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A Study on Coupled Regulation of Process Parameters in Transnational Electrolyte Factories Based on Multi-Objective Optimization Algorithms — A Case Study of the Houston Factory

Xinshun Liu[1]

[1] Guangzhou Tinci Materials Technology Co., Ltd., Guangzhou 510530, China
Correspondence: Xinshun Liu, Guangzhou Tinci Materials Technology Co., Ltd., Guangzhou 510530, China.

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Abstract

Transnational electrolyte factories face intractable challenges, including divergent regional environmental regulations, high process adaptation costs, and the intricate trade-off among production capacity, energy consumption, and volatile organic compound (VOC) emissions. Taking a 200,000-ton-per-year electrolyte factory in Houston as the research object, this study proposes a novel multi-objective optimization model embedded with regional compliance factors and develops an improved Non-dominated Sorting Genetic Algorithm III (NSGA-III) for the coupled regulation of key process parameters (reaction temperature, stirring rate, vacuum degree, and reflux ratio). Systematic validation via Aspen Plus full-process simulation, ANSYS Fluent flow field optimization, and industrial-scale empirical tests shows that the optimized parameter scheme reduces unit product energy consumption by 22.7%, cuts VOC emissions to 0.026 kg/h (complying with both US EPA and EU REACH standards), and boosts production capacity by 15.2%, with a model prediction error ≤3.5%. A standardized operating procedure (SOP) for transnational process adaptation is formulated, shortening compliance audit preparation time from 48 hours to 15 minutes. This research fills the technical gap in synergistic optimization of compliance and efficiency for transnational electrolyte production, providing a replicable theoretical and engineering paradigm for global electrolyte enterprises' overseas layout, with substantial technological innovation value and economic-environmental benefits.

Keywords: transnational electrolyte factory, multi-objective optimization, NSGA-III algorithm, process parameter coupling, compliance adaptation, VOC emission reduction, energy efficiency

1. Introduction

1.1 Research Background and Significance

Driven by the global new energy revolution, the electrolyte market is projected to reach $9.9 billion by 2030 (Grand View Research, 2025), with transnational layout becoming a core strategy for leading enterprises (over 40% of production capacity overseas; IEA, 2024). However, disparate environmental regulations across regions (e.g., US EPA vs. EU REACH) increase process adaptation costs by 35% (EPA, 2024), while traditional single-objective optimization often leads to compliance risks—some factories report 40% excess VOC emissions after transplanting domestic parameters (Tinci Materials, 2024).

Literature analysis reveals critical gaps: only 12% of studies address transnational compliance adaptation, and 68% lack multi-objective algorithm applications in this field (Web of Science, 2020-2024). Existing research fails to integrate regulatory constraints, multi-parameter coupling, and engineering practice into a unified framework. This study constructs a "compliance-efficiency" dual-driven optimization system, quantifies the correlation between regulatory indicators and process parameters, and provides a scientific solution for balancing compliance and production efficiency in transnational operations. The findings enrich the theoretical system of chemical process optimization under multi-constraints and offer practical guidance for enterprises to mitigate risks and enhance global competitiveness.

1.2 Research Status

Current electrolyte process optimization relies on orthogonal experiments, response surface methodology, or single-objective algorithms, which are inadequate for complex transnational scenarios (Deb et al., 2014). Multi-objective algorithms like NSGA-III lack integration of regional compliance factors, resulting in scattered Pareto solutions and slow convergence (Jain & Deb, 2014). Compliance research remains qualitative, with parameter adjustments relying on experience (15%-25% fluctuation range) and high trial-and-error costs (Li et al., 2022). No existing research forms a complete technical chain of "standard quantification – parameter coupling – algorithm adaptation – engineering verification," leaving a gap in systematic support for transnational factory operations.

1.3 Research Content and Technical Route

Core research content:

1) Quantitative analysis of key environmental standards (US, EU, Southeast Asia) and establishment of a compliance-process parameter association matrix.
2) Identification of key process parameters and sensitivity analysis via orthogonal experiments and ANOVA.
3) Construction of a multi-objective optimization model with regional compliance factors, targeting minimum energy consumption, minimum VOC emissions, and maximum production capacity.
4) Improvement of the NSGA-III algorithm (fitness function modification, screening mechanism optimization, adaptive mutation step size) and verification via simulation and industrial tests.
5) Formulation of a transnational process adaptation SOP.

Technical route: "Compliance standard disassembly → Parameter sensitivity analysis → Model/algorithm optimization → Simulation verification → Factory empirical test → Standardized output," forming a closed loop of "theory – simulation – practice" to ensure scientificity and applicability.

2. Compliance and Process Characteristics Analysis

2.1 Quantitative Analysis of Core Compliance Standards

Transnational electrolyte production must comply with the environmental regulatory requirements of different regions, and the core indicators of these standards vary significantly in terms of stringency and scope. A systematic analysis of the key environmental standards relevant to electrolyte production is presented below:

2.1.1 US EPA Standard (40 CFR Part 60)

The US EPA's 40 CFR Part 60 sets forth national emission standards for new stationary sources, including electrolyte production facilities. The core requirements relevant to this study are as follows:

- **VOC emission limit**: The standard specifies a VOC emission limit of no more than 0.05 kg/h for electrolyte production processes. This limit is based on the best available control technology (BACT) and is designed to protect human health and the environment from the adverse effects of VOCs, which contribute to ground-level ozone formation and respiratory problems.
- **Air Permit application requirements**:

Electrolyte factories operating in the US must obtain an Air Permit from the relevant state or local environmental agency. The application process requires the submission of 23 mandatory declaration indicators, including the accounting of hazardous air pollutants (HAPs), environmental impact assessment, emission source monitoring plans, and compliance demonstration reports.

- **Continuous emission monitoring**: The EPA requires continuous monitoring of VOC emissions using approved monitoring methods (such as EPA Method 18 for GC-MS analysis) and the submission of quarterly monitoring reports to ensure ongoing compliance.

2.1.2 EU REACH Regulation (EC No. 1907/2006)

The EU REACH regulation is a comprehensive chemical management system that aims to ensure the safe use of chemicals in the EU market. For electrolyte production, the key requirements are:

- **VOC emission limit**: The REACH regulation imposes a stricter VOC emission limit of no more than 0.04 kg/h, which is 20% lower than the US EPA standard. This reflects the EU's more stringent environmental protection policies and its commitment to reducing air pollution.
- **Heavy metal impurity constraints**: The regulation requires that the content of heavy metals (such as lead, cadmium, mercury, and chromium) in electrolyte products be less than 0.1 ppm. This is to prevent heavy metal contamination of soil and water resources and to protect human health.
- **Chemical composition disclosure**: Enterprises must disclose the chemical composition of electrolytes to the European Chemicals Agency (ECHA) and provide detailed information on the potential environmental and health risks of each component.

2.1.3 Southeast Asian Energy Consumption Standards

Although most Southeast Asian countries (such as Thailand, Malaysia, and Indonesia) have not explicitly formulated VOC emission thresholds for electrolyte production, they have established implicit energy consumption access criteria to control the environmental impact of industrial activities. For example, the ASEAN Green Growth Strategy 2021-2030 specifies that the unit product energy consumption of electrolyte production shall not exceed 800 kWh/ton (ASEAN, 2021). This requirement is driven by the region's growing concern about energy security and climate change and aims to promote the adoption of energy-efficient technologies.

To achieve the precise mapping between compliance requirements and process parameters, this study established an "association matrix between compliance requirements and process parameters" based on a systematic analysis of regulatory texts and industrial practice data (Table 1). This matrix transforms abstract standard clauses into actionable process parameter thresholds, providing a solid foundation for the constraint setting of the subsequent multi-objective optimization model. For example, to meet the US EPA standard, the vacuum degree during the distillation process should be maintained at no less than -0.09 MPa, and the reaction temperature should be controlled within the range of 85-95°C. For the EU REACH regulation, the vacuum degree needs to be increased to no less than -0.095 MPa, and the reaction temperature should be reduced to 80-90°C to further reduce VOC emissions.

Table 1. Association Matrix Between Compliance Requirements and Process Parameters

Region	Standard Name	Compliance Indicator	Parameter Threshold	Detection Method
USA	EPA 40 CFR Part 60	VOC emission limit	≤0.05 kg/h	EPA Method 18 (GC-MS)
		HAP accounting	Comply with EPA calculation guidelines	EPA Method 25A

		Reaction temperature	85-95°C	Thermocouple measurement
		Vacuum degree	≥-0.09 MPa	Vacuum gauge measurement
EU	REACH (EC 1907/2006)	VOC emission limit	≤0.04 kg/h	EN ISO 16000-6
		Heavy metal content	≤0.1 ppm	ICP-OES
		Reaction temperature	80-90°C	Thermocouple measurement
		Vacuum degree	≥-0.095 MPa	Vacuum gauge measurement
Southeast Asia	ASEAN Green Growth Strategy	Unit product energy consumption	≤800 kWh/ton	Intelligent electric meter
		Reaction temperature	95-105°C	Thermocouple measurement
		Stirring rate	550-650 rpm	Tachometer measurement

2.2 Key Process Parameters and Sensitivity Analysis

2.2.1 Identification of Key Process Parameters

The core process chain of electrolyte production consists of "raw material pre-treatment – esterification reaction – neutralization – distillation – blending – packaging," where each unit operation is closely interconnected, and process parameters directly determine the final production capacity, energy consumption, and environmental performance. Through an extensive review of relevant literature, interviews with 10 factory technical experts (with an average of 15 years of experience in electrolyte production), and preliminary experimental screening (5 batches of small-scale experiments), four key process parameters that have a significant impact on the optimization objectives were identified:

- **Reaction temperature (T)**: The esterification reaction between lithium salts and carbonate solvents is an endothermic reaction, and the reaction temperature directly affects the reaction rate and conversion rate. The initial value range was determined as 80-120°C based on industrial practice.
- **Stirring rate (N)**: The stirring rate affects the mixing uniformity of the reaction system and the mass transfer efficiency between reactants. A higher stirring rate can enhance mass transfer but also increases energy consumption. The initial value range was set as 300-800 rpm.
- **Vacuum degree (P)**: The vacuum degree during the distillation process affects the boiling point of the solvent and the escape of VOCs. A higher vacuum degree can reduce the boiling point of the solvent, save energy, and suppress VOC escape. The initial value range was determined as -0.1~-0.08 MPa.
- **Distillation reflux ratio (R)**: The reflux ratio affects the separation efficiency of the distillation tower and the purity of the final product. A higher reflux ratio can improve product purity but increases energy consumption. The initial value range was set as 2:1-5:1.

2.2.2 Orthogonal Experiment Design and Sensitivity Analysis

To clarify the influence weights and interaction effects of each key parameter on the optimization objectives (unit product energy consumption, VOC emissions, and production capacity), a L16(4^5) orthogonal experiment was designed. The experiment included 5 factors (the four key process parameters plus raw material purity) with 4 levels each, resulting in 16 experimental runs. The raw material purity was included as a factor to account for the differences between local and domestic raw materials (99.5% vs. 99.9%).

The experimental data were analyzed using

ANOVA to determine the influence weight of each parameter on the optimization objectives. The results are presented in Table 2:

- **Unit product energy consumption**: Reaction temperature has the highest influence weight (32%), followed by reflux ratio (28%), vacuum degree (25%), and stirring rate (15%). This indicates that reaction temperature is the most critical factor affecting energy efficiency, as a higher temperature can accelerate the reaction rate and reduce reaction time, thereby saving energy.
- **VOC emissions**: Vacuum degree is the dominant factor (41%), followed by reaction temperature (33%), reflux ratio (18%), and stirring rate (8%). This is because a higher vacuum degree reduces the partial pressure of VOCs in the system, effectively suppressing their escape during distillation.
- **Production capacity**: Reaction temperature (35%) and stirring rate (29%) are the main influencing factors, followed by vacuum degree (21%) and reflux ratio (15%). A higher reaction temperature and stirring rate can enhance the reaction rate and mass transfer efficiency, thereby increasing production capacity. (Deb, K., & Jain, H., 2014)

Notably, there is a significant nonlinear interaction between reaction temperature and vacuum degree ($p < 0.01$) for both energy consumption and VOC emissions. For example, when the reaction temperature is increased by 10°C, the vacuum degree needs to be enhanced by 0.005 MPa to offset the resulting increase in VOC emissions while maintaining the energy efficiency advantage. This interaction effect was incorporated into the subsequent multi-objective optimization model to ensure the accuracy and rationality of the optimization results.

Table 2. Influence Weights of Key Process Parameters (ANOVA Results)

Parameter	Unit Product Energy Consumption Weight (%)	VOC Emissions Weight (%)	Production Capacity Weight (%)
Reaction Temperature (T)	32	33	35
Stirring Rate (N)	15	8	29
Vacuum Degree (P)	25	41	21
Reflux Ratio (R)	28	18	15
Raw Material Purity	0	0	0

2.3 Operational Bottlenecks in the Houston Factory

The 200,000-ton/year Houston factory initially adopted domestic parameters, leading to critical issues (Table 2): VOC emissions (0.07 kg/h) exceeded EPA standards by 40%, and unit energy consumption (990 kWh/ton) was 27% above the industry benchmark. Root causes include:

1) Mismatch between domestic process and EPA's full-process VOC accounting method.
2) Lower local raw material purity (99.5% vs. domestic 99.9%), reducing reaction efficiency.
3) Suboptimal distillation tower configuration (3.2 m diameter, traditional sieve plates) leading to poor mass transfer.

Table 3. Operational Bottlenecks of the Houston Factory

Issue Category	Performance	Data Comparison
VOC Emissions	Non-compliant	Actual: 0.07 kg/h; EPA limit: 0.05 kg/h
Energy Consumption	Higher than industry level	990 kWh/ton vs. industry benchmark 780 kWh/ton
Raw Material Purity	Local material inferiority	US: 99.5%; Domestic: 99.9%

Equipment Configuration	Low distillation efficiency	Tower diameter: 3.2 m (US) vs. 2.8 m (domestic); internals: traditional sieve plates

3. Multi-Objective Optimization Model Construction

3.1 Objective Functions

3.1.1 Energy Efficiency Objective

Based on the first law of thermodynamics, unit product energy consumption (E) is defined as:

$E = frac{sum_{i=1}^{n} E_{eq,i} + E_{mat} + E_{aux}}{Q$

Where E_{eq,i = equipment energy consumption (kWh), E_{mat = material loss energy consumption (kWh), E_{aux = auxiliary system energy consumption (kWh), $$ = production capacity (tons). Parameters are calibrated using Houston factory operational data.

3.1.2 VOC Emission Objective

Total VOC emissions (V) cover reaction volatilization (V_1), distillation escape (V_2), and storage losses (V_3):

$V = k_1 cdot T exp(-k_2 cdot P) + k_3 cdot (1 - eta) cdot R + k_4 cdot $

Where k_1-$k_$ = empirical constants, et = distillation efficiency, $$ = storage time. Calibrated via GC-MS online monitoring data.

3.1.3 Production Capacity Objective

Production capacity (Q) is modeled using reaction kinetics and mass transfer theory:

$Q = k_5 cdot T^{0.3} cdot N^{0.2} cdot P^{-0.1} cdot x$

Where $k_$ = process coefficient, x = raw material purity correction factor.

3.2 Constraints

Constraints cover three dimensions (Table 3):

- Compliance constraints: Adhere to regional environmental and quality standards (e.g., EPA VOC ≤0.05 kg/h, product purity ≥99.9%).
- Process constraints: Parameter ranges and operational feasibility (e.g., $T cdot N leq 8 times 10^$ to avoid local overheating).
- Economic constraints: Unit cost ≤$1800/ton, investment payback period ≤18 months.

Table 4. Model Constraints

Constraint Type	Specific Conditions
Environmental	US: V≤0.05 kg/h; EU: V≤0.04 kg/h
Quality	Moisture ≤15 ppm; purity ≥99.9%; heavy metal ≤0.1 ppm (EU)
Process	80≤T≤120°C; 300≤N≤800 rpm; -0.1≤P≤-0.08 MPa; 2≤R≤5
Operational Feasibility	$T cdot N leq 8 times 10^$; $P cdot R geq -0.0$
Economic	Unit cost ≤$1800/ton; payback period ≤18 months

3.3 Integration of Regional Compliance Factors

A regional compliance factor (λ) is introduced to adjust objective weights:

$lambda = frac{L_{text{local}}}{L_{text{benchmark}}$

Where $L_{text{local}$ = regional limit, $L_{text{benchmark}$ = international benchmark (0.045 kg/h for VOC). For the US, $lambda_{text{US}} = 1.$; for the EU, $lambda_{text{EU}} = 1.$. The modified fitness function:

$F = alpha cdot frac{E}{E_{text{max}}} + beta cdot lambda cdot frac{V}{V_{text{max}}} + gamma cdot frac{Q_{text{max}}}{Q$

($alpha + beta + gamma = $; $E_{text{max}}, V_{text{max}}, Q_{text{max}$ = maximum values within parameter ranges)

4. Improved NSGA-III Algorithm and Simulation Verification

4.1 Algorithm Improvement

The traditional NSGA-III is improved in three aspects:

1) Integration of compliance factors into the fitness function to prioritize regional regulatory requirements.
2) Triple screening mechanism ("non-dominated sorting + crowding

distance + compliance priority") to improve solution quality and efficiency.

3) Adaptive mutation step size: larger steps (0.05-0.1) for high-sensitivity parameters (P, T); smaller steps (0.01-0.03) for low-sensitivity parameters (N).

Comparative tests show the improved algorithm increases Pareto solution coverage by 35%, shortens convergence time by 40%, and reduces fitness function standard deviation by 28% compared with traditional NSGA-III and MOPSO.

4.2 Aspen Plus Simulation

An Aspen Plus model (12 unit modules, UNIQUAC thermodynamic method) is calibrated with Houston factory data (relative error <5%). Under EPA standards, the optimized parameter combination is T=95°C, N=550 rpm, P=-0.095 MPa, R=3:1. Simulation results (Table 4) show unit energy consumption reduced to 780 kWh/ton, VOC emissions to 0.028 kg/h, and product purity to 99.93%, all meeting requirements.

Table 5. Simulation Results

Indicator	Before Optimization	After Optimization	Improvement
Unit Energy Consumption (kWh/ton)	990	780	-21.2%
VOC Emissions (kg/h)	0.07	0.028	-60.0%
Product Purity (%)	99.85	99.93	+0.08%
EPA Compliance	Non-compliant	Compliant	-

4.3 ANSYS Fluent Flow Field Optimization

ANSYS Fluent simulation (k-ε turbulence model, DPM) identifies vortex areas in the distillation tower (accounting for 45% of VOC escape). Optimization measures: replacing traditional sieve plates with efficient guide sieve plates, adjusting plate spacing to 350 mm, and installing porous liquid distributors. Post-optimization, gas-liquid contact area increases by 23%, VOC escape reduces by 18%, and distillation efficiency improves by 12%. (Zhang, X., et al., 2023)

5. Factory Empirical Study

5.1 Empirical Scheme

A 30-day parallel control experiment is conducted:

- Control group: Domestic process parameters.
- Optimization group: Simulated optimal parameters (T=95°C, N=550 rpm, P=-0.095 MPa, R=3:1).

Data collection: VOC emissions (GC-MS, EPA Method 18), energy consumption (intelligent electric meters, ±0.5% accuracy), product quality (Karl Fischer moisture determinator, ICP-OES), and production capacity. RSD of test results is controlled within 3%.

5.2 Empirical Results

Empirical data (Table 5) confirms significant improvements:

- Unit energy consumption: 765 kWh/ton (-22.7% vs. control group), annual electricity cost savings exceed $1.2 million.
- VOC emissions: 0.026 kg/h (-63.9% vs. control group), complying with EPA and REACH standards.
- Production capacity: 17,280 tons/month (+15.2%), product qualification rate: 99.8% (+2.3%).
- Model prediction error: 2.9% (energy consumption), 3.1% (VOC), 1.7% (production capacity), all ≤3.5%.

Table 6. Empirical Results

Indicator	Control Group	Optimization Group	Improvement
Unit Energy Consumption (kWh/ton)	990	765	-22.7%

VOC Emissions (kg/h)	0.072	0.026	-63.9%
Monthly Production Capacity (tons)	15,000	17,280	+15.2%
Product Qualification Rate (%)	97.5	99.8	+2.3%

5.3 Long-Term Stability

Six-month continuous operation shows stable performance: energy consumption fluctuation ±2.1%, VOC emission fluctuation ±1.8%, product qualification rate ≥99.5%. The optimized solution exhibits strong robustness against raw material purity (99.4%-99.6%) and ambient temperature (15-35°C) fluctuations.

6. Standardization and Promotion

6.1 Transnational Process Adaptation SOP

Based on the simulation optimization results and industrial empirical data, this study formulated a standardized operating procedure (SOP) for transnational electrolyte process adaptation. The SOP takes "compliance standard disassembly – parameter adjustment – compliance verification" as the core framework, forming a closed-loop guidance system that covers the entire process of transnational process adaptation. The SOP is designed to be user-friendly and operable, enabling technical personnel to quickly adapt the process to different regional requirements without relying on extensive experience.

6.1.1 Compliance Standard Disassembly Module

This module systematically sorts out the environmental regulatory standards of major target regions (including the US, EU, and Southeast Asia) and transforms the abstract standard clauses into quantitative technical indicators. The key steps are as follows:

- **Standard collection and analysis**: Collect the latest environmental regulatory standards of the target region, including VOC emission limits, heavy metal content constraints, energy consumption thresholds, and reporting requirements.
- **Indicator extraction**: Extract key compliance indicators from the standard texts and clarify their quantitative thresholds and detection methods. For example, the US EPA standard is disassembled into 12 key technical indicators, including VOC emission limit (≤0.05 kg/h), HAP accounting method (EPA Method 25A) (EPA, 2023), and emission source monitoring frequency (continuous monitoring).
- **Indicator classification**: Classify the extracted indicators into environmental indicators (VOC emissions, heavy metal content), quality indicators (product purity, moisture content), and management indicators (reporting requirements, permit application procedures) to facilitate subsequent parameter adjustment and compliance verification.

Table 7. Compliance Standard Disassembly Results

Region	Indicator Category	Key Indicators	Quantitative Threshold	Detection Method
USA	Environmental	VOC emission limit	≤0.05 kg/h	EPA Method 18 (GC-MS)
		HAP accounting	Comply with EPA guidelines	EPA Method 25A
	Quality	Product purity	≥99.9%	HPLC
		Moisture content	≤15 ppm	Karl Fischer
	Management	Air Permit application	Submit 23 declaration indicators	Online application
EU	Environmental	VOC emission limit	≤0.04 kg/h	EN ISO 16000-6
		Heavy metal content	≤0.1 ppm	ICP-OES
	Quality	Product purity	≥99.9%	HPLC

		Moisture content	≤15 ppm	Karl Fischer
	Management	Chemical composition disclosure	Submit to ECHA	Online disclosure
Southeast Asia	Environmental	Unit product energy consumption	≤800 kWh/ton	Intelligent electric meter
	Quality	Product purity	≥99.8%	HPLC
		Moisture content	≤20 ppm	Karl Fischer
	Management	Energy consumption reporting	Annual report	Local environmental agency

6.1.2 Parameter Adjustment Module

Based on the multi-objective optimization model and empirical results, this module provides the optimal process parameter combination for different target regions and detailed adjustment logic. The key contents are as follows:

- **Optimal parameter combination**: Provide the optimal process parameter combination for each target region, including reaction temperature, stirring rate, vacuum degree, and reflux ratio. The parameters are derived from simulation optimization and industrial empirical data to ensure their feasibility and effectiveness.
- **Adjustment logic**: Explain the influence mechanism of each parameter on compliance indicators and provide adjustment rules for different scenarios. For example, if the raw material purity decreases by 0.1%, the reaction temperature should be increased by 2-3°C to maintain the reaction conversion rate; if the local VOC emission limit is tightened by 0.01 kg/h, the vacuum degree should be enhanced by 0.003-0.005 MPa.
- **Boundary conditions**: Clarify the boundary conditions of parameter adjustment to avoid parameter combinations that exceed equipment limits or process feasibility. For example, the reaction temperature should not exceed 120°C (equipment temperature resistance limit), and the stirring rate should not exceed 800 rpm (motor power limit).

Table 8 shows the optimal process parameter combinations for key target regions:

Table 8.

Region	Reaction Temperature (°C)	Stirring Rate (rpm)	Vacuum Degree (MPa)	Reflux Ratio	Adjustment Logic
USA (EPA)	95	550	-0.095	3:1	1. If raw material purity <99.5%, increase T by 2-3°C; 2. If VOC emission >0.04 kg/h, enhance P by 0.003 MPa
EU (REACH)	90	500	-0.098	3.5:1	1. If heavy metal content >0.08 ppm, reduce T by 2-3°C; 2. If product purity <99.9%, increase R by 0.5:1
Southeast Asia (Energy Consumption Constraint)	100	600	-0.09	2.5:1	1. If unit energy consumption >780 kWh/ton, reduce T by 3-5°C; 2. If production capacity

					<17,000 tons/month, increase N by 50-100 rpm

6.1.3 Compliance Verification Module

This module provides a rapid verification method for the optimized process parameters to ensure that all indicators meet the regional standards. The key contents are as follows:

- **Verification indicators**: List the key verification indicators for each target region, including VOC emissions, product quality, and energy consumption.
- **Detection methods**: Specify the detection methods and equipment for each verification indicator, including sampling points, sampling frequency, and analysis procedures. For example, VOC emissions can be quickly verified using a portable GC-MS analyzer (detection limit: 0.001 kg/h) at the distillation tower outlet, with a sampling frequency of once every 2 hours during the initial operation period.
- **Acceptance criteria**: Set clear acceptance criteria for each verification indicator. For example, the VOC emission acceptance criterion is that the measured value is less than 90% of the regulatory limit to ensure a safety margin.
- **Problem-solving measures**: Provide targeted adjustment suggestions for common problems encountered during verification. For example, if the VOC emission exceeds the acceptance criterion, the vacuum degree can be increased or the reaction temperature can be reduced; if the product purity is insufficient, the reflux ratio can be increased or the stirring rate can be adjusted.

6.2 Application Effect of the SOP

The SOP was piloted in the Houston factory from October 2024 to November 2024, and the application effect was evaluated based on process adaptation efficiency, compliance rate, and cost savings:

- **Process adaptation efficiency**: The compliance audit preparation time was shortened from 48 hours to 15 minutes, a reduction of 96.9%. The process adaptation success rate was increased from 75% (before SOP application) to 100%, eliminating the need for repeated parameter adjustments and trial runs.
- **Compliance rate**: During the pilot period, the factory passed all EPA inspections and audits, with a compliance rate of 100%. No regulatory penalties or complaints were received.
- **Cost savings**: The SOP reduced the process adaptation cost by 80% compared with the traditional empirical method. The cost savings mainly come from the reduction in trial run time, raw material consumption, and labor costs.

The pilot results show that the SOP is effective in improving the efficiency and accuracy of transnational process adaptation, providing a reliable tool for the global expansion of electrolyte enterprises.

6.3 Industry Promotion Value

The multi-objective optimization model, improved NSGA-III algorithm, and transnational process adaptation SOP proposed in this study have extensive industry promotion value, covering economic, environmental, and technical aspects:

6.3.1 Economic Benefits

Based on the global transnational electrolyte factory production capacity of 5 million tons/year, the comprehensive promotion of the optimized solution.

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