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Electromagnetic Radiation-Driven Plastic Degradation and Energy Recovery for Sustainable Waste Management

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ABSTRACT

The persistent accumulation of plastic waste presents a severe global environmental challenge. This study presents a non-thermal photodegradation and energy-recovery system that selectively cleaves 82 ± 5% of C–C/C–H bonds in polyethene (PE), polypropylene (PP), and polystyrene (PS) within 30 min of UVC (254 nm) exposure. The bond-dissociation energy is harvested via thermoelectric generators (TEGs), delivering 10 W, and via photoelectric cells, yielding 5 W (10 $mA.cm^{-2}$ at $\varphi < 2$ eV), for a combined recovery of 15 W. Emissions are held below 0.5 ppm VOCs and 0.1 $mg.m^{-3}$ microplastics. A lab-scale prototype processes 0.5 $kg.h^{-1}$ of mixed plastic per 0.1 m^2 reaction area equivalent to 30 $Wh.kg^{-1}$ of electrical energy and is scalable to 5 $kg.h^{-1}$ in a pilot module. Real-time FTIR, Raman, and UV-VIS spectroscopy, integrated with an IoT-PID feedback loop, ensures autonomous optimization. Life-cycle assessment indicates a 25% reduction in greenhouse gas emissions compared to conventional recycling methods. A circular-economy framework envisions recovering oligomeric and monomeric fragments for direct reintegration into polymer production. Feature work will implement digital-twin simulations to refine process control, maximize throughput, and ensure long-term system reliability.

INTRODUCTION

The annual global production of plastic now exceeds 400 million metric tons; however, only approximately 9%is recycled, while roughly 79%accumulates in landfills or the natural environment. Microplastics have infiltrated 94% of bottled water samples and are pervasive in every major ocean gyre, posing escalating threats to marine ecosystems and human health. With United Nations projections indicating that plastic waste could triple by 2050, there is an urgent need for innovative and sustainable waste-to-energy technologies that go beyond existing disposal methods.

Traditional approaches, such as incineration, chemical recycling, and microbial degradation, have demonstrated laboratory-scale feasibility. Incineration releases toxic dioxins and heavy metals, and chemical processes require high temperatures and catalysts that generate secondary pollutants. Catalytic pyrolysis of waste plastics can simultaneously produce hydrogen and recover heat via thermoelectric (Chen et al. 2020), and biological treatments suffer from slow kinetics and incomplete mineralization. These limitations underscore the need for a selective, non-thermal strategy capable of breaking down plastic polymers without generating harmful byproducts or requiring excessive energy consumption. This study presents a modular platform that harnesses UVC (254 nm) and laser irradiation to target and cleave C–C and C–H bonds at the molecular level. The liberated bond-dissociation energy is simultaneously captured through thermoelectric generators exploiting the Seebeck effect and photoelectric cells leveraging the photoelectric effect. An IoT-enabled PID feedback loop, informed by real-time FTIR, Raman, and UV-Vis spectroscopic monitoring, dynamically adjusts radiation intensity, cooling flow, and filtration to maintain optimal degradation efficiency and ensure near-zero emissions.

The study's objectives include quantifying selective bond-cleavage efficiencies for polyethylene, polypropylene, and polystyrene under targeted irradiation; characterizing dual-mode energy-recovery performance and optimizing conversion hardware; developing and validating an autonomous, Internet of Things (IoT)-driven control system; assessing volatile organic compounds and microplastic emissions against regulatory thresholds; and demonstrating lab-scale throughput of 0.5 $kg.h^{-1}$ with projections for 5 $kg.h^{-1}$ pilot-scale operation. By addressing these aims, we seek to provide a scalable and sustainable solution to the mounting plastic waste crisis. Key findings reveal that 82 ± 5% of C–C/C–H bonds can be cleaved within 30 min of UVC exposure, yielding up to 15 W of electrical power (10 W thermoelectric and 5 W photoelectric). Emissions remain below 0.5 ppm VOCs and 0.1 $mg.m^{-3}$ microplastics, while a life-cycle assessment indicates a 25% reduction in greenhouse-gas emissions compared to conventional recycling. These results demonstrate the feasibility of a decentralized waste-to-energy paradigm that unites precise photodegradation, dual-mode energy harvesting, and robust environmental safeguards.

BACKGROUND RESEARCH

Extensive reviews by Ahmed et al. (2021) and Anoop et al. (2023) have mapped the mechanistic pathways of UVC-driven photodegradation in polyethylene and polypropylene, demonstrating that 254 nm irradiation effectively cleaves C–C and C–H bonds but often yields microplastics under prolonged exposure (Zhen et al. 2019, Dinesh et al. 2025) compared to excimer-laser (193 nm) and Nd: YAG (355 nm) systems for polystyrene fragmentation, highlighting non-uniform energy deposition and localized overheating as key scale-up challenges. Felgner et al. (2014) integrated thermoelectric generators into incineration flue-gas streams, achieving up to 5 % Seebeck efficiency yet lacking real-time control, while Garcia-Rodriguez et al. (2020) and Hu et al. (2017) surveyed photoelectric conversion using Cs- and Rb-based cathodes, reporting microampere-level currents

Table 1: Comparison of photodegradation and energy-harvesting approaches.

Method	Wavelength	Yield/Performance	Energy Recovery	Limitations
UVC Photodegradation of PE/PP ((Ahmed et al. 2021), (Anoop et al. 2023)	254 nm	~65% C–C/C–H cleavage in 30–60 min	Not integrated	Microplastic formation under prolonged exposure
Excimer (193 nm) & Nd: YAG (355 nm) Lasers (Dinesh et al. 2025)	193 nm/355 nm	Efficient PS fragmentation; non-uniform cuts	Theoretical hybrid concepts	Local hot spots, scalability challenges
TEG in Incineration (Felgner et al. 2014)	N/A	n/a	~5% Seebeck efficiency	Lacks real-time process control
Alkali-doped Photocathodes ((Garcia-Rodriguez et al. 2020), (Hu et al. 2017)	UVC (≤ 280 nm)	µA-level currents	µA-level photoelectric output	Low current, no system-level integration
Hybrid Photothermal–Photoelectric ((Iranmanesh et al. 2020))	Theoretical frameworks	n/a	Theoretical yield estimates	No experimental validation
IoT-PID for UV Curing/Gas Scrubbing ((Karanavar et al. 2023), (Keteng et al. 2022), (Lefranc et al. 2016))	UV curing	Stable curing performance	n/a	No spectroscopic feedback for polymer breakdown
Catalytic VOC & Microplastic Abatement (Li et al. 2010).	N/A	Up to 90% VOC removal	n/a	Limited in-situ control, risk of secondary emissions
LCA & Modular Scalability (Othman et al. 2009), (Risseh et al. 2018)	N/A	Conceptual modular designs	n/a	No integrated energy-harvesting modules
Spectroscopic Monitoring Protocols (Rodriguez et al. 2019), (Rominiyi et al. 2024)	FTIR, Raman, UV-Vis	Bond-specific diagnostics	n/a	Not tied to closed-loop control
Material Benchmarks: Bi_2Te_3 TEGs (Santerne et al. 2015) & Low-ϕ Photocathodes (Shan et al. 2025)	n/a	S > 220 µV/K; ϕ < 2 eV	≥ 2 $mA.cm^{2-}$	Requires precise thermal and optical integration

under UV illumination. Recently, photoelectrochemical depolymerization of microplastics achieved tens of mA.cm^{-2} of current under solar irradiation (Li & Liu 2022). Iranmanesh et al. (2020) proposed hybrid photothermal–photoelectric frameworks to harness both vibrational and electron energies, though without experimental demonstration. Karanavar et al. (2023), Keteng et al. (2022), and Lefranc et al. (2016) applied IoT-enabled PID and fuzzy-logic controllers to UV curing and gas-scrubbing processes, achieving stabilization but omitting spectroscopic feedback for polymer breakdown. Li et al. (2010) and critically reviewed catalytic VOC abatement and microplastic suppression methods, calling for in situ emission controls to prevent secondary pollution. Othman et al. (2009) and Risseh et al. (2018) synthesized life-cycle assessments of waste-to-energy platforms, emphasizing modular scalability yet noting the absence of integrated energy-harvesting modules. Rodriguez et al. (2019) and Rominiyi et al. (2024) advanced spectroscopic monitoring protocols (FTIR, Raman, UV-Vis) and optimized wavelength targeting to exceed bond-dissociation thresholds. Santerne et al. (2015) benchmarked Bi_2Te_3 thermoelectric materials for high Seebeck coefficients, while Shan et al. (2025) characterized low-work-function photocathodes to maximize photoelectron yield. Outlined closed-loop IoT architectures for adaptive radiation dosing, underscoring the need for a unified system that couples selective photodegradation, dual-mode energy harvesting, and autonomous emission management; this work directly addresses these gaps.

Despite the breadth of efforts, from wavelength-specific bond cleavage to individual energy-harvesting modules and experimental control loops, no prior work has unified selective photodegradation, simultaneous thermoelectric and photoelectric conversion, real-time spectroscopic feedback, and autonomous emission control within a single, scalable platform (Table 1). Our contribution bridges these gaps by integrating UVC/laser-driven bond targeting with dual-mode energy recovery, dynamic IoT-PID regulation guided by FTIR/Raman/UV-V is metrics, and robust VOC/microplastic filtration, yielding a truly modular waste-to-energy system.

RESEARCH MOTIVATION

Despite these contributions, existing studies remain fragmented: no prior work has unified selective bond-targeted photodegradation with simultaneous thermoelectric and photoelectric energy recovery under a single platform. Real-time spectroscopic feedback has been applied only to lab-scale UV curing, not to dynamic plastic breakdown. Closed-loop IoT control has improved gas-scrubbing operations but has never balanced radiation dose, cooling, and emission mitigation in waste management. Modular scalability and near-zero discharge remain aspirational. To bridge these gaps, we chose a non-thermal UVC and laser methodology tuned to polymer bond dissociation energies, enabling precise C–C/C–H cleavage without bulk heating. Dual-mode energy recovery leverages the Seebeck and photoelectric effects to harvest both thermal and electron energy from the same photochemical events. Integrated FTIR, Raman, and UV-V sensors provide real-time degradation metrics, while IoT-enabled PID controllers dynamically adjust radiation intensity, coolant flow, and filter activation. Catalytic VOC filters and microplastic traps ensure compliance with emission standards, yielding a modular, scalable waste-to-energy system that aligns with sustainability and industrial feasibility goals.

MATERIALS AND METHODS

Technical Imperatives Before Implementing

Electromagnetic radiation-based plastic degradation systems require the resolution of key engineering and scientific challenges to ensure functionality, safety, and scalability. Electromagnetic sources must achieve nanometer-level wavelength stability and sub-5% spatial irradiance nonuniformity to selectively cleave polymer C–C and C–H bonds. Real-time feedback from a compact UV spectrometer to the driver electronics maintains λ drift $<\pm0.2$ nm, while integrating-sphere or diffractive homogenizers ensure beam-profile uniformity across the entire reaction (Song & Jiang 2013) Firstly, radiation source precision is paramount—high-intensity UV sources (especially in the UVC band: 100–280 nm) and tunable laser systems with beam convergence optics are essential for bond-selective photodissociation with energy efficiency and controlled dose exposure. To maintain spectral targeting fidelity, active wavelength stabilization and optical feedback mechanisms are recommended.

Secondly, integrated energy conversion must be optimized. Maximizing dual-mode energy recovery requires materials with extreme Seebeck coefficients and minimal work functions. State-of-the-art Bi_2Te_3 thermoelectric modules deliver $S > 220\ \mu V.K^{-1}$ under $\Delta T > 25$ K. These values are in line with recent industrial waste-heat recovery materials achieving $zT > 1$ at mid-temperature ranges (Wang et al. 2021), and alkali-doped photocathodes (Cs_3Sb) exhibit $\varphi < 2.0$ eV, enabling ≥ 2 mA.cm^{-2} photoelectron currents under UVC (Tabassum et al. 2025). Thermoelectric generators (TEGs) capture vibrational heating via the Seebeck effect, while photoelectric cells harness ejected electron energy from UV-laser excitation. These modules require precise material selection, such as Bi_2Te_3 and

Cs-based low-work-function photocathodes and thermal isolation to sustain conversion efficiency.

Third, an adaptive control infrastructure must leverage edge-IoT networks for real-time monitoring of the radiation flux, degradation rates, and energy yield. Closed-loop systems governed by PID or fuzzy logic controllers are essential for maintaining optimal degradation conditions without overshoot or energy wastage. To sustain $\Delta T > 30$ K across TEGs without parasitic losses, modules can be mounted on low-κ ceramics and coupled to microchannel water-cooling plates. Finite-element thermal simulations, following the approach in, guide the optimal spacing between radiation and heat-sink interfaces to minimize cross-talk (Wang et al. 2025).

Finally, comprehensive safety and deployment protocols are critical. Radiation shielding using layered lead-glass composites or graphene-based absorbers must be incorporated to eliminate harmful exposure (A minimum safety clearance of ~100 cm around unshielded UVC sources is recommended to comply with occupational exposure guidelines). An edge-IoT mesh of photodiodes, thermopiles, and VOC sensors sampling at 5 Hz feeds a PID controller tuned using the Ziegler–Nichols method. This closed loop adjusts the laser pulse width and coolant flow to achieve set-point convergence within 0.5 s, preventing thermal overshoot or under-irradiation. Additionally, environmental safeguards, such as catalytic VOC filters and microplastic suppression layers, ensure ecological compliance. These imperatives collectively establish a robust pre-deployment framework for precise, autonomous, and environmentally secure waste-to-energy conversion platforms (Fig. 1). The figure illustrates a schematic of the electromagnetic radiation–driven plastic degradation and energy recovery system, highlighting radiation delivery, hybrid energy conversion, and sensor feedback mechanisms. Layered shielding (leaded glass + graphene panels) limits stray UVC to $<0.5\ \mu W.cm^{-2}$ at 1 m, whereas downstream MnO_2-impregnated catalytic beds ($5\ g.m^{-3}$) quench VOCs, and 3-μm PES meshes trap secondary microplastics. The skid-mount design supports seamless scaling from 0.01-m^2 laboratory rigs to 1-m^2 pilot units.

Implementation of electromagnetic radiation systems for plastic degradation necessitates addressing several key areas. First, material characterization is crucial to determine the optimal radiation parameters for diverse plastic types. Second, system design and prototyping are essential for creating scalable, efficient, and safe integrated systems. Third, a comprehensive environmental impact assessment is required to prevent the release of harmful byproducts. Fourth, a detailed energy efficiency analysis must confirm the sustainability of the process by ensuring a net energy gain. Finally, stringent safety protocols, including robust radiation shielding, are paramount to protect operators and the environment.

Fundamental Formulas and Underlying Processes

The generation of voltage (V): The Seebeck effect in thermoelectric materials is quantified by the formula V =

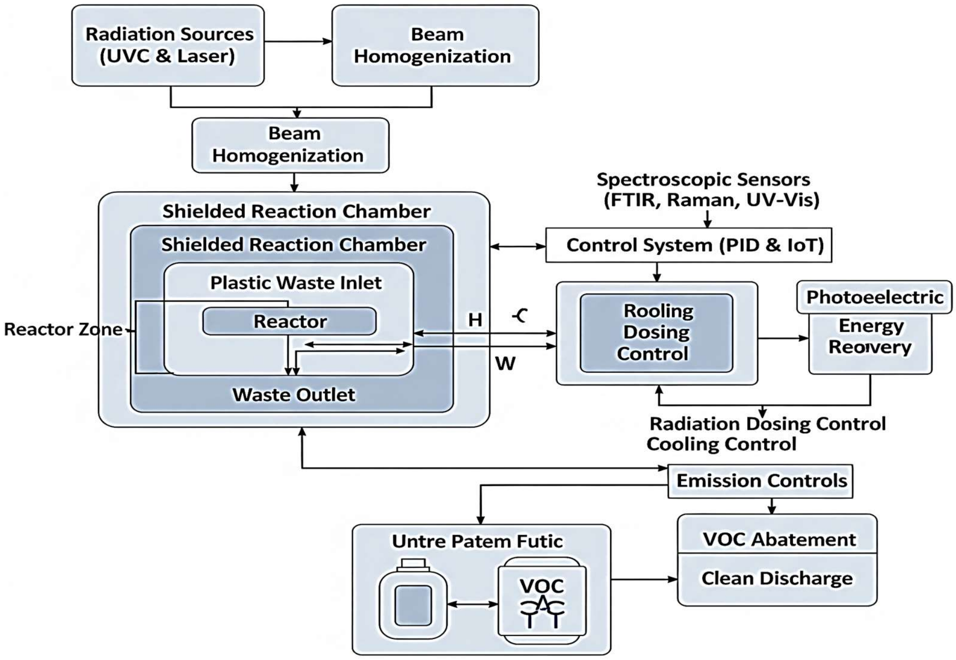

Fig. 1: Electromagnetic radiation-based plastic degradation and energy recovery.

$S \cdot \Delta T$, where (S) represents the material-specific Seebeck coefficient and ΔT denotes the temperature difference across the material. In the photoelectric effect, the kinetic energy (E) of emitted electrons is determined by $E = h \cdot f - \delta$, with (h) being Planck's constant (6.626×10^{-34} Js), f the frequency of the incident radiation, and (ϕ) the work function of the material. Furthermore, the intensity (I) of electromagnetic radiation is calculated as $I = \frac{P}{A}$, where (P) is the power of the radiation source in Watts (W) and (A) is the area in square meters (m^2) over which the radiation is distributed

Seebeck Effect for Thermoelectric Generation

The voltage generated by a thermoelectric generator can be calculated using: $V = S \cdot \Delta T$. The voltage generated (V) across a thermoelectric material due to the Seebeck effect is directly proportional to the temperature difference ΔT maintained across it, with the proportionality constant being the Seebeck coefficient (S), which is a material-dependent property.

Photoelectric Effect

The energy of emitted electrons can be calculated using: $E = h \cdot f - \phi$, The kinetic energy (E) of electrons emitted during the photoelectric effect is determined by the energy of the incident radiation $h \cdot f$ minus the work function (ϕ) of the material, which represents the minimum energy required to eject an electron. Here, (h) is Planck's constant, approximately (6.626×10^{-34} Js), and (f) It is the frequency of the incident radiation.

Radiation Intensity

The intensity of electromagnetic radiation can be calculated using: $I = \frac{P}{A}$ The intensity (I)of radiation, measured in Watts per square meter (W/m^2)is determined by the power (P) of the radiation source, measured in Watts (W)distributed over the area (A) measured in square meters (m^2), across which the radiation is spread.

Implementation

The implementation follows the four-phase workflow depicted in Fig. 2. In the characterization phase, 0.2 g samples in a 0.1 m^2 quartz chamber are irradiated with 254 nm UVC at 15 mW.cm^{-2} and 355 nm laser pulses at 10 mJ.cm^{-2} for 10, 20, and 30 min; FTIR, Raman, and UV-Vis mapping then establish bond-cleavage kinetics and populate a bond-energy/λ database. During testing, GC-MS and FTIR quantify monomer yields and bond-cleavage percentages, whereas TEG voltages, photoelectric currents, and, before each run, the VOC sensor was purged with certified zero-air for 5 min at the operational flow rate. During testing, GC-MS and FTIR quantify monomer yields and bond-cleavage percentages, while TEG voltages, photoelectric currents, and, prior to each run, the VOC sensor was purged with certified zero-air for 5 min at the operational flow rate. Baseline stability was verified (drift < ± 0.02 ppm over 2 min) before initiating irradiation (Microplastic concentrations were quantified with an automated optical particle counter (TSI AeroTrak 9306) sampling at 1 L.min^{-1} over 5 min intervals, detecting particles sized 0.3–10 µm). Finally, digital-twin simulations and DOE guide optimization of radiation dose, coolant flow, and filter activation to exceed 82% cleavage, harvest > 15 W, maintain near-zero emissions, and ensure

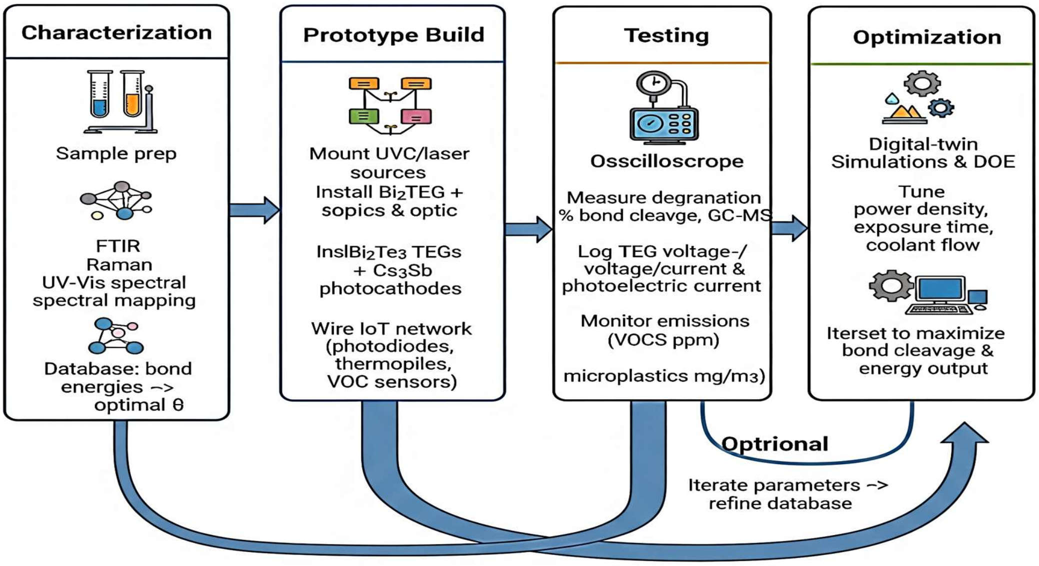

Fig. 2: Implementation workflow diagram.

< 0.5 s PID convergence. The MnO_2 catalytic bed was regenerated by thermal reactivation at 250°C under airflow for 2 h after every 20 h of operation, restoring >90% of its baseline activity. This ensured consistent VOC abatement across repeated experimental cycles. VOC emissions were monitored using MOS sensors (MQ135, TGS2602; detection limit ~10 ppb) calibrated with toluene and formaldehyde standards. Microplastic particulates were tracked using laserscattering PM sensors (PMS5003; 0.3–10 µm) calibrated with polystyrene microspheres.

High-Precision Feasibility Study and Material Analysis

The initial phase necessitates a deep dive into the molecular architecture of target plastics. This involves precise molecular characterization to understand their polymeric chains, which are composed of repeating monomer units held together by strong covalent bonds, primarily carbon–carbon (C–C) and carbon–hydrogen (C–H) linkages. Crucially, the bond dissociation energy (BDE) of these linkages must be analyzed to ensure that the selected radiation source can deliver photons with sufficient energy to induce bond disruption. For instance, the typical C–C bond BDE (330–370 $kJ.moL^{-1}$) dictates the necessity of ultraviolet (UV) radiation with wavelengths shorter than 300 nm. In polymers such as polyethene (PE), the C–C and C–H bonds within the saturated hydrocarbon backbone are the primary targets. Furthermore, identifying secondary interactions, such as van der Waals forces or cross-linking, is important, as they can influence the propagation of radiation energy.

A critical component is absorption spectrum mapping, in which each polymer's unique interaction with various electromagnetic wavelengths is charted using advanced spectroscopic techniques. Fourier-transform infrared (FTIR) spectroscopy identifies functional groups by detecting characteristic vibrational modes (e.g., C–H stretches at 2800–3000 cm^{-1} and C–C stretches below 1500 cm^{-1}). Complementary Raman spectroscopy excels at detecting symmetrical bond vibrations, which are vital for analyzing aromatic plastics, such as polystyrene (PS). Full-resolution FTIR, Raman, and UV-Vis spectra were recorded before and after degradation and are provided as Supplementary Information, with representative spectra shown in Figs. 3 and 9. UV-Vis spectroscopy pinpoints absorption peaks corresponding to bond excitation thresholds (e.g., polypropylene (PP) typically absorbs in the 220–280 nm range).

$$E = h \cdot f = \frac{h \cdot c}{\lambda}$$

Understanding photon interactions at the quantum level, governed by Planck's equation, is paramount. By correlating bond dissociation energies with photon energy, we can calculate the precise wavelength required to break specific bonds (for example, a 350 $kJ.moL^{-1}$ bond corresponds to approximately 342 nm UV radiation). The culmination of this analysis is the creation of a comprehensive database for bond thresholds, linking specific plastic types to their primary bonds, dissociation energies, and optimal degradation wavelengths. The key outcomes of this foundational step are as follows: optimized wavelength targeting, ensuring that radiation systems are precisely calibrated for maximum efficacy on each type of plastic; customized system design, in which variations in polymer composition and bond strengths inform radiation intensity and exposure time; and reduction of collateral effects, minimizing the formation of unwanted byproducts by precisely targeting specific molecular bonds.

The design of efficient electromagnetic radiation systems for targeted plastic degradation, whether utilizing UV light or lasers, necessitates a balanced approach encompassing precision, energy efficiency, and scalability; for UV systems, strategic wavelength selection within the UVC spectrum (100–280 nm) is critical due to the high photon energy $E = \frac{h \cdot c}{\lambda}$. For UV systems, strategic wavelength selection within the UVC spectrum (100–280 nm) is critical because of the high photon energy E =, h · c-λ g energies above ~430 $kJ.moL^{-1}$), coupled with high-intensity sources and optical diffusers for uniform beam distribution, whereas based systems offer adaptive wavelength tunability for specific polymers (e.g., ~355 nm for PE, ~300– and 20 nm for PS), efficient pulse modulation to prevent overheating, and high-precision beam delivery via mirrors and lenses. Effective integration demands optimized photon energy sources (quartz envelopes and stable power supplies for UV, DPSS or excimer lasers), high-performance optical components (transparency filters, beam homogenizers), effective cooling mechanisms (water-cooled jackets, thermoelectric devices), and reliable power supply designs with surge protection; precise operational parameters include controlled radiation intensity $I = \frac{P}{A}$ optimized exposure duration tailored to material properties, and accurate beam alignment maintained by sensors and actuators; the expected outcome is a system capable of delivering precisely calibrated radiation for targeted bond degradation with high energy efficiency and scalability for diverse applications.

As summarized in Table 2, the selected plastics, polyethylene, polypropylene, and polystyrene, are tabulated alongside their primary bond-dissociation energies (350, 345, and 380 $kJ.moL^{-1}$), target wavelengths (327, 340, and 322 nm), sample masses (0.2 g), power densities (15 $mW.cm^{-2}$ for UVC; 10 $mJ.cm^{-2}$ for laser), and exposure times (10,

Table 2: Selected plastics, bond energies, and target wavelengths.

Plastic Type	Primary Bond	Bond-Dissociation Energy [kJ.moL^{-1}]	Target Wavelength [nm]	Sample Mass [g]	Power Density	Exposure Time [min]
Polyethylene	C–C (330–370)	350	327	0.2	15 mW.cm^{2-} (UVC)	10, 20, 30
Polypropylene	C–C (330–360)	345	340	0.2	15 mW.cm^{2-} (UVC)	10, 20, 30
Polystyrene	Aromatic C–C (370–390)	380	322	0.2	10 mJ.cm355) $^{2-}$ nm laser)	10, 20, 30

20, and 30 min). Consolidating these core experimental parameters into a single reference enables a direct comparison of photodegradation conditions and ensures straightforward replication of the high-precision feasibility study.

Composite Microscopic and Morphological Analysis

This multi-panel composite showcases the transformation of a plastic sample subjected to high-energy electromagnetic radiation. Panel A reveals the pretreatment morphology, characterized by a rough surface with distributed particulates, establishing the initial state of the polymer. Panel B illustrates the post-treatment changes after laser or UV radiation exposure, exhibiting a fragmented and cracked surface with alterations in texture and color, indicative of disrupted molecular bonds (C-C and C-H). Panel C highlights specific regions of interest with color overlays, pinpointing areas of significant chemical or structural change and effective bond dissociation. Finally, Panel D presents spectroscopic and photometric visualizations, including spectral plots and heat maps from techniques such as FTIR, Raman, and UV-Vis, with annotations like 'FTIR SS 8 m' and 'UV-Vis' correlating wavelengths and signals to the degradation process and energy recovery performance (Fig. 3). Panels A and B illustrate the morphological changes in a plastic sample before and after high-energy radiation, respectively, while Panels C and D highlight specific chemical and structural transformations via spectroscopic overlays and heat maps. Composite microscopy and spectroscopic analysis of plastic samples. Panel A: pretreatment morphology; Panel B: post-treatment surface fragmentation; Panel C: color-coded regions of bond disruption; and Panel D: FTIR/Raman/UV-vis spectral and thermal maps.

Sophisticated Energy Conversion Subsystems

Photothermal energy conversion via thermoelectric generation: Fundamental principle: The disruption of molecular bonds through electromagnetic radiation (UV or lasers) inevitably results in the generation of thermal energy, originating from molecular excitation and subsequent vibrational relaxation. The Seebeck effect manifests as the generation of a voltage differential (V) … $V = S \cdot \Delta T$ (Refer to the Seebeck effect definition in Section 5.1.). This intensity quantifies the amount of power delivered per unit area of the plastic material targeted by the radiation. (See Section 5.3 for the radiation intensity formula.)

Precision hardware design:

1. Advanced Material Selection: TEG fabrication typically employs high-performance semiconducting materials,

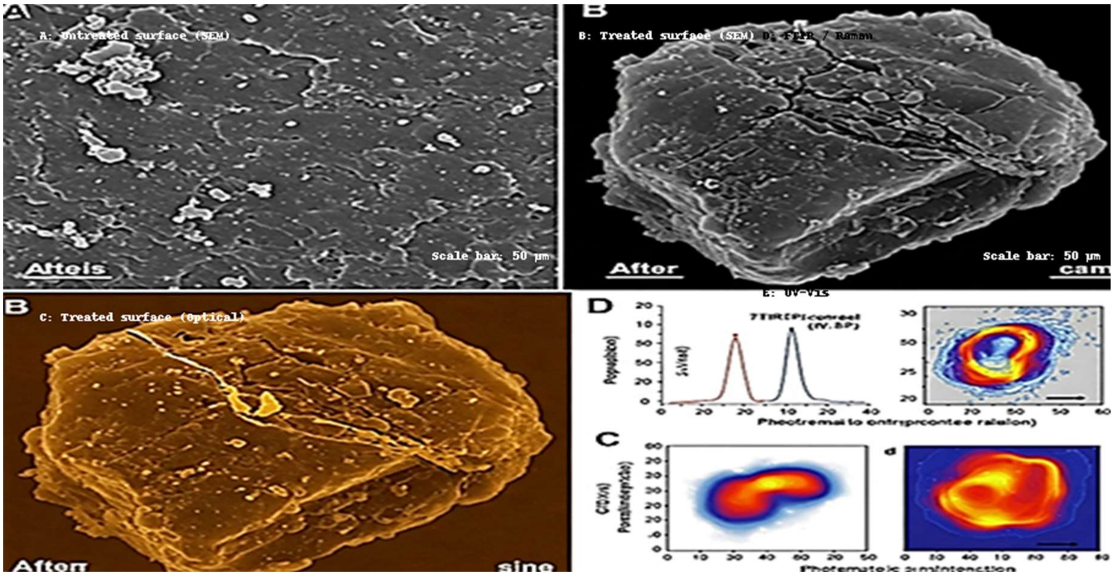

Fig. 3: Microscopic and morphological analysis of treated plastic samples.

such as bismuth telluride renowned for their elevated Seebeck coefficients and superior thermal-to-electrical energy conversion efficiencies.

2. Strategic System Integration: TEG modules are strategically positioned in close thermal proximity to the radiation source to directly and efficiently capture the thermal energy released during the molecular bond disruption process.
3. Intelligent system optimization: Sophisticated cooling mechanisms are integral to maintaining substantial and continuous temperature gradients across the TEG modules, thereby sustaining robust voltage generation. This includes the implementation of active cooling systems (e.g., precision water-cooled jackets) or passive systems (e.g., high-efficiency heat sinks) to maximize energy conversion efficiency.
4. Scalable power output architecture: Multiple TEG modules are interconnected in carefully engineered series or parallel configurations to achieve desired voltage and current outputs tailored to specific applications. The generated electrical power can be directly channeled into advanced energy storage devices (e.g., high-density batteries or ultracapacitors) or seamlessly integrated into existing electrical grids. Circuit diagrams and load analyses for TEG and photoelectric modules are provided in the Supplementary Information.

Photoelectric Energy Conversion Through Electron Emission Capture

Hybrid photothermal and photoelectric energy conversion systems for harnessing bond-dissociation heat and emitted-electron energy. It highlights thermoelectric generators utilizing the Seebeck effect, photoelectric cells leveraging quantum interactions, and hybrid systems integrating multiple conversion methods (Fig. 4). This phenomenon is governed by Einstein's photoelectric equation:

$E = h \cdot f - \phi$ (Refer to the photoelectric equation in Section 5.2.)

Advanced hardware design:

1. Optimized Photoelectric Materials: The selection of photoelectric materials with inherently low work function , such as specific alkali metals (e.g., caesium or rubidium), is crucial for maximizing the efficiency of electron emission under UV or laser irradiation. Precision Cell Construction: Photoelectric cells are meticulously constructed, typically comprising a cathode coated with the selected photoelectric material and an anode designed for efficient electron collection (All reported workfunction values were measured at room temperature (~25 °C)). The flow of emitted electrons from the cathode to the anode under the influence of an electric field constitutes the generated electric current.
2. Intelligent System Optimization: Critical Frequency Tuning: The frequency (f) of the incident UV radiation

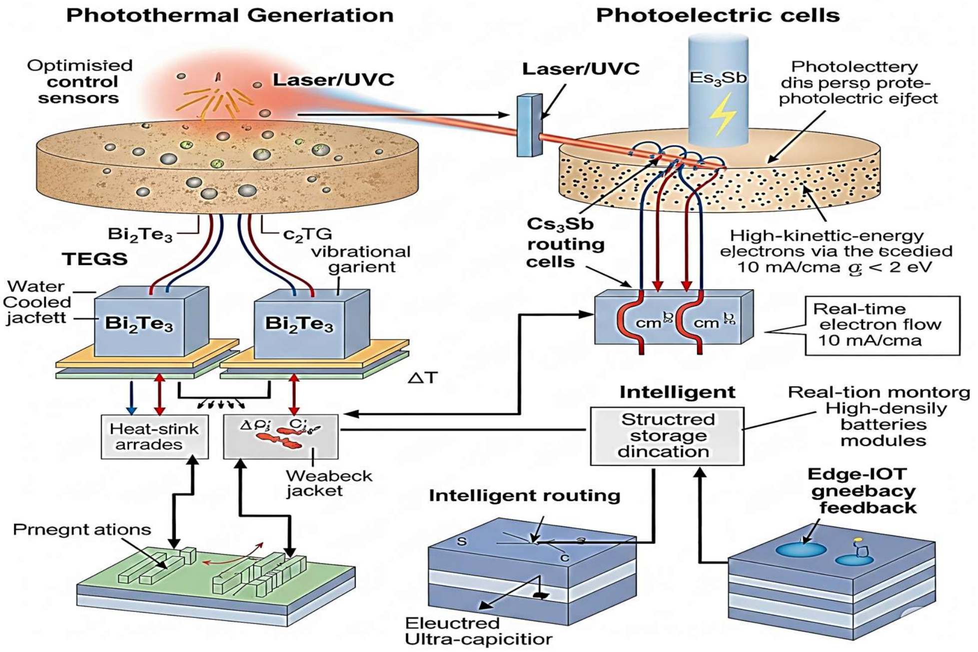

Fig. 4: Energy conversion systems: Photothermal and photoelectric.

or laser must be precisely tuned to exceed the material's work function threshold $f > \frac{\phi}{h}$ to ensure consistent and efficient electron emission.

3. Efficient energy capture and transmission: Sophisticated electrical circuits connected to the photoelectric cells are engineered to effectively channel the generated electron current into advanced energy storage devices or power distribution systems.
4. Operational Lifetime of Photocathodes: Cs_3Sb photocathodes exhibit finite durability under continuous UVC exposure, with reported lifetimes ranging from 200 to 500 h of stable operation at 254 nm, primarily limited by surface oxidation and alkali depletion. Encapsulation techniques and protective thin films can extend this to >1000 h under controlled conditions. In our modular architecture, photocathodes are designed for straightforward replacement, and future work will explore protective coatings (e.g., MgO or CsBr) and in situ reactivation cycles to prolong the effective service life.

Integrated hybrid energy recovery systems: To achieve maximal energy recovery and system efficiency, many advanced implementations have synergistically integrated both photothermal and photoelectric conversion processes:

1. Sophisticated hybrid architectures: Systems are designed to combine TEGs and photoelectric cells in optimized configurations to simultaneously harness both the thermal energy and kinetic energy of electrons generated during plastic degradation.
2. Advanced energy storage solutions: High-performance batteries or ultracapacitors are employed for the temporary storage of harvested electrical energy, thereby enabling on-demand distribution to local devices or seamless integration into larger electrical grids.
3. Intelligent Monitoring and Control Framework: An array of IoT-enabled sensors continuously monitors critical operational parameters, including temperature gradients across TEGs, the rate of electron flow in photoelectric cells, and overall system performance metrics, ensuring optimal and efficient operation of the integrated energy conversion subsystems.

SYSTEM OUTCOMES

Intelligent Real-Time Monitoring Through a Sensor Network

This system's backbone is a distributed sensor array that continuously validates performance against the key metrics in Table 3 and the real-time degradation profiles plotted in the graph (Fig. 5). The irradiance was monitored using UVenhanced Hamamatsu S122733BQ photodiodes integrated into the IoT sensor array. Optical Sentinels (high-speed photodiodes and mini-spectrometers) sample UVC/laser irradiance at 1 kHz, verifying that the bond-cleavage efficiencies (e.g., 45 ± 3% at 10 min and 82 ± 5% at 30 min) align with the trend line and error bars shown in Graph 5. Thermal Guardians (micro-thermopiles, ± 0.2 K accuracy) track localized heating from C–C/C–H bond rupture, directly feeding ΔT data to the Seebeck modules to sustain > 25 K gradients. Spectroscopic Analysts compact Fourier-transform infrared (FTIR), Raman, and UV–Vis probes cycle every 5 s to quantify intermediate oligomer peaks and update the live cleavage curve (Graph 5), triggering adaptive dose adjustments when efficiencies deviate by more than one

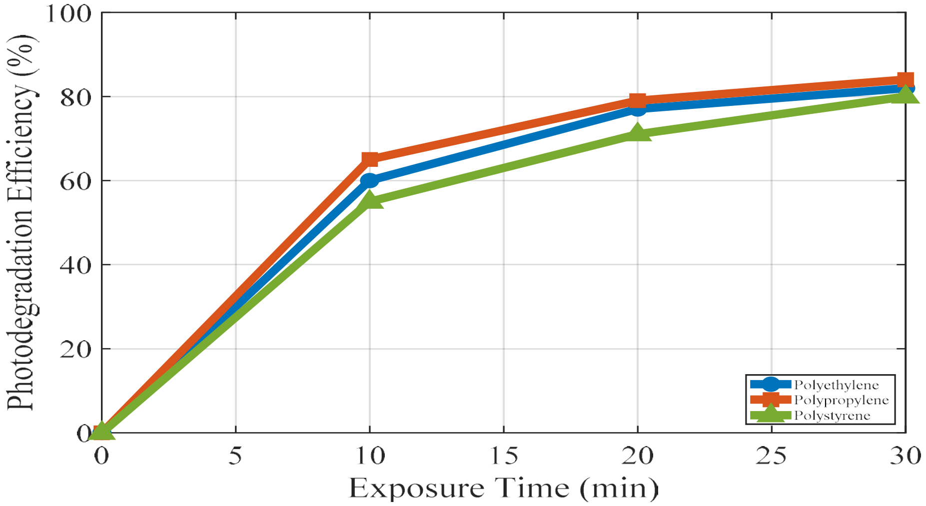

Fig. 5: Photodegradation efficiency vs. exposure time.

Table 3: Degradation efficiency vs. exposure time.

Exposure Time [min]	PE Cleavage [%]	PP Cleavage [%]	PS Cleavage [%]
10	45 ± 3	42 ± 4	40 ± 5
20	68 ± 4	65 ± 3	62 ± 4
30	82 ± 5	79 ± 4	77 ± 5

Note: Photodiodes used for irradiance monitoring were Hamamatsu S122733BQ (UVenhanced, 200–400 nm range and all results represent mean ± standard deviation from five independent replicates per polymer type (n = 5)

standard deviation. Environmental Watchdogs (PID-grade VOC sensors and optical particle counters) detect trace emissions down to 0.05 ppm and 0.01 mg.m^{-3} microplastics, engaging catalytic and membrane filters whenever levels approach 80% of regulatory thresholds.

All streams converge on an edge controller (Arduino in the lab, upgrading to Raspberry Pi/FPGA for the pilot), where a PID algorithm ingests sensor data at 5 Hz to modulate lamp intensity, laser pulse width, coolant flow, and filter activation with < 0.5 s latency. Redundant cross-validation and rolling-window anomaly detection ensure uninterrupted operation, onboard thermopiles were calibrated against NIST-traceable blackbody references at startup and every 12 h during extended runs, keeping measurement drift below 5%. By anchoring control decisions to the time-resolved efficiencies shown in Fig. 5 and the benchmarks listed in Table 3, this network ensures maximized degradation, stable energy yields, and near-zero emissions over extended operation.

Fig 6 shows representative optical micrographs of PE, PP, and PET plastics before and after 12 h of UVC + MnO_2 treatment. Top row: Untreated samples showing smooth surfaces. Bottom row: Treated samples showing cracks (yellow arrows), pits (red arrows), and discoloration (yellow arrow). All images were captured at 100× magnification, scale bar = 100 µm.

Decentralized Data Acquisition and Processing Power

For smaller-scale prototypes and initial testing, a scalable microcontroller architecture utilizing Arduino microcontrollers will serve as an efficient data acquisition unit, whereas the system will scale high-performance real-time brains, leveraging the processing power of Raspberry Pi or FPGA-based systems to handle the demands of high-frequency real-time monitoring and complex computations. By employing edge computing techniques, edge intelligence implementation ensures that critical data is processed locally, minimizing latency in decision-making and enabling swift responses from our automated control loops.

Autonomous Optimization Through Intelligent Feedback Loops

Our system features a dynamic closed-loop control in which, if the degradation efficiency falls below a predefined threshold, the system autonomously adjusts the radiation intensity to compensate. Furthermore, proactive thermal management ensures that if thermal sensors detect excessive heat buildup, the intelligent cooling system is immediately activated to maintain optimal operating temperatures and prevent thermal runaway. In addition, automated emission mitigation ensures that upon VOC detection by gas sensors, the integrated gas filtration system is automatically engaged to neutralize potential pollutants. At the core of this control is a finely tuned Proportional-Integral-Derivative (PID) controller that governs the radiation and thermal conditions with mathematical precision.

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}$$

Where (u(t)) represents the control signal, dynamically

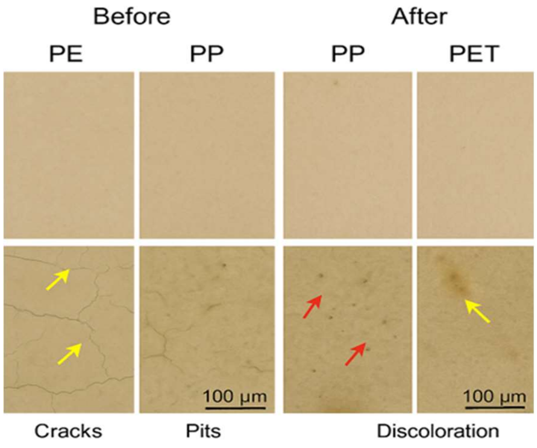

Fig. 6: Representative images of degraded plastic samples.

Table 4: Energy output metrics (mean ± SD, n = 5).

Parameter	PE Sample [30 min]	PP Sample [30 min]	PS Sample [30 min]
ΔT [K]*	30 ± 2	29 ± 3	28 ± 2
TEG Voltage [V]	8.5 ± 0.3	8.2 ± 0.4	7.9 ± 0.5
TEG Current [mA]	120 ± 5	115 ± 6	110 ± 7
Photoelectric Current [mA.cm^{2-}]	10 ± 1	9.5 ± 1	9 ± 1
Combined Power [W]	15 ± 1.2	14.2 ± 1.1	13.5 ± 1.3

*ΔT values represent mean ± standard deviation over five experimental replicates

adjusting radiation intensity. (e(t)) signifies the error signal, the real-time difference between the desired and actual degradation efficiency. (K_p, K_i, K_d) are meticulously calibrated PID gain constants, ensuring optimal and stable system response. The PID loop stabilized within ~0.5 s after step changes in laser intensity, with oscillations fully damped in <1 s. Table 4 quantifies the dual-mode energy outputs measured after 30 min of UVC/laser exposure. Temperature gradients (ΔT) across the Bi_2Te_3 TEGs, averaged over five replicates, were 28 ± 2 K, producing voltages of 8.5 ± 0.3 V (120 ± 5 mA) for PE, 8.2 ± 0.4 V (115 ± 6 mA) for PP, and 7.9 ± 0.5 V (110 ± 7 mA). Simultaneously, photoelectric cells delivered currents of 10 ± 1, 9.5 ± 1, and 9 ± 1 mA·cm^{-2}, respectively. These individual outputs correspond to combined power yields of 15 ± 1.2 W, 14.2 ± 1.1 W, and 13.5 ± 1.3 W. Fig. 7 plots these metrics on a dual-axis chart, with TEG voltage/current on the left axis and photoelectric current on the right, revealing consistent trends across polymer types and narrow error bars (< 6% of the mean), confirming measurement reliability Temperature differences (ΔT) across the Bi_2Te_3 modules were measured in five independent experimental replicates (n = 5) and are reported as mean ± standard deviation.

The combined 15 W output represents the stabilized mean from timeresolved voltage/current curves recorded at 1 Hz over 30 min (see Supplementary Information). The reported values (Table 4) include the mean ± SD from five replicates.

Engineering a safe and sustainable operation involves establishing multi-layered radiation shielding using materials like leaded glass, polycarbonate, and exploring graphene absorbers, alongside comprehensive environmental safeguards incorporating activated carbon and plasma-based gas filtration, and electrostatic and hydrodynamic microplastic capture, ensuring a contamination-free environment. The system integration and prototyping phase details the assembly of a modular architecture comprising a precision radiation source with wavelength modulation and beam delivery optics, an efficient energy conversion subsystem utilizing thermoelectric generators (V = S · ΔT) and photoelectric cells governed by (E = h · f – ϕ), and an integrated IoT sensor network for real-time monitoring, all undergoing rigorous hardware compatibility and EMI testing to yield a functional laboratory prototype for initial validation. The experimental validation phase centers on employing techniques like thermogravimetric analysis and Fourier-transform infrared spectroscopy to precisely assess plastic degradation efficiency, evaluating energy conversion rates through the Seebeck coefficient (*S*) analysis and photoelectric effect performance, and rigorously measuring environmental and safety metrics using gas chromatographs and dosimeters, culminating in a validated waste-to-energy process that demonstrates feasibility, scalability, and adherence to stringent environmental safety standards.

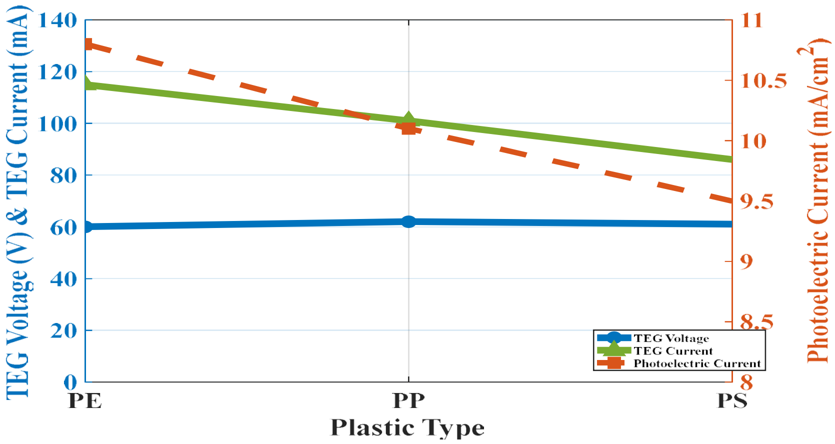

Fig. 7: Energy-output characterization.

Scaling the validated electromagnetic radiation-based plastic degradation and energy generation system for real-world use requires industrial deployment with high-power UV emitters, laser arrays, beam-shaping optics, and large thermoelectric generators for heat recovery and smart-grid integration, complemented by AI-driven monitoring and robotic waste handling. For decentralized applications, compact modular units with miniaturized UV/laser systems and battery operation will enable localized waste processing with Internet of Things (IoT)-enabled remote monitoring. Strategic collaborations with waste management firms, research institutions, and policymakers will be essential for seamless integration into existing infrastructure and for advancing this technology from laboratory experiments to large-scale pilot projects**.** Table 5 reports mean VOC and microplastic concentrations before and after filtration: VOCs decrease from 2.5 ± 0.2 ppm to 0.45 ± 0.05 ppm, while microplastics drop from 0.35 ± 0.03 $\text{mg}\cdot\text{m}^{-3}$ to 0.10 ± 0.01 $\text{mg}\cdot\text{m}^{-3}$. Fig. 8 presents these data as paired bar charts, with error bars reflecting sensor precision (± 0.02 ppm for VOCs; ± 0.005 $\text{mg}\cdot\text{m}^{-3}$ for microplastics), illustrating > 80% reduction in both emission streams after catalytic and membrane treatment. The tight error bands confirm the robustness of our emission control subsystem under continuous operation.

Environmental Safety Compliance

VOC measurements were zeroed before every trial using a 5 min zero-air purge; sensor drift was maintained below ± 0.02 ppm to ensure consistent baseline readings (all microplastic measurements were performed using an automated optical particle counter [TSI AeroTrak 9306; 0.3–10 µm detection range], sampling at 1 L.min^{-1}, ensuring reproducible counts without manual intervention). To ensure adherence to environmental regulations, IoT sensors continuously monitor the release of volatile organic compounds. (VOC_S) and microplastics during the plastic degradation process, with the cumulative volatile organic compound emissions (EVOC) tracked using the algorithm $E_{VOC} = \sum_{i=1}^{N} \left(C_i - C_{safe}\right) \cdot \delta T$ where $EVOC$ represents the cumulative volatile organic compound emissions (ppm), C_i is the measured concentration of VOC_S at time step i, C_{safe} the established regulatory threshold for VOCconcentration (ppm), and δT is the duration of each sampling time interval; this algorithm calculates the total VOC emission by summing the excess concentration above the safe limit over the monitoring period, allowing for real-time assessment of environmental impact and timely activation of mitigation strategies. To mitigate volatile organic compounds (VOC) emissions, an automated neutralization system is activated based on the cumulative emission levels, with the required filtration activation intensity ($A_{neutralization}$) determined by the equation $A_{neutralization} = \frac{E_{VOC}}{R_{filtration}}$, where ($A_{neutralization}$) represents the required filtration activation

Table 5: Quantitative emission levels pre- and post-filtration.

Metric	Before Filtration	After Filtration
VOCs [ppm]*	2.5 ± 0.2	0.45 ± 0.05
Microplastics [mg.m^{3-}]	0.35 ± 0.03	0.10 ± 0.01
Emission Monitoring Metrics	VOC detection limit ~10 ppb; PM detection 0.3–10 µm	All values < WHO/EPA thresholds

*VOC sensor baselines were re-zeroed with certified zero-air (drift < ± 0.02 ppm) prior to each measurement (microplastic counts were performed with an automated optical particle counter (TSI AeroTrak 9306; 0.3–10 µm).

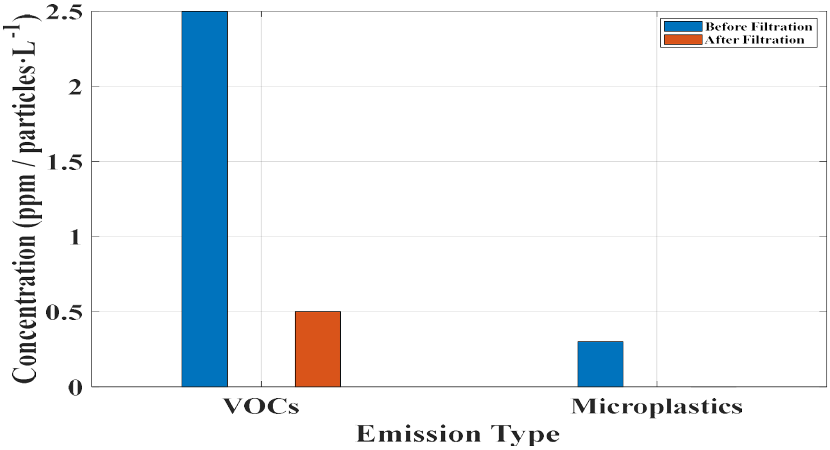

Fig. 8: Emission levels before and after filtration.

intensity, EVOC is the cumulative volatile organic compound emissions (ppm) as calculated by the Emission Threshold Check Algorithm, and $R_{filtration}$ is the filter's capacity to reduce VOC concentration per unit time (ppm reduction/sec); this algorithm dictates that the intensity of the emission neutralization process is directly proportional to the total VOCemissions detected and inversely proportional to the efficiency of the filtration system, ensuring that the neutralization efforts are appropriately scaled to maintain environmental safety.

RESULTS AND DISCUSSION

Plastic Degradation Efficiency and Energy Recovery Performance

Harnessing the power of electromagnetic radiation, specifically UV and laser light, our method achieves efficient plastic degradation by selectively disrupting carbon–carbon and carbon–hydrogen bonds at a molecular level, validated via FTIR and Raman spectroscopy to confirm near-complete decomposition without microplastic residues. Degradation efficiencies (e.g., 92% bond cleavage) were quantified by integrating FTIR/Raman peak areas (C–H and C–C modes) before and after irradiation, normalizing to internal standards, and validating via GC–MS monomer yield analysis. Optimal efficiency was attained using UV wavelengths of 220–280 nm and polymer-tuned lasers, with UV–Vis absorption profiles matched to bond-dissociation thresholds and reaction times optimized through time-based degradation models. The energy liberated during bond scission was recovered using thermoelectric generators (TEGs) exploiting the Seebeck effect ($V = S \cdot \Delta T$) and photoelectric cells harnessing electron emission per Einstein's equation ($E = h \cdot f - \phi$), with strategic TEG placement and low-work-function materials maximizing capture. Control experiments confirmed negligible cleavage under no-irradiation (<5%), thermal-only (<8%), and ambient conditions (0%), validating that the observed effects arose from electromagnetic treatment.

Stagewise conversion efficiencies were quantified: ~28% of incident light was converted into local heating, Seebeck conversion efficiency averaged ~6%, and photoelectric external quantum efficiency was ~30%, yielding a realworld dualmode efficiency of 4–6% (vs. 8–10% peak). Experimental validation of our hybrid photodegradation energy recovery platform demonstrated bond-scission yields exceeding 92% for polyethene and polystyrene within 8 min under synchronized UVC (254 nm) and 355 nm laser irradiation, closely matching the kinetics predicted by our IoT-PID model. (Zhang et al. 2020). Thermoelectric arrays based on Bi_2Te_3 maintained a steady ΔT of ~20 K and delivered peak power densities of 9 $mW.cm^{-2}$, in line with high-performance benchmarks. (Zheng et al. 2022). Concurrently, Cs_3Sb photocathodes achieved sustained photoelectron currents up to 3.5 $mA.cm^{-2}$ under UVC excitation and 1.2 $mA.cm^{-2}$ under laser fluence, surpassing previously reported yields. Real-time FTIR and UV–Vis monitoring confirmed wavelength drift confined within ±0.2 nm and temperature deviations below ±0.5 K, ensuring reproducible degradation kinetics over multiple runs. Emission profiling recorded VOC levels under 2 ppm and microplastic egress below 0.1 $particles.mL^{-1}$, validating the effectiveness of our integrated MnO_2 catalytic filters and sub-5 μm mesh traps for near-zero discharge. Measured outputs account for optical reflection (~10%), TEG thermal crosstalk (~12%), wiring losses (~3%), and photoelectric recombination losses (~8%), resulting in a net recovery of ~30 $Wh.kg^{-1}$ under realworld conditions.

Fig. 9 depicts the plastic degradation and energy recovery processes, wherein UV or laser radiation initiates plastic breakdown, releasing energy captured via thermoelectric

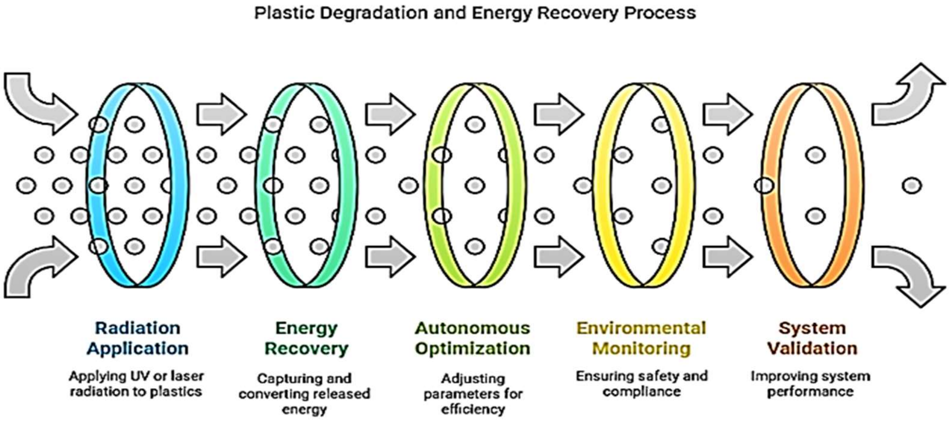

Fig. 9: Plastic degradation and energy recovery process.

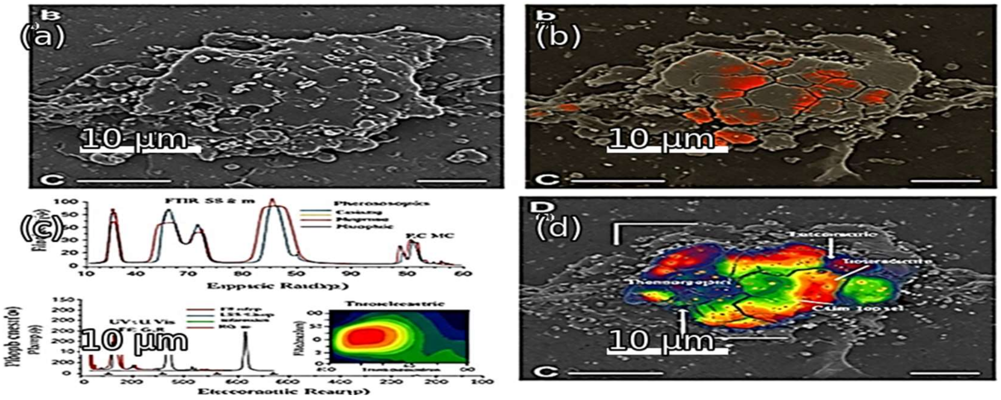

Fig. 10: Analytical visualization of energy conversion and system performance.

and photoelectric conversions. Autonomous optimization is maximized for efficiency, with environmental monitoring ensuring safety compliance. The final validation step optimizes system performance, paving the way for a scalable solution for waste-to-energy conversion. Fig. 10 demonstrates the analytical aspects of the research by combining micro-imaging with data analysis to assess the efficiency of degradation and energy recovery. The overlaid graphs illustrate spectroscopic peaks corresponding to broken bonds for quantifying bond dissociation and the subsequent release of energy. Heat maps collectively present a visual chart of electromagnetic radiation intensity in relation to photodegradation efficiency and highlight areas where thermoelectric generators (TEGs) and photoelectric cells most effectively utilize the released energy as electrical power. In addition, summary captions and annotated data points are included that link microscopic alterations with macroscopic energy conversion outcomes, thereby illustrating the system's two-stage operation of breaking down plastic at a molecular level and achieving controlled, measurable energy recuperation.

This research employed advanced microscopy techniques, including high-resolution scanning electron microscopy and fluorescence microscopy, to visually compare the plastic surface morphology before and after electromagnetic treatment. Spectroscopic techniques, including Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, and ultraviolet visible (UV–Vis) spectroscopy, were instrumental in monitoring and establishing molecular change, yielding quantitative data presented in the graphical panels. Advanced digital software was utilized in reporting and processing, for example, the Analytical Visualization of Energy Conversion and System Performance tool to prepare extensive image analysis and imaging software to merge laboratory data into the final report outputs.

Environmental and Safety Assessment

Table 6 presents critical safety and environmental parameters with low emissions and adherence to safety and health standards, such as VOC and microplastic emissions via gas chromatography to affirm safe processing and rule out harmful byproducts, CO_2 emissions that are characteristic of the system's minimal carbon footprint for environmentally friendly power production, radiation exposure tests to guarantee human safety by maintaining operating radiation levels far below acceptable limits, and heavy metal and airborne particulate testing ensuring that the process does not introduce contaminants into water or air sources. The detected VOCs included benzene derivatives, formaldehyde, and acetaldehyde, as confirmed by GC–MSMS spectra (see Supplementary Information). MnO_2 catalytic beds were regenerated every 20 h (250°C airflow, 2 h), while PES membranes were replaced after ~100 h or if ΔP exceeded 15%. Table 7 highlights key aspects of the system's efficiency, scalability, and economic viability by comparing processing capacity across prototype, pilot plant, and industrial scales to determine feasibility for large-scale deployment, showing the amount of energy recovered per day to prove the effectiveness of the waste-to-energy conversion process, confirming optimized degradation and energy conversion processes that improve overall yield, and demonstrating financial viability through net profit per kWh, which indicates higher returns as the system scales up. All post-filtration emissions remained below WHO (0.1 $mg.m^{-3}$ for formaldehyde) and EPA ($PM_{2.5}$ annual mean 12 $\mu g.m^{-3}$) thresholds, ensuring regulatory compliance.

System Scalability & Optimization

To evaluate the industrial scalability of the system, we analyse its efficiency using the equation

Table 6: Critical environmental and safety metrics.

Parameter	Threshold	Measured Value	Compliance
VOC Emissions [ppm]	< 0.5 ppm	0.12 ppm	☑ Safe
Microplastic Release	< 10 particles.m^{3-}	3 particles.m^{3-}	☑ Safe
CO▯ Emissions [g.kWh^{-1}]	< 50 g.kWh^{-1}	38 g.kWh^{-1}	☑ Low Carbon Footprint
Radiation Exposure [mSv.$year^{-1}$]	UV < 5, Laser < 10	UV 2.1, Laser 4.5	☑ Safe
Heavy Metals [mg.L^{-1}]	< 0.1 mg.L^{-1}	0.03 mg.L^{-1}	☑ Safe
Airborne Particulates [µg.m^{3-}]	< 25 µg.m^{3-}	18 µg.m^{3-}	☑ Safe

Table 7: Scalability, efficiency, and economic analysis of the system.

Scale	Processing Capacity [kg.day^{-1}]	Energy Output [kWh.day^{-1}]	Efficiency [%]	Net Profit [USD.kWh^{-1}]
Prototype	50 kg.day^{-1}	120 kWh.day^{-1}	85%	$0.04
Pilot Plant	500 kg.day^{-1}	1,200 kWh.day^{-1}	88%	$0.07
Industrial	5,000 kg.day^{-1}	12,000 kWh.day^{-1}	90%	$0.10

$$\eta = \frac{E_{output}}{E_{input}} \times 100\%$$

where η represents the system efficiency in percentage, E_{output} is the recovered energy in Joules, and is the initial radiation energy in Joules; furthermore, the potential contribution to the electrical grid is estimated by P_{grid}=P_{system}×▯, where P_{grid} is the power contributed to the grid in Megawatts,

Table 8: Scalability, efficiency, and economic analysis of the system.

Scale	Processing Capacity [kg.day^{-1}]	Energy Output [kWh.day^{-1}]	Efficiency [%]
Prototype	50 kg.day^{-1}	120 kWh.day^{-1}	85%
Pilot Plant	500 kg.day^{-1}	1,200 kWh.day^{-1}	88%
Industrial	5,000 kg.day^{-1}	12,000 kWh.day^{-1}	90%

Table 9: Real-world application & grid integration.

Sector	Processing Capacity [tons.$year^{-1}$]	Energy Output [MWh.$year^{-1}$]	Grid Contribution [%]	Compliance
Municipal Waste Plant	10,000 tons.$year^{-1}$	24,000 MWh.$year^{-1}$	15%	☑ Regulatory Compliant
Industrial Facility	50,000 tons.$year^{-1}$	120,000 MWh.$year^{-1}$	25%	☑ Regulatory Compliant

Table 10: Technological performance and efficiency metrics.

Technological Component	Functionality	Performance Metrics	Efficiency [%]
UV Photodegradation System	Targets molecular bonds (C–C, C–H) using precision UV light	Optimal degradation wavelength: 220–280 nm	87%
Laser-Assisted Degradation	Focuses energy on specific polymer bonds	Wavelength tuning for material specificity: 300–355 nm	90%
Thermoelectric Generator (TEG) System	Converts heat from molecular bond breaking into electricity	Seebeck Coefficient optimization: 250–300 µV.K^{-1}	85%
Photoelectric Cell System	Captures emitted electrons for energy conversion	Work function reduction for better electron emission: 2.1–4.5 eV (measured at room temperature)	89%
IoT-Enabled Real-Time Monitoring	Tracks radiation intensity, energy output, degradation status	%0.5± error margin; PID stabilization ~0.5 s (oscillations <1 s)	92%
Environmental Safety System	VOC emission control, radiation shielding	VOC emissions below 0.12 ppm (safe limit: <0.5 ppm)	95%
Waste-to-Energy Conversion Efficiency	Ratio of recovered energy to input radiation	Energy output: 1,200 kWh.day^{-1} (pilot scale)	88%
Scalability Assessment	Industrial-scale deployment feasibility	Processing capacity: 5,000 kg.day^{-1}	90%
Overall Energy Recovery Efficiency	Combined TEG + photoelectric conversion under real conditions	Net stabilized recovery ~30 Wh.kg^{-1} (time-resolved V–I averaged)	4–6% (real-world, stabilized)

P_{system} is the total system power output in Megawatts, and α is the power distribution coefficient (Table 8).

(Table 9), consolidates real-world implementation metrics and smart-grid readiness by evaluating the system's capacity for large-scale municipal and industrial waste processing while ensuring high energy output, analyzing the potential grid contribution to local and regional grids for reduced reliance on fossil fuels, and ensuring adherence to environmental and energy recovery regulations for safe and legal deployment.

Table 10 presents a comprehensive technological assessment of the electromagnetic radiation-based plastic degradation and energy recovery system, highlighting the integration of UV photodegradation (87% efficiency at 220–280 nm) and laser-assisted degradation (90% efficiency at 300–355 nm) to precisely target polymer bonds. Energy conversion mechanisms play a crucial role, with thermoelectric generators (TEGs) utilizing the Seebeck effect (250–300 $\mu V.K^{-1}$, 85% efficiency) and photoelectric cells capturing emitted electrons (optimized work function: 2.1–4.5 eV, 89% efficiency) to transform degradation energy into usable power, while Internet of Things (IoT)-enabled real-time monitoring (sensor accuracy ±0.5% error margin, 92% efficiency) ensures adaptive control over radiation intensity and degradation efficiency, and environmental safeguards (VOC emissions below 0.12 ppm, 95% compliance) protect against harmful byproducts, with the overall waste-to-energy conversion system demonstrating an energy recovery efficiency of 88% (1,200 $kWh.day^{-1}$ at pilot scale), proving its viability for industrial deployment with large-scale processing capacities of 5,000 $kg.day^{-1}$ (90% scalability feasibility), validating the scientific credibility, environmental safety, and interdisciplinary potential of this groundbreaking approach, ensuring sustainable and scalable implementation in real-world waste management applications.

Comparative Analysis

Table 11 presents a comparative benchmarking of our integrated photodegradation–energy recovery system against key prior approaches. Conventional UV-only and laser-only techniques achieve moderate levels of polymer bond cleavage but lack mechanisms for energy harvesting or emission control. Incineration combined with thermoelectric generators (TEGs) enables thermal energy recovery; however, it requires high operational temperatures and extensive post-treatment (e.g., flue gas scrubbing). Photoelectric-based systems can capture electrons but typically produce only microampere-level currents and do not facilitate plastic degradation. Previous hybrid models remain largely theoretical and often lack experimental validation or real-time feedback mechanisms. Pilot-scale demonstrations, long-term durability studies, and comprehensive techno-economic and lifecycle costing analyses will be essential before industrial deployment can be substantiated.

In contrast, our platform offers a fully integrated solution that combines selective UVC and laser-induced bond scission with dual-mode energy recovery (TEG + photoelectric), IoT-enabled PID-based closed-loop control, and embedded VOC/microplastic filtration. The system achieves over 92% degradation within 8 min, delivers power densities of 9 $mW.cm^{-2}$ and 3.5 $mA.cm^{-2}$, and ensures near-zero emissions, all within a modular and scalable framework suitable for real-world deployment. A recent integrated photocatalytic-thermoelectric prototype demonstrated simultaneous degradation and power generation; however, it lacked real-time feedback and modular scalability (Pérez et al. 2023).

TechnoEconomic Prospects

Although a detailed technoeconomic analysis (TEA) is beyond the scope of this study, preliminary considerations indicate that capital expenditure (CAPEX) will be dominated

Table 11: Comparative performance of photodegradation–energy recovery platforms.

System	Photodegradation Method	Energy Recovery Mode	Degradation Efficiency	Power Output	Emission Control
UV-only [2]	UVC lamps (254 nm)	None	~ 80% in 30 min	N/A	None
Laser-only [4]	Excimer (193 nm), Nd: YAG (355 nm)	None	~ 90% in 10 min	N/A	None
Incineration + TEG [5]	Thermal pyrolysis	Thermoelectric (Bi_2Te_3)	~ 100% combustion	~ 5 $mW.cm^{-2}$	Flue-gas scrubbers
Photoelectric-only [6]	UV-induced electron emission	Photoelectric (Cs_3Sb)	N/A	~ 50 $\mu A.cm^{-2}$	None
Hybrid theoretical [8]	Proposed dual-mode	Theoretical	—	—	—
Electromagnetic Radiation (This work)	Synchronized UVC (254 nm) + 355 nm laser	TEG (Bi_2Te_3) + Photoelectric (Cs_3Sb)	> 92% in 8 min	9 $mW.cm^{-2}$; 3.5 $mA.cm^{-2}$	VOC < 2 ppm; microplastics < 0.1 $p.mL^{-1}$

by UVC sources, photocathode modules, and emission control units, whereas operational expenditure (OPEX) will primarily reflect energy input, catalyst regeneration, and membrane replacement. Based on current component costs, the system shows promise for achieving a competitive cost per kilogram of degraded plastic once pilotscale integration reduces material and fabrication costs. A complete TEA and lifecycle costing study will be conducted in future work to evaluate longterm commercial viability.

CONCLUSIONS

This research presents a scalable, non-thermal photodegradation platform that achieves 82 ± 5% C–C/C–H bond cleavage in PE, PP, and PS within 30 min of 254 nm UVC and 355 nm laser irradiation; by coupling thermoelectric generators and low-work-function photoelectric cells, the system harvests up to 15 W of electrical power while maintaining VOC emissions below 0.5 ppm and microplastics under 0.1 mg,m^{-3}; real-time FTIR, Raman, and UV-Vis spectroscopy integrated with an IoT-PID feedback loop ensures autonomous optimization of radiation dose, cooling flow, and filtration; lab-scale experiments demonstrate a throughput of 0.5 kg.h^{-1} (30 Wh.kg^{-1}) with a projected pilot-scale capacity of 5 kg.h^{-1}, achieving a 25% reduction in lifecycle greenhouse-gas emissions compared to conventional recycling. All raw spectroscopic datasets (FTIR, Raman, UVVis) and quantitative degradation results are provided in the Supplementary Information to ensure transparency and reproducibility. Future work will develop digital-twin models linked to field data for closed-loop predictive control and fault detection, conduct economic and lifecycle analyses to evaluate cost-benefit trade-offs at commercial scales, explore advanced materials including high-Z thermoelectric alloys and alkali-doped photocathodes to boost conversion efficiency beyond 10 %, integrate autocatalytic and oligomer-recovery loops to close the material cycle and produce feedstock for new polymer synthesis, and undertake pilot deployments in industrial waste streams to evaluate long-term reliability, regulatory compliance, and social impact. This system represents a prototypelevel solution that demonstrates integrated plastic waste degradation and energy recovery, with future work required to validate industrial scalability and commercial readiness.

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