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Research paper

Bio-Based and Eco-Friendly Solvent Systems for Sustainable Industrial and Biological Applications

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ABSTRACT

Traditional organic solvents provide considerable environmental and health risks, although their widespread use in chemical manufacturing, pharmaceutical production, and materials processing sectors. This study examines the rational design, systematic assessment, and industrial validation of environmentally benign solvent alternatives, such as deep eutectic solvents, bio-based solvents, and supercritical fluids, aimed at substituting hazardous conventional solvents in extraction, synthesis, and formulation processes. Four case studies investigated the crystallisation of pharmaceutical active ingredients, extraction of natural products, processing of polymers, and treatment of metal surfaces, contrasting green solvents with traditional options in terms of performance, environmental impact, health, safety, and economic factors. Deep eutectic solvents formulated from choline chloride and glycerol attained a 94% yield in pharmaceutical crystallisation, compared to 89% with dichloromethane, while mitigating toxicity and decreasing waste production by 76%. Bio-based ethyl lactate extracted 87-92% of bioactive chemicals from plant materials, in contrast to 91-95% for ethyl acetate, while providing total biodegradability and renewable source. Supercritical carbon dioxide processing of polymers attained comparable product quality to traditional organic solvents, resulting in 65% energy savings and zero emissions of volatile organic compounds. Magnetic deep eutectic solvents achieved metal degreasing with 96% efficiency and total solvent recovery, in contrast to 78% efficiency and 45% losses associated with trichloroethylene. Environmental assessments using solvent selection recommendations indicated a 60-85% enhancement in health and environmental hazard ratings for eco-friendly alternatives. Life cycle study indicated reductions of 35-68% in global warming potential and 42-79% in human toxicity consequences, albeit 15-35% increased material prices in the majority of applications. Industrial pilot experiments validated scalability and process compatibility, demonstrating economic payback times of 1.2 to 3.8 years when factoring in waste treatment savings and regulatory compliance expenses. This study shows that scientifically formulated eco-friendly solvents may equal or surpass the efficacy of traditional solvents while significantly diminishing environmental impact and health hazards, offering viable alternatives for sustainable industrial solvent substitution.

1. Introduction

Solvents constitute a major category of industrial chemicals, with worldwide consumption surpassing 20 million metric tonnes each year in pharmaceutical manufacturing, chemical synthesis, extraction processes, coatings and adhesives, electronics fabrication, and cleaning operations (Capello et al., 2007). These omnipresent materials perform essential roles such as dissolving reactants and products, regulating reaction rates and selectivity, aiding in separations and purifications, and easing the formulation of consumer and industrial goods. The prevalence of petroleum-based volatile organic solvents, such as chlorinated hydrocarbons, aromatic compounds, ethers, and ketones, imposes significant

environmental and health challenges, prompting extensive research into safer, more sustainable alternatives (Prat et al., 2016).

The environmental consequences of conventional solvents arise through various mechanisms, including emissions of volatile organic compounds that contribute to ground-level ozone and photochemical smog, greenhouse gas emissions from solvent production and incineration, water pollution due to improper disposal and industrial discharge, soil contamination at manufacturing and disposal sites, and ecosystem toxicity impacting aquatic and terrestrial organisms (Jessop, 2011). The pharmaceutical industry produces an estimated 25-100 kilogrammes of solvent waste for every kilogramme of active pharmaceutical ingredient produced, with solvents constituting 80-90% of the total material mass in standard synthetic methods. A study examining solvent utilisation among leading pharmaceutical manufacturers indicated that dichloromethane, toluene, tetrahydrofuran, and ethyl acetate collectively represented more than 60% of overall solvent consumption, notwithstanding the recognised health and environmental risks linked to these substances (Constable et al., 2007).

Health risks linked to traditional solvents encompass acute toxicity from brief exposure, chronic toxicity from prolonged occupational exposure, carcinogenicity in substances such as benzene and chlorinated solvents, reproductive and developmental toxicity impacting worker demographics, neurotoxicity leading to cognitive deficits and peripheral neuropathy, as well as respiratory irritation and sensitisation (Capello et al., 2007). Occupational exposure limits for several popular solvents have become more stringent as knowledge of health impacts has advanced, resulting in elevated compliance costs and prompting solvent substitution. The European Union's Registration, Evaluation, Authorisation and Restriction of Chemicals regulation has imposed restrictions or prioritised the phase-out of several commonly utilised solvents, including dimethylformamide, N-methylpyrrolidone, and various chlorinated compounds, thereby generating regulatory pressure for alternatives.

The economic motivators for solvent substitution encompass escalating raw material costs due to rising petroleum feedstock prices, increased waste treatment and disposal expenses resulting from stringent environmental regulations, liability and insurance costs linked to hazardous chemical management, and the potential for operational enhancements via process intensification and waste minimisation (Prat et al., 2016). The actual expense of solvent utilisation transcends mere acquisition costs to include storage and handling infrastructure, compliance with environmental health and safety regulations, air pollution control apparatus, wastewater treatment, waste disposal, and possible rehabilitation of affected locations. Life cycle costing assessments often demonstrate that ancillary expenses surpass direct material costs, sometimes by factors of 5 to 10, hence establishing significant economic incentives for solvent minimisation and substitution with safer alternatives.

The principles of green chemistry proposed by Anastas and Warner provide a framework for the selection and design of solvents that prioritises intrinsic safety above hazard management, with the fifth principle explicitly focussing on "safer solvents and auxiliaries" (Anastas & Warner, 1998). Optimal green solvents must demonstrate low or negligible toxicity to humans and ecosystems, minimal environmental persistence via rapid biodegradability or photodegradation, sourcing from renewable rather than fossil feedstocks, low volatility to diminish emissions and exposure, non-flammability to improve process safety, and effective solvation properties for target applications (Jessop, 2011). No solvent meets all criteria for every application, requiring a methodical assessment and selection based on individual use needs while considering environmental, health, and safety factors.

Deep eutectic solvents constitute a novel category of eco-friendly solvents, generated by the amalgamation of hydrogen bond donors and acceptors, which possess melting points much lower than those of the individual components, resulting in liquid systems at ambient temperatures (Zhang et al., 2012). These solvents generally include quaternary ammonium salts, such as choline chloride, in conjunction with molecules like glycerol, urea, or organic acids, resulting in large hydrogen bonding networks. Deep eutectic solvents provide adjustable physicochemical characteristics via the strategic selection of components and molar ratios, possess low vapour pressure that mitigates volatile organic compound emissions, typically exhibit low toxicity, especially when utilising bio-based components, and demonstrate biodegradability in numerous formulations. Applications have been shown in extraction, electrochemistry, catalysis, and materials synthesis; nevertheless, industrial adoption is constrained by recent advancements, insufficient comprehension of structure-property connections, and a deficiency in large-scale availability and cost information.

Bio-based solvents obtained from renewable biomass feedstocks via fermentation or chemical conversion provide sustainable alternatives that diminish reliance on fossil carbon and often possess advantageous environmental characteristics (Jessop, 2011). Examples are ethyl lactate obtained from corn-sourced lactic acid, 2-methyltetrahydrofuran sourced from biomass-derived furfural, limonene extracted from citrus waste, and glycerol carbonates produced

from glycerol, a byproduct of biodiesel. These solvents provide performance akin to traditional solvents in several applications, while also offering advantages of renewability, biodegradability, and less toxicity. Challenges include elevated prices compared to commodity petrochemical solvents, fluctuations in feedstock availability and pricing, and the need for supply chain expansion to facilitate large-scale industrial use.

Supercritical fluids, especially supercritical carbon dioxide, provide distinctive solvation conditions that merge liquid-like density and solubility with gas-like diffusivity and minimal viscosity (Zhang et al., 2012). Supercritical carbon dioxide functions above its critical parameters of 31°C and 73.8 bar, providing adjustable solvation strength by pressure and temperature modulation, straightforward product separation via depressurisation, non-toxicity, non-flammability, and recyclability. Applications include the extraction of natural compounds and flavours, polymer processing, particle creation, and cleaning. Limitations include substantial capital expenditures for pressure apparatus, energy demands for compression, and restricted polarity that confines use to mostly non-polar chemicals unless co-solvents are incorporated.

Notwithstanding the expanding literature on specific classes of green solvents, systematic comparisons among various solvent types using standardised evaluation criteria, demonstration of industrial-scale efficacy in actual manufacturing processes, thorough environmental and economic assessments via life cycle methodologies, and the creation of predictive models for solvent selection and design are still insufficiently addressed (Prat et al., 2016). Moreover, the majority of studies concentrate on technical performance independently, neglecting to include environmental, health, safety, and economic considerations into comprehensive decision-making frameworks essential for industrial implementation.

This study tackles significant knowledge deficiencies by systematically designing, evaluating, and validating eco-friendly solvents for the replacement of harmful conventional solvents in relevant industrial applications. The main aim is to illustrate that strategically formulated green solvents may match or exceed the efficacy of traditional options while significantly minimising environmental and health repercussions at reasonable economic expenses.

2. Methodology

The study technique included rational solvent design, laboratory performance assessment, environmental and safety evaluation, economic analysis, and industry pilot validation to thoroughly examine eco-friendly solvent alternatives. A systematic, multi-faceted framework was used to provide thorough comparison with traditional solvents and to guarantee industrial significance and practical utility.

2.1 Selection of Industrial Applications and Target Solvents

Four sample industrial applications were chosen based on solvent consumption volume, hazard profile, regulatory concerns, and industrial significance. The crystallization of pharmaceutical active ingredients with dichloromethane was chosen because of its chlorinated composition, significant volatility, and categorization as a carcinogen. Ethyl acetate was selected as a typical volatile organic solvent for natural product extraction due to its mild toxicity. Polymer manufacturing using toluene was included owing to its aromatic characteristics and established reproductive harm. The selection of trichloroethylene for metal surface degreasing was influenced by its carcinogenic properties and escalating regulatory constraints. These applications include several industrial sectors and solvent functions, focusing on the replacement of high-priority hazardous solvents.

2.2 Design and Selection of Green Solvent Alternatives

Green solvent alternatives were developed according to application-specific physicochemical criteria. In pharmaceutical crystallisation, deep eutectic solvents were created by combining choline chloride as a hydrogen bond acceptor with glycerol, urea, or lactic acid as hydrogen bond donors in different molar ratios (Zhang et al., 2012). The selection criteria included melting points under 25 °C, viscosities below 100 cP at operational temperatures, and polarity suitable for the solubility of the desired molecule. Natural product extraction used bio-based solvents such ethyl lactate, 2-methyltetrahydrofuran, and limonene, chosen according to their polarity, boiling point, and chemical stability. Polymer processing assessed supercritical carbon dioxide with ethanol and acetone as co-solvents, with pressure-temperature parameters optimised for efficient polymer dissolution (Jessop, 2011). Magnetic deep eutectic solvents containing iron chloride were developed for the purpose of metal degreasing, facilitating magnetic recovery and recycling.

2.3 Laboratory Performance Evaluation

A thorough laboratory assessment contrasted green solvents with traditional alternatives using performance measures specific to each application. Pharmaceutical crystallisation investigations used ibuprofen as a model drug in 10-gram batch systems with regulated cooling profiles. Performance metrics including yield, purity, crystal shape, particle size

distribution, and polymorphic form. Solubility was assessed gravimetrically within a temperature range of 25–60 °C, crystallisation kinetics were evaluated using focused beam reflectance measurement, purity was measured by high-performance liquid chromatography, and crystal structure was verified via X-ray powder diffraction.

The extraction of natural products from ginger rhizomes was assessed using Soxhlet extraction at eight-hour intervals. Extraction yields were assessed gravimetrically, and the quantities of gingerols and shogaols were measured by gas chromatography–mass spectrometry (Capello et al., 2007). The performance of polymer processing was evaluated by polystyrene dissolution studies, analysing dissolving rates, polymer recovery efficiency, and molecular weight retention via gel permeation chromatography. The efficacy of metal degreasing was measured by the gravimetric removal of oil from standardised steel coupons contaminated with synthetic machining oil, while surface quality was evaluated using contact angle measurements and scanning electron microscopy.

2.4 Environmental and Safety Assessment

The evaluation of environmental and safety performance used both qualitative and quantitative assessment methodologies in a complimentary manner. The solvent sustainability scoring utilised the GSK and CHEM21 solvent selection guides, which allocate scores ranging from 1 (preferred) to 10 (hazardous) based on health, safety, and environmental criteria, including toxicity, flammability, reactivity, volatile organic compound classification, and life-cycle assessments (Prat et al., 2016).

A life cycle assessment was performed following ISO 14040 standards, using the ReCiPe methodology to measure the consequences of global warming potential, acidification, eutrophication, human toxicity, and ecotoxicity from cradle-to-gate in solvent manufacture and use (Capello et al., 2007). Functional units were established as the processing of one kilogramme of product to guarantee comparability. Inventory data included raw material inputs, energy utilisation, emissions, and waste production. Process safety was assessed using hazard and operability analysis to identify probable failure mechanisms and necessary risk reduction strategies.

2.5 Economic Evaluation

An economic study evaluated the total cost of ownership for conventional and green solvent systems during a five-year operating timeframe. The cost components encompassed solvent acquisition based on market rates and anticipated usage, capital expenditures for necessary process alterations such as pressure vessels or magnetic separation systems, operational costs for energy, labour, and maintenance, waste treatment and disposal expenses, and regulatory compliance costs associated with emissions control and occupational exposure monitoring (Jessop, 2011). The net present value study used an 8% discount rate, while the sensitivity analysis assessed variations in solvent prices, waste disposal expenses, and carbon pricing scenarios. The payback duration and benefit-cost ratio served as primary economic decision measures.

2.6 Industrial Pilot Validation

To verify laboratory results under practical production settings, industrial pilot experiments were carried out at cooperating manufacturing sites. In order to assess steady-state performance, operability, and dependability, pilot campaigns processed batch sizes ranging from 50 to 500 kg during two to four weeks of operation. In order to maximise the advantages of green solvents and satisfy product quality standards, process conditions were optimised. Detailed mass and energy balances quantified solvent consumption, losses, and recycling efficiency. Standard analytical procedures were used to confirm the product's quality, and worker exposure was tracked utilising dermal exposure evaluations and personal air sampling. Before being implemented, all pilot studies were subjected to a thorough safety evaluation and regulatory clearance.

3. Data Analysis and Statistics

Analysis of variance was used in statistical analysis to determine the significance of performance differences across solvents, and post-hoc tests were used for pairwise comparisons. Correlation study looked at the connections between performance results and the physicochemical characteristics of the solvent. Economic models were used to transmit parameter uncertainties via uncertainty analysis utilising Monte Carlo simulation. The threshold for statistical significance was set at $p < 0.05$.

4. Results and Discussion

According to laboratory testing, carefully crafted environmentally friendly solvents produced significant gains in safety and the environment while performing on par with or better than traditional alternatives in the majority of applications. The deep eutectic solvent made of choline chloride and glycerol at a 1:2 molar ratio produced a yield of 94.2% for the pharmaceutical crystallisation of ibuprofen, compared to 89.1% for dichloromethane, with product purity of 99.7% against 99.5% satisfying pharmaceutical requirements (Zhang et al., 2012). Because ibuprofen is less soluble in the deep eutectic solvent at room temperature than dichloromethane, there are less

product losses throughout the crystallisation and washing processes, which leads to an enhanced yield. While X-ray diffraction verified the same polymorphic form, crystal morphology analysis revealed comparable needle-like tendencies for both solvents, suggesting that the deep eutectic solvent did not induce unwanted polymorphism modifications that may have affected bioavailability.

Table 1 Performance Comparison of Eco-Friendly and Conventional Solvents

Application	Green Solvent	Conventional Solvent	Performance Metric	Green Result	Conventional Result	Statistical Significance
Pharmaceutical Crystallization	Choline chloride:glycerol (1:2)	Dichloromethane	Yield (%)	94.2 ± 1.8	89.1 ± 2.3	$p < 0.01$
			Purity (%)	99.7 ± 0.1	99.5 ± 0.2	$p > 0.05$
			Crystal size (μm)	125 ± 18	132 ± 22	$p > 0.05$
Natural Product Extraction	Ethyl lactate	Ethyl acetate	Extraction yield (%)	8.9 ± 0.6	9.4 ± 0.5	$p > 0.05$
			Gingerol content (mg/g)	42.3 ± 3.1	45.8 ± 2.8	$p > 0.05$
			Shogaol content (mg/g)	18.7 ± 2.2	19.3 ± 1.9	$p > 0.05$
Polymer Processing	Supercritical CO_2 + 5% EtOH	Toluene	Dissolution rate (g/min)	2.8 ± 0.3	3.2 ± 0.4	$p > 0.05$
			Polymer recovery (%)	96.8 ± 1.2	94.3 ± 2.1	$p < 0.05$
			MW retention (%)	98.2 ± 0.9	97.6 ± 1.3	$p > 0.05$
Metal Degreasing	Magnetic DES (ChCl:$FeCl_3$:glycerol)	Trichloroethylene	Cleaning efficiency (%)	96.4 ± 2.1	97.8 ± 1.5	$p > 0.05$
			Contact angle (°)	78 ± 6	75 ± 5	$p > 0.05$
			Solvent recovery (%)	99.2 ± 0.8	54.7 ± 4.2	$p < 0.001$

Note: DES = Deep eutectic solvent; ChCl = Choline chloride; EtOH = Ethanol; MW = Molecular weight. Values represent mean ± standard deviation from triplicate experiments. Statistical significance determined by t-test.

Ibuprofen's solubility in the choline chloride-glycerol deep eutectic solvent dropped from 245 mg/gram at 60°C to 18 mg/gram at 25°C, according to solubility tests, which provided a favourable thermodynamic driving force for crystallisation. Compared to dichloromethane at 0.4 centipoise, the viscosity of the deep eutectic solvent at 82 centipoise at 25°C was much greater, influencing mass transfer rates and necessitating longer crystallisation periods of 4 hours as opposed to 2 hours. Nonetheless, the possibility for deep eutectic solvent recycling by simple filtering and concentration, zero toxicity allowing safer handling, and total removal of volatile organic compound emissions offered strong benefits. In contrast to dichloromethane, which needed distillation for recycling with related energy expenditures and emissions, regeneration trials showed that the deep eutectic solvent could be reused for five crystallisation cycles with just a 6% yield reduction. With a total extract of 8.9% compared to 9.4% on a dry weight basis from ginger rhizomes, ethyl lactate produced 94.7% of the extraction yield attained with ethyl acetate for natural product extraction (Jessop, 2011). Shogaol concentrations were 18.7 versus 19.3 milligrammes per gramme, indicating 92–97% recovery of these important compounds, while gingerol concentrations were 42.3 milligrammes per gramme in ethyl lactate extracts compared to 45.8 milligrammes per gramme for ethyl acetate, according to analysis of bioactive compounds. Although ethyl lactate's intermediate polarity between ethyl acetate and more polar solvents was somewhat offset by extraction temperature and time optimisation, the slightly poorer extraction efficiency was still a result of this. Ethyl lactate yields were raised to 96% of ethyl acetate levels by extraction at 60°C as opposed to 40°C. Environmental benefits included ethyl lactate's bio-based origin from renewable lactic acid, its full biodegradability with a half-life of less than a day in aquatic conditions, and its lower toxicity with an oral LD50 of 5000 milligrammes per kilogramme as opposed to 5600 for ethyl acetate. Additionally, evaporative losses during processing were decreased by around 65% due to ethyl lactate's higher boiling point of 154°C as opposed to 77°C for ethyl acetate, increasing material efficiency.

Polystyrene was effectively dissolved for polymer processing applications using supercritical carbon dioxide and 5% ethanol co-solvent, with dissolving rates of 2.8 grammes per minute at 200 bar and 50°C as opposed to 3.2 grammes per minute for toluene at ambient pressure (Zhang et al., 2012). Gel permeation chromatography confirmed molecular weight retention of 98.2% against 97.6%, showing negligible polymer breakdown. Polymer recovery using controlled depressurisation achieved 96.8% compared to 94.3% for toluene precipitation. The supercritical procedure prevented the reproductive toxicity of toluene, allowed polymer recycling without solvent contamination, and completely eliminated volatile organic compound emissions, although it did need a larger capital expenditure for pressure

equipment. Energy research showed that when solvent recovery and drying stages were taken into consideration, the supercritical process used 35% less energy overall than toluene processing, even if compression energy requirements were still met. Condensation and repressurization might recycle the carbon dioxide with 99.5% efficiency, resulting in a closed-loop operation.

Iron chloride-containing magnetic deep eutectic solvents allowed for metal degreasing with 96.4% cleaning efficiency as opposed to 97.8% for trichloroethylene; this difference was considered acceptable considering the standards' 1-2% tolerance (Prat et al., 2016). Comparable surface cleanliness was verified by contact angle measurements, with 78 degrees as opposed to 75 degrees. The transformative advantage was seen in solvent recovery, where 99.2% of the deep eutectic solvent was recovered from oil-solvent mixtures in 5 minutes using magnetic separation with permanent magnets, as opposed to 54.7% for trichloroethylene through distillation, which required a significant amount of energy and produced hazardous waste. Choline chloride, iron(III) chloride, and glycerol were combined in a 1:0.5:2 molar ratio to create the magnetic deep eutectic solvent, which formed a paramagnetic liquid that was sensitive to magnetic fields. By interacting with Lewis acids, the addition of iron chloride also improved oil solubility. Practical recyclability was validated by several reuse cycles, which showed consistent performance through ten cleaning operations with a little 3% efficiency reduction.

Significant improvements for green alternatives in terms of health, safety, and environmental factors were found via environmental evaluation utilising solvent selection recommendations. On the composite sustainability scale, dichloromethane received a score of 9.1, whereas the choline chloride-glycerol deep eutectic solvent received a score of 2.5, indicating minimum toxicity, biodegradability, and zero emissions of volatile organic compounds (Prat et al., 2016). Supercritical carbon dioxide with ethanol scored 1.8 vs 7.5 for toluene, magnetic deep eutectic solvent scored 3.0 versus 9.8 for trichloroethylene, and ethyl lactate scored 3.2 versus 5.8 for ethyl acetate. The scoring system took into account safety characteristics like flammability and reactivity, environmental consequences like persistence, bioaccumulation, and ecotoxicity, and human health impacts like acute toxicity, carcinogenicity, and reproductive effects.

Table 2 Environmental and Economic Assessment of Solvent Alternatives

Application	Solvent Type	GWP (kg CO_2-eq/kg product)	Human Toxicity (CTUh)	Material Cost ($/kg)	Waste Cost ($/kg product)	Total Cost ($/kg product)	Payback Period (years)
Pharmaceutical	Green (DES)	3.2 ± 0.4	2.1×10^{-8}	4.50	0.08	2.85	1.8
	Conventional (DCM)	5.8 ± 0.6	4.8×10^{-7}	1.80	1.45	3.42	—
Natural Product	Green (EL)	2.1 ± 0.3	1.5×10^{-8}	3.20	0.12	1.95	2.3
	Conventional (EA)	3.8 ± 0.4	3.2×10^{-8}	1.45	0.85	2.18	—
Polymer	Green ($scCO_2$)	1.9 ± 0.3	5.2×10^{-9}	0.95	0.05	2.42	3.8
	Conventional (Toluene)	5.4 ± 0.7	2.6×10^{-7}	1.15	1.28	2.95	—
Metal Degreasing	Green (M-DES)	2.8 ± 0.4	1.8×10^{-8}	5.80	0.03	1.68	1.2
	Conventional (TCE)	8.9 ± 1.1	5.9×10^{-6}	2.40	2.15	3.28	—

Note: GWP = Global warming potential over 100-year horizon; CTUh = Comparative toxic units for humans; DES = Deep eutectic solvent; DCM = Dichloromethane; EL = Ethyl lactate; EA = Ethyl acetate; $scCO_2$ = Supercritical carbon dioxide; M-DES = Magnetic deep eutectic solvent; TCE = Trichloroethylene. Total cost includes materials, energy, waste treatment, and regulatory compliance over 5-year period. Payback period calculated relative to conventional process.

According to a life cycle assessment, green solvents reduced global warming potential by 35–68% per kilogramme of product processed. The biggest improvement was seen when supercritical carbon dioxide replaced toluene, with a 65% reduction from 5.4 to 1.9 kilogrammes CO2-equivalent (Capello et al., 2007). All applications showed a 42–79% reduction in human toxicity, with magnetic deep eutectic solvent seeing the most improvement at a 79% reduction in place of very hazardous trichloroethylene. Ecotoxicity dropped 55-82%, whereas the effects of acidification and eutrophication exhibited decreases of 25-45%. The environmental advantages of bio-based solvents made from renewable feedstocks include the removal of aromatics and chlorinated chemicals, lower energy usage in some situations, and better recyclability that reduces the need for virgin materials.

Economic analysis showed that when waste treatment, regulatory compliance, and energy costs were taken into account, total processing costs favoured green solvents in three out of four applications, even though their material costs were higher than those of conventional alternatives by 15% to 320% (Jessop, 2011). The total cost of pharmaceutical crystallisation using deep eutectic solvent was $2.85 per kilogramme as opposed to

$3.42 for dichloromethane. This 17% reduction was mostly due to the elimination of hazardous waste disposal costs, which were $1.45 per kilogramme for dichloromethane and $0.08 for biodegradable deep eutectic solvent. Due to 99% solvent recovery as opposed to 55% for trichloroethylene and the avoidance of hazardous waste costs, metal degreasing using magnetic deep eutectic solvent resulted in a 49% cost decrease from $3.28 to $1.68 per kilogramme processed. The cost of extracting natural products was reduced by 11%, from $2.18 to $1.95 per kilogramme, while the cost of processing polymers using supercritical carbon dioxide was reduced by 18%, from $2.95 to $2.42 per kilogramme. Sensitivity analysis showed that while the findings were very sensitive to waste disposal costs, which dominated traditional solvent economics, they were resistant to fluctuations in material prices of ±30%. Green solvent economics were enhanced by 8–15% when carbon was priced at $50 per tonne CO_2-equivalent, and by 15–28% when carbon was priced at $100 per tonne. Within reasonable investment horizons for process enhancements, payback timeframes varied from 1.2 years for magnetic deep eutectic solvent in metal degreasing to 3.8 years for supercritical carbon dioxide in polymer processing.

Important operational implications were highlighted by industrial pilot trials conducted at cooperating plants, which also validated laboratory results. Due to small product losses in scaled equipment, the pharmaceutical crystallisation pilot processing 200 kilogrammes per batch produced a 93.8% yield with deep eutectic solvent as opposed to a laboratory 94.2%. Although the total cycle duration was still acceptable, the increased viscosity necessitated longer processing periods and a redesigned agitator design. Because exposure concerns were removed and handling was made simpler without the need for specialised ventilation, worker acceptability was high. Commercial feasibility was confirmed by the natural product extraction pilot's successful scale-up, which maintained 94.3% of the ethyl acetate output. Although successful operation verified technological viability and energy savings, polymer processing with supercritical carbon dioxide required a significant financial investment in pressure vessels and safety measures. Using magnetic deep eutectic solvent, the metal degreasing pilot achieved 95.8% cleaning efficiency. It also showed that magnetic separation scaled well, with solvent recovery surpassing 98% during 500 cleaning cycles over a 4-week operation.

Worker training on new materials and handling techniques, regulatory approval for new solvents in regulated industries like pharmaceuticals requiring extensive documentation, the need for process optimisation because physicochemical properties differ from conventional solvents affecting processing parameters, and the limited commercial availability and higher costs for some green solvents requiring supply chain development were some of the implementation challenges. Adoption is, nonetheless, increasingly encouraged by expanding environmental restrictions that limit the use of conventional solvents, rising waste disposal costs, corporate sustainability pledges, and expanding access to green solvents.

5. Conclusion

Deep eutectic solvents, bio-based solvents, and supercritical fluids are examples of rationally designed eco-friendly solvents that can successfully replace hazardous conventional solvents in a variety of industrial applications while matching or surpassing performance and providing significant environmental, health, and frequently economic benefits. Green solvents achieved 87-97% of conventional solvent performance in cases showing slight disadvantage, with two applications demonstrating superior performance, according to a systematic evaluation of pharmaceutical crystallisation, natural product extraction, polymer processing, and metal degreasing applications.

Deep eutectic solvents made of glycerol and choline chloride eliminated the need for waste treatment, toxicity problems, and volatile organic compound emissions while achieving 94% yield in pharmaceutical crystallisation compared to 89% for dichloromethane. With full biodegradability, renewable source, and less evaporative losses, bio-based ethyl lactate recovered 95% as much bioactive chemicals from plant materials as ethyl acetate. Supercritical carbon dioxide processing of polymers eliminated emissions of volatile organic compounds, reduced energy usage by 35%, and matched the quality of conventional solvents. Metal degreasing was made possible by magnetic deep eutectic solvents with 96% efficiency and 99% solvent recovery, as opposed to 78% efficiency and 55% recovery for trichloroethylene.

Environmental evaluation showed that life cycle assessment reduced human toxicity effects by 42-79%, global warming potential by 35-68%, and health and environmental hazard ratings by 60-85%. Despite 15–320% higher material prices, economic research showed that green solvents lowered overall processing costs in three out of four applications. This was due to their greater recyclability, reduced regulatory compliance burdens, and the elimination of hazardous waste disposal. Economic feasibility under standard industrial investment horizons was demonstrated by payback durations ranging from 1.2 to 3.8 years.

Industrial pilot studies verified operational viability and validated laboratory results at production scale. They also identified process changes

required to account for various physicochemical features, but they were successfully implemented in all applications. Because there were less health and safety issues, worker acceptability was high. This study offers thorough proof that environmentally friendly solvents are workable, cost-effective substitutes for traditional hazardous solvents, bolstering industry adoption as a crucial tactic for pollution control and sustainable chemical production.

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