reflecting the averaged response of a heterogeneous bulk material rather than a single well-defined polymer structure. Similarly, the solution-state NMR spectra necessarily represent only the soluble fraction of u-PSSA; they cannot fully capture the composition of the insoluble crosslinked network, which would be more appropriately analysed using solid-state NMR techniques. These intrinsic limitations do not affect the reproducibility of the synthesis described, but they highlight the structural complexity expected for waste-derived PSSA materials.

© 2026 The Author(s). Published by the Royal Society of Chemistry

Open Access Article. Published on 19 March 2026. Downloaded on 5/2/2026 10:32:42 AM.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

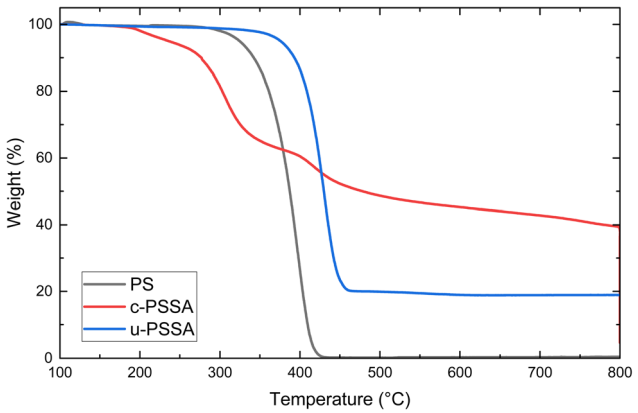


Fig. 3 TGA thermograms of all three polymers, heated at a heating rate of 10 °C min^{-1} from 100 to 800 °C under a nitrogen atmosphere (flow rate: 25 mL min^{-1}).

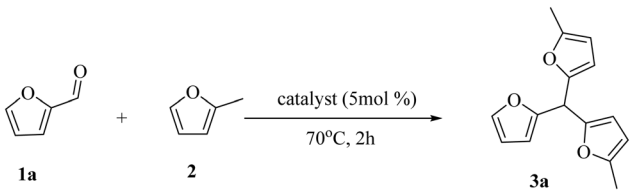
The thermal stability of the different polymers was evaluated by thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). PS started decomposing at around 300 °C during the TGA measurements (see Fig. 3). Interestingly, c-PSSA showed a much lower degradation onset (190 °C), whilst the synthesised u-PSSA only started decomposing at 390 °C. We hypothesise that the differences in decomposition temperature between the c-PSSA and u-PSSA are primarily caused by differences in molecular weight as well as variations in cross-linking densities between the two samples. Furthermore, the TGA measurements revealed significant differences in residual weight for c-PSSA (40%) and u-PSSA (20%) when heated under nitrogen atmosphere to 800 °C. Only after switching to an oxidative atmosphere, c-PSSA started fulling degrading with a residual weight of less than 5%. The u-PSSA sample however was unaffected by the oxidative atmosphere, and no additional weight loss was observed. This observation was unexpected, and we are uncertain about the origins of the differences in terminal weight. One possibility could be that the u-PSSA sample contains a large amount of sulphate salts, left-overs from the synthetic process, which resulted in the larger terminal weight value. To further investigate the thermal properties, we recorded the DSC thermograms of all polymer samples (see Fig. S13–S15 in the SI). Both the PS and u-PSSA sample displayed glass transition temperatures (T_g) at 110 °C in the second heating cycle, whereas not transitions were observed for the c-PSSA sample, further highlighting some fundamental structural differences between the samples, in line with the TGA data discussed previously.

A fully documented and video-recorded protocol for the synthesis of u-PSSA, prepared by our chemistry students, is available on the RECOMPENSE website.[36]

Application of u-PSSA in Friedel–Crafts reactions with 2-methylfuran

After establishing a reproducible process for preparing u-PSSA from waste expanded PS, we evaluated its catalytic performance in the synthesis of biofuel precursor **3a**, comparing the results with those obtained using c-PSSA. Given the expected structural heterogeneity of u-PSSA, its comparison with c-PSSA in catalytic tests is intended to be functional rather than structural. Although both materials contain aryl-sulfonic acid groups, the underlying polymer architectures are not expected to be identical.

Table 5 Comparison of catalytic activities of c-PSSA and u-PSSA for the synthesis of biofuel precursors **3a**



Entry	Catalyst	Yield[c] (%)
1[a]	c-PSSA	>99
2[b]	u-PSSA	>99

[a] Reaction conditions: furfural, **1a** (0.5 mmol), 2-methylfuran, **2**, 0.5 mL, catalyst c-PSSA (5 mg). [b] Reaction conditions: furfural, **1a** (0.5 mmol), 2-methylfuran, **2**, 0.5 mL, catalyst u-PSSA (10 mg). [c] Isolated yield.

To ensure reproducibility, all catalytic experiments were performed using a single u-PSSA batch with a sulfonation degree of 44% (corresponding to 2.37 mmol of H^+ per gram of resin), and each reaction was carried out in at least triplicate for every substrate tested. Under the same conditions previously applied to c-PSSA, the reaction proceeded efficiently on a 0.5 mmol scale of furfural (**1a**), using 0.5 mL of 2-methylfuran (**2**) as both solvent and reactant. With 5 mol% of u-PSSA, the reaction reached completion within 2 hours, affording the product **3a** in quantitative yield (entry 2, Table 5). Since u-PSSA was insoluble, it was easily recovered by vacuum filtration. These results demonstrate that upcycling PS waste into solid acid catalysts for organic synthesis is a viable strategy, as u-PSSA performs comparably to c-PSSA under the tested conditions.

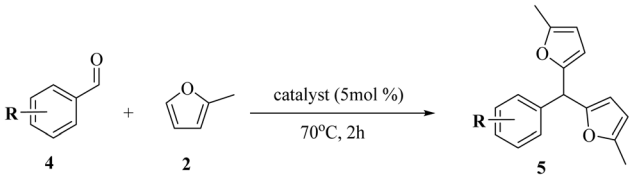
A fully documented and video-recorded protocol for the synthesis of **3a** using u-PSSA, prepared by our chemistry students, is available on the RECOMPENSE website.[37]

We further evaluated u-PSSA in Friedel–Crafts reactions involving α-aryl aldehydes, benzaldehyde (**4a**), *p*-anisaldehyde (**4c**), and *p*-bromobenzaldehyde (**4i**), and compared the results with those obtained using c-PSSA. Overall, u-PSSA demonstrated similar efficiency to c-PSSA under the tested conditions (Table 6). Products **5a** and **5i** (entries 1, 2 and 5, 6) were obtained using u-PSSA with comparable reaction times and yields. However, twice the amount of u-PSSA was required, reflecting its lower sulfonation degree (44%) compared to c-PSSA (90%). Interestingly, for *p*-anisaldehyde (entries 3 and 4), u-PSSA delivered a faster reaction but a slightly lower yield.

We cannot fully exclude the possibility of partial dissolution or leaching of low-molecular-weight sulfonated fragments from u-PSSA under the reaction conditions. If such leaching occurs, a fraction of the observed catalytic activity may originate from a homogeneous acid contribution rather than exclusively from the solid polymer network. While the high recyclability observed for c-PSSA suggests predominantly heterogeneous

Open Access Article. Published on 19 March 2026. Downloaded on 5/2/2026 10:32:42 AM. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Table 6 Comparison of catalytic activities of c-PSSA and u-PSSA for the synthesis of Friedel–Crafts products **5a**, **5c** and **5i**



Entry	R	Substrate	Catalyst	Time (h)	Yield[c] (%)	Product
1[a]	H	Benzaldehyde, **4a**	c-PSSA	2	>99	**5a**
2[b]	H	Benzaldehyde, **4a**	u-PSSA	2	>99	**5a**
3[a]	*p*-OMe	*p*-Anisaldehyde, **4c**	c-PSSA	3.5	>99	**5c**
4[b]	*p*-OMe	*p*-Anisaldehyde, **4c**	u-PSSA	2	93	**5c**
5[a]	*p*-Br	*p*-Bromobenzaldehyde, **4i**	c-PSSA	2	>99	**5i**
6[b]	*p*-Br	*p*-Bromobenzaldehyde, **4i**	u-PSSA	2	>99	**5i**

[a] Reaction conditions: α-aryl aldehyde (0.5 mmol), 2-methylfuran 0.5 mL, catalyst c-PSSA (5 mg). [b] Reaction conditions: α-aryl aldehyde (0.5 mmol), 2-methylfuran 0.5 mL, catalyst u-PSSA (10 mg). [c] Isolated yield.

behaviour, the behaviour of waste-derived u-PSSA may differ due to its greater structural heterogeneity. A more detailed assessment, including hot-filtration experiments, leaching tests, and acidity quantification of recovered filtrates, will be pursued in future work.

Further applications of u-PSSA in organic synthesis are currently under development and will be uploaded to the RECOMPENSE website[22] and YouTube channel[24] in due course.

Conclusions and future outlook

This work demonstrates that polystyrene waste, one of the least recycled plastics globally, can be successfully upcycled into polystyrene sulfonic acid (u-PSSA) and applied as a heterogeneous catalyst in organic synthesis. The RECOMPENSE project not only provides a practical and reproducible protocol for this transformation but also integrates sustainability into chemical education through open science and student-led research. Our findings confirm that u-PSSA performs comparably to commercial PSSA in key Friedel–Crafts reactions, validating the potential of waste-derived catalysts for green chemistry applications. Future studies will involve a more comprehensive evaluation of the heterogeneous nature of u-PSSA. Planned analyses include solid-state NMR, elemental sulfur analysis, NH_3-TPD acidity measurements, and hot-filtration or leaching tests to distinguish heterogeneous from homogeneous contributions to catalytic activity. We also intend to carry out expanded recyclability and durability assessments under a range of reaction conditions. These studies are beyond the scope of the present education-focused work but will be essential for fully establishing u-PSSA as a robust waste-derived catalyst.

Beyond technical achievements, RECOMPENSE highlights the transformative role of collaboration and co-creation in advancing sustainable chemistry. By engaging students as active partners in research and resource development, we foster ownership, creativity, and systems-thinking skills essential for addressing global challenges. This approach strengthens the link between education and research, ensuring that sustainability principles are embedded in both practice and pedagogy.

Looking ahead, the success of RECOMPENSE depends on expanding its reach and impact through community engagement. Our open-access platform has already attracted visitors from more than 20 countries, reflecting strong international interest in accessible, sustainable solutions. We aim to build on this momentum by inviting contributions from educators, researchers, and students worldwide to co-develop new protocols, share case studies, and explore innovative applications of u-PSSA. Future work will focus on broadening the scope of reactions catalysed by u-PSSA, improving sulfonation efficiency, and integrating digital tools to enhance resource accessibility.

By combining technical innovation with educational collaboration, RECOMPENSE sets a precedent for how chemistry can contribute to a circular economy while preparing the next generation of scientists to lead the transition toward sustainability.

Author contributions

Victoria Lageard: data curation, investigation, methodology, writing – review & editing. YuHan Yan: data curation, investigation, methodology, writing – review & editing. Jiayin Liu: data curation, investigation, methodology, writing – review & editing. Yueze Gong: data curation, investigation, methodology, writing – review & editing. Shuoxi Liu: data curation, investigation, methodology, writing – review & editing. Bob C. Schroeder: data curation, formal analysis, investigation, methodology, resources, writing – review & editing. David Palomas: conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, writing – original draft, writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

© 2026 The Author(s). Published by the Royal Society of Chemistry

Open Access Article. Published on 19 March 2026. Downloaded on 5/2/2026 10:32:42 AM. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information: general procedures, full characterization of both the catalyst and the synthesized compounds. General procedures and video recorded protocols are also freely available on the RECOMPENSE project website: https://recompenseproject.com/ and YouTube channel: https://www.youtube.com/@RECOMPENSEproject. See DOI: https://doi.org/10.1039/d5su00927h.

Acknowledgements

The authors are thankful to the Department of Chemistry at UCL for support. This research was supported by a Royal Society of Chemistry (RSC) Sustainable Laboratories Grant (L24-1620176060). YG is grateful for a departmental summer internship. JL and SL are grateful for summer internships supported by the RSC Sustainable Laboratories Grant. BCS acknowledges financial support from the UKRI Future Leaders Fellowship (grant MR/Y003802/1).

References

1 European Commission, *A European Strategy for Plastics in a Circular Economy*, 2018.
2 Plastics Europe, *Plastics – the Facts 2021*, https://plasticseurope.org/knowledge-hub/plastics-the-facts-2021/, accessed 18 November 2025.
3 UNEP – UN Environment Programme, *Plastic pollution*, https://www.unep.org/topics/chemicals-and-pollution-action/plastic-pollution, accessed 18 November 2025.
4 M. a. Urbina, A. J. R. Watts and E. Erin, *Nature*, 2015, **528**, 479.
5 T. Freese, N. Elzinga, M. Heinemann, M. M. Lerch and B. L. Feringa, *RSC Sustainability*, 2024, **2**, 1300–1336.
6 A. H. Tullo, *Chem. Eng. News*, 2019, **97**, 29–34.
7 C. P. Rader, S. D. Baldwin, D. D. Cornell, G. D. Sadler and R. F. Stockel, in *ACS Symposium Series*, 1995, vol. 609, pp. 89–96.
8 A. Ravve, *Principles of Polymer Chemistry*, Springer New York, New York, NY, 2012.
9 H. Lei, Z. Wang, S. Li and M. Zhu, *Green Chem.*, 2025, **27**, 9357–9413.
10 D. Xu, H. Wang, K. Zhang, Z. Ya, H. Wang and S. Zhang, *Environ. Sci. Technol.*, 2025, **59**, 16112–16129.
11 Z. Xu, D. Sun, J. Xu, R. Yang, J. D. Russell and G. Liu, *ChemSusChem*, 2024, **17**, e202400474.
12 I. Bekri-Abbes, S. Bayoudh, M. Baklouti, E. Papon and D. LeClercq, *Prog. Rubber, Plast. Recycl. Technol.*, 2006, **22**, 179–193.
13 H. Tabekh, M. H. Al Kurdi and Z. Ajji, *Polimeri*, 2015, **36**, 11–14.
14 A. E. El-Tabey, A. H. Mady, O. A. A. El-Shamy and A. A. Ragab, *Polym. Bull.*, 2021, **78**, 951–963.
15 M. E. Mahmoud, A. E. H. Abdou and S. B. Ahmed, *ACS Sustain. Chem. Eng.*, 2016, **4**, 819–827.
16 N. H. Aprilita, T. F. P. Ofens, M. Nora, T. A. Nassir and E. T. Wahyuni, *Global NEST J.*, 2024, **26**, 1–10.
17 C. Vieira Grossi, E. de Oliveira Jardim, M. H. de Araújo, R. M. Lago and M. J. da Silva, *Fuel*, 2010, **89**, 257–259.
18 N. Alonso-Fagúndez, V. Laserna, A. C. Alba-Rubio, M. Mengibar, A. Heras, R. Mariscal and M. L. Granados, *Catal. Today*, 2014, **234**, 285–294.
19 C. W. S. Yeung, W. W. Loh, H. H. Lau, X. J. Loh and J. Y. C. Lim, *Mater. Today Chem.*, 2021, **21**, 100524.
20 M. S. P. Ribeiro, R. R. S. Pinto, K. A. da Silva Rocha and C. G. Vieira, *Waste Biomass Valorization*, 2021, **12**, 4695–4702.
21 B. Moazzen, R. Kamrouz and A. Khorshidi, *Sci. Rep.*, 2025, **15**, 250.
22 RECOMPENSE Project, *An Open Science platform for DIY protocols to use upcycled Polystyrene waste in Organic Synthesis*, https://recompenseproject.com/, accessed 18 November 2025.
23 Faculty of Mathematical & Physical Sciences, *MSc Sustainable Chemistry*, https://www.ucl.ac.uk/mathematical-physical-sciences/chemistry/study/postgraduate-taught/msc-sustainable-chemistry, accessed 18 November 2025.
24 YouTube, *RECOMPENSE project*, https://www.youtube.com/@RECOMPENSEproject, accessed 18 November 2025.
25 S. Pal, D. Das and S. Bhunia, *Org. Biomol. Chem.*, 2024, **22**, 1527–1579.
26 A. Corma, O. de la Torre, M. Renz and N. Villandier, *Angew. Chem., Int. Ed.*, 2011, **50**, 2375–2378.
27 Z. Li, X. Liu, Y. Yin, Y. Li, J. Wang and X. Yu, *ChemistrySelect*, 2018, **3**, 599–601.
28 G. A. Hurst, *Nat. Rev. Chem.*, 2024, **8**, 717–718.
29 Sustainable Laboratories Grant, https://www.rsc.org/funding-and-support/funding/sustainable-laboratories-grant, accessed 18 November 2025.
30 H. Vink, *Die Makromolekulare Chemie*, 1981, **182**, 279–281.
31 A. E. Holboke and R. P. Pinnell, *J. Chem. Educ.*, 1989, **66**, 613.
32 D. Baigl, T. A. P. Seery and C. E. Williams, *Macromolecules*, 2002, **35**, 2318–2326.
33 C.-Y. Lo, K. P. Koutsoukos, D. M. Nguyen, Y. Wu, D. A. Angel Trujillo, T. Miller, T. Shrestha, E. Mackey, V. S. Damani, U. Kanbur, R. Opila, D. C. Martin, D. Kaphan and L. V. Kayser, *JACS Au*, 2024, **4**, 2596–2605.
34 X. Zhang, Y. Zhao, S. Xu, Y. Yang, J. Liu, Y. Wei and Q. Yang, *Nat. Commun.*, 2014, **5**, 3170.
35 J. E. Coughlin, A. Reisch, M. Z. Markarian and J. B. Schlenoff, *J. Polym. Sci., Part A: Polym. Chem.*, 2013, **51**, 2416–2424.
36 RECOMPENSE Project, *Synthesis of Polystyrene Sulfonic Acid from waste expanded Polystyrene*, https://recompenseproject.com/2025/10/24/synthesis-of-polystyrene-sulfonic-acid-from-waste-expanded-polystyrene/, accessed 18 November 2025.
37 RECOMPENSE Project, *Synthesis of Biofuel precursor with a Polystyrene sulfonic acid resin from waste Polystyrene*, https://recompenseproject.com/2025/10/25/synthesis-of-biofuel-precursor-with-a-polystyrene-sulfonic-acid-resin-from-waste-polystyrene/, accessed 18 November 2025.

© 2026 The Author(s). Published by the Royal Society of Chemistry