

Aguas SB T1 Method

Recirculation, combined treatment and experimental testing

Edition 2.1 · Engine 2.3 · 8 October 2026. Prepared for editorial review and authorised publication.

Aguas SB

Electrocoagulation · Electrooxidation · Cavitation · Venturi aeration

Synthetic public examples. Private commercial data excluded.

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01. The T1 method and the engineering question

The Aguas SB T1 method organises preliminary sizing of a combined treatment around three questions: how much treatment exposure the water receives, what fraction of its load responds under the selected conditions, and where the removed material ends up. It connects recirculation, composition, modules, operating hours and consumption through executable code. Its contribution is to make those relationships examinable, not to replace chemistry with a universal percentage.

Edition 2.0 describes the T1 2.3 calculation core captured on 7 October 2026. Aguas SB develops and sells the equipment. The method therefore has applied and commercial interests; publication enables review but does not constitute an independent assessment of the manufacturer. Public numerical examples are synthetic unless explicitly attributed to a scientific publication.

The problem to be solved

An industrial operator may know the daily water volume and a laboratory analysis without knowing how long a unit should run or what result to expect. A researcher may know removal achieved in a small reactor without enough information to transfer it to an installation. Both questions encounter the same difficulty: a percentage without exposure, matrix and measurement boundaries does not specify a treatment.

A statement that a unit removes 60% does not identify whether it concerns COD, colour, solids or an individual compound. Nor does it establish whether the sample was settled, whether dilution occurred, how long the trial lasted or how much electrical charge was supplied. Equal percentages can describe very different processes. Different percentages can be consistent with the same mechanism under different loads or exposures.

The method turns a commercial description into a calculable question: for this water, target, topology and exposure budget, what outlet does the model estimate and what test would support or revise it? The answer includes a concentration, an operating balance and a domain of applicability. It does not end with a module count.

Three connected pillars

Exposure. Recirculation accounts for volume passed through the units relative to a reference volume. Current and time, energy, pressure, aeration and separation must accompany it. The same turnover count does not imply the same dose when equipment or its operating point changes.

Treatable capacity. A removal curve can approach a plateau. T1 represents this through operational ceilings and matrix factors. A plateau may reflect finite dose, a persistent fraction, slow transport, changing composition or incomplete separation. The proposed parameter enables calculation; its physical interpretation requires those possibilities to be distinguished.

Material fate. Reducing a pollutant in the aqueous phase is useful even when some of it enters sludge. However, transfer, transformation and mineralisation are different processes. A plant balance must retain the management of solids and other streams even when effluent quality improves substantially.

A synthetic example connects these pillars. In 10 m³, a COD of 1000 mg O₂/L represents 10 kg of oxygen-demand equivalent. If separated water leaves at 400 mg O₂/L with the same volume, that stream retains 4 kg. The 6 kg difference cannot be called mineralised without examining solids, other streams

and transformation. If duration or electrical charge is also unknown, the result cannot size another unit solely from tank litres.

Relationship with the literature

Published work already uses per-pass models for hydrodynamic cavitation and investigates scale dependence. These are relevant antecedents for our exposure coordinate without automatically identifying T1 coefficients. [Per-pass model](#), [vortex-device scale-up](#).

An institutional report on industrial treatment offers an operation-selection perspective. Hernández Lehmann's thesis studies electrocoagulation. Research on olive-mill wastewater combines separation and Fenton oxidation. These references address different aspects of the problem; bringing them together does not add their efficiencies or imply their authors endorse T1. [madri+d report](#), [UPM thesis](#), [integrated treatment study](#).

The gap addressed here is practical: an integrated, reproducible formulation for the commercial configuration considered, connected to scale questions and comparable test conditions. This does not require claiming that nobody previously combined processes or proving the worldwide absence of related models.

The meaning of engineering inference

Installation experience can motivate relationships before a complete identification campaign exists. Removing solids between stages might change the response of the next stage; a more concentrated matrix might consume more treatment capacity; a hydraulic change might alter yield per exposure. Such propositions are useful when they specify what remains constant and what observation would contradict them.

Inference becomes stronger through balances, experience and external testing, but repetition across pages does not change its evidential category. A sizing rule must remain identified as a model rule. A measured coefficient must retain the conditions under which it was estimated. This distinction enables improvement without retroactively constructing supposed validation.

The choice is not between experience and science. It is to translate experience into observable hypotheses and use literature to design a more precise comparison. A located discrepancy adds knowledge: it may reveal an omitted separator, inconsistent units or a transport limit that a reduced model does not represent.

Using the corpus

For sizing, start with hydraulics, equations and worked examples. When comparing a paper, first identify matrix, regime and energy boundary, then consult the chapter on the relevant mechanism. For a measurement campaign, use measurement, uncertainty and protocol. When adding results to software, preserve the previous version and the conditions supporting the change.

The minimum reproducible result contains inputs, units, topology, schedule, flows, options, engine version and output. A numerical pass only means meeting specified targets; it is not a permit, a detailed design or a water-safety test.

A university can test the exposure hypothesis using its own device. If the relationship does not transfer, the result defines its limits rather than making the corpus useless. Conversely, agreement for one effluent does not establish universality. The purpose is a common language through which both outcomes can inform development.

The editorial criterion is specific: each chapter answers a different question, every example declares its origin, and each recommendation identifies its conditioning variables. Length serves that task. Method quality is judged by whether calculations can be repeated, challenged and improved, not by page or citation counts.

02. Hydraulics and the meaning of turnovers

A recirculation turnover is a volume ratio, not a guarantee that every portion of water has undergone an identical pass. Using it for design requires the reference volume, actual flow, period and hydraulic regime to be stated. The distinction affects both concentration prediction and capacity calculation.

Four quantities that must remain distinct

Let V_b denote useful tank liquid volume, Q_r the flow through the treatment circuit, Q_f net feed flow and V_d volume treated over one day. If feed varies, V_d is its integral rather than a spot reading automatically multiplied by 24.

For a closed, constant-volume batch, mean hydraulic exposure is $c = Q_r \cdot t / V_b$. For variable flow use $c = \int (Q_r(t) / V_b) dt$. Significant sampling, purges or evaporation require volume updates and a closed balance. Retaining a volume that no longer exists distorts exposure and load.

The configurator's daily index is $c_d = \sum (q_i \cdot h_i) / V_d$. Its denominator is daily production, not tank capacity. It describes the volume processed through units relative to production; alone, it does not determine residence-time distribution or the minimum exposure received by every fraction.

Synthetic example: a 5 m³ batch recirculated at 15 m³/h reaches $c=4$ after $4 \cdot 5 / 15 = 1.3333$ h, or 80 minutes. Another installation moves 15 m³/h for 20 hours while treating 75 m³/day, also giving $c_d=4$. Numerical agreement does not make the second system the first experiment.

Discrete passes and continuous mixing

If an entire portion passes through a unit, is collected separately and only then passes through again, a discrete sequence may be approximated. With constant removal fraction ϕ , the residual after n passes is $(1-\phi)^n$. This excludes bypass and assumes comparable conditions for each pass.

A perfectly mixed tank with continuous withdrawal and return behaves differently. Water representative of the gradually changing tank concentration is withdrawn at every instant. If the side-stream reactor removes fraction ϕ of susceptible contaminant, the balance is:

$$V_b \cdot dC/dt = -Q_r \cdot \phi \cdot C$$

$$C/C_0 = \exp(-\phi \cdot c)$$

The difference is not cosmetic. For $\phi=0.5$ and $c=4$, the discrete sequence leaves 6.25% of the original fraction; the mixed tank leaves 13.53%. A more optimistic numerical curve does not establish superior equipment performance: it may describe another regime.

Under an idealisation of independent random visits to a negligible-volume side-stream reactor, visit count can be represented by a Poisson distribution with mean c . The unvisited fraction is then $\exp(-c)$: 1.83% at four mean turnovers. This explains mixing mathematically; it is not a measured T1 residence-time distribution. Short-circuiting or dead zones can cause major departures.

The engine curve alone does not identify the regime

The identity $0.5^c = \exp(-\ln(2) \cdot c)$ allows the T1 curve to be read as an effective exponential response. It neither establishes nor excludes a mixed tank. With fixed treatable fraction $\theta = 0.64$, the current curve gives 60% total removal at four turnovers. A mixed balance separately assuming $\phi = 0.5$ would give 55.34%; an effective coefficient of $\ln(2)$ would also give 60%. These differences follow from assumptions, not new measurements.

The current curve is therefore not automatically replaced by the lower-yield curve. First identify what the coefficient represents and test it against flow, mixing and an exposure series. Until then, the T1 calculation is an engineering scenario with effective exposure, not experimental identification of the actual hydraulics.

Continuous feed

In a steady, mixed tank with feed Q_f , equal outlet flow and side-stream circulation Q_r , with no other reactions:

$$\begin{aligned} Q_f(C_{in} - C) &= Q_r \phi C \\ \beta &= Q_r / Q_f \\ C / C_{in} &= 1 / (1 + \beta \phi) \end{aligned}$$

For $\beta = 4$ and $\phi = 0.5$, removal is 66.67%. Load enters continuously and treated water leaves continuously. This must not be equated without explanation to a batch treated until a selected end time. Net hydraulic residence time $\tau = V_b / Q_f$ and ratio β complete the description.

These ideal balances help interpret per-pass literature without replacing measured hydraulics. A perspective on cavitation reactors discusses regimes and effective parameters. [Cavitation reactor modelling](#).

Parallel and series modules

Two independent 15 m³/h parallel branches can provide 30 m³/h total circulation if the installation actually maintains those flows. Pump curves, head losses and branch distribution determine the real value; doubling units does not guarantee doubled flow.

With two modules hydraulically in series, the same 15 m³/h crosses both. There are two unit exposures per circuit, but the tank does not receive 30 m³/h return. Summing unit exposure is legitimate when explicitly described; using that sum to size pipework or claim hydraulic tank turnovers is not.

A third layout comprises successive tanks with separation between them. Each stage then has its own volume, time and composition. Mathematical module grouping does not establish that the physical arrangement exists. Draw feed, returns, purges, separators and sampling points before applying a numerical cascade.

Checking hydraulics efficiently

An initial check combines flow measurement, useful volume and operating-hour records. Measurements should represent operating conditions: loaded filters, usual valve positions, representative liquid level and gas where it affects the reading. Catalogue data are a starting point, not a replacement for actual flow.

If residence distribution is decisive, a compatible tracer test can reveal early arrival, tails and poorly used volume. Selecting tracer and detector depends on safety and matrix conditions. No particular reagent is proposed without compatibility assessment.

For a steady-operation test, observations during startup and stabilisation prevent transient samples being mistaken for sustained performance. When influent changes, inlet and outlet samples must be linked through the system's delay and mixing, not merely by date.

For example, inlet and outlet samples both taken at 10:00 may represent different loads if water remains in the system for hours. Computing a percentage is straightforward but the physical pairing may be wrong. Composite samples and a flow record can be more valuable than extra decimal places in the equation.

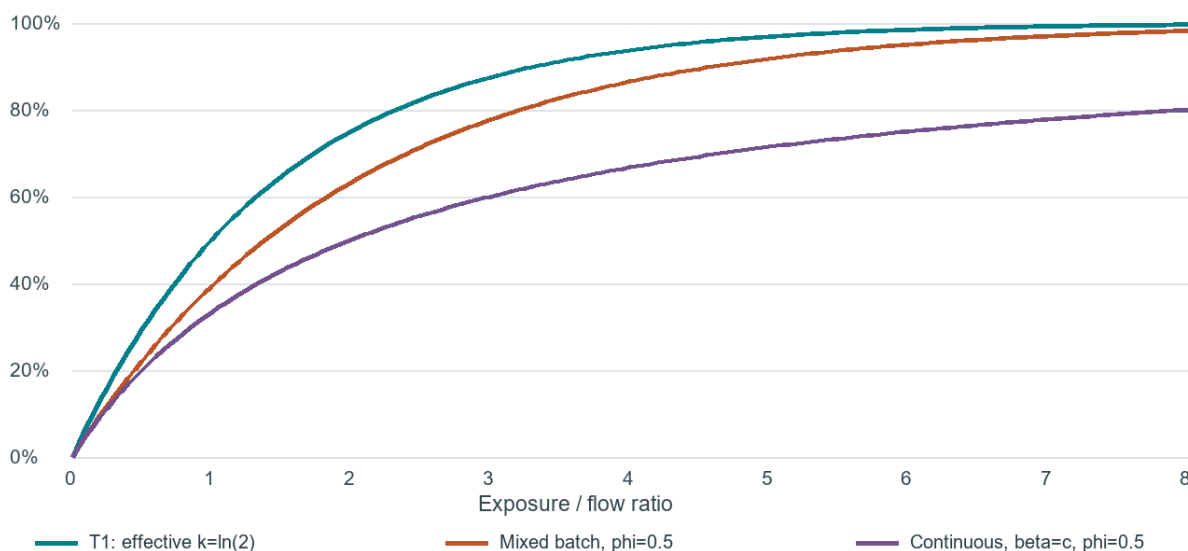
What an additional turnover adds

Extra exposure does not identify the limiting operation. Increasing Q_r at fixed current increases circuits per hour without increasing electrical charge per hour. Increasing pressure at unchanged flow alters hydraulic energy without changing c . Removing sludge between circuits changes the matrix even when total recirculated volume is unchanged.

We therefore accompany c with specific energy, charge per volume, pressures, gas and separation. This does not weaken the indicator; it makes its meaning testable. Configurations can be compared while retaining the other variables rather than silently absorbing them into the word turnover.

The practical decision is simple. Use turnovers to plan exposure and time, balances to distinguish regimes, and measurement to confirm hydraulics. When two installations have identical c but different results, first investigate the conditions that the index does not represent before changing the equation arbitrarily.

Exposure and hydraulic regime



Ideal curves for the treatable fraction; not T1 measurements.

03. Engine equations and operational ceilings

The T1 2.3 core combines an exposure curve, an inlet-dependent operational capacity, configuration factors and module grouping into stages. This chapter describes that version rather than a newly fitted equation. The frozen code accompanying the edition reproduces examples and exposes each branch.

Parameter provenance and status

Traceability separates where a value is implemented from which evidence identifies its magnitude. Frozen assets answer the first question; displaying code does not answer the second. The material examined for this edition did not yield a reproducible fit linking each decisive coefficient to an identified experimental series. This does not deny operating experience or application measurements; it limits what a reader can independently verify.

Group	Available basis in this edition	Missing test for identification
Curve 1-0.5^c	Engine rule and exponential identity; no recoverable experimental fit	Exposure series with recorded regime, dose and residual
Ceilings, load transitions and sensitivities	Engineering parameterisation reproducible in code	Comparable batches and held-out evaluation within each domain
Chemical and module factors	Configuration rules; neither dose specifications nor proof of independent effects	Matched comparisons, active-reagent records and physical layout
Bonus from c=12	Discrete software condition	Measurements around the threshold; no demonstrated physical transition identified
Global/serial envelope	Selection of the better numerical result	Comparison against actual physical stages and intermediate separation
Concentration floors	Numerical outlet limits	Operating domain and low-inlet behaviour; these are not laboratory limits
Equipment flows and powers	Nominal and manufacturer-declared values	Flow and energy measured at the operating point
Volume, mass and energy balances	Physical identities under stated boundaries and assumptions	Measurements to test closure; the identity does not calibrate efficacy

The benchmark loads `t1_parametros.js` before `t1_motor_v2.js`. Effective parameters override fallback values; an external `T1_CONFIG`, where present, may override them again. This benchmark adds no such external configuration. Reproducing a website run also requires retaining any overrides, not just its version number.

Bonus and stage branches are reported as model scenarios, not automatically measured improvements. A validated predictive domain is neither claimed universally nor inferred from error-free execution. Each result must retain its options and distinguish calculation, estimate and observation.

Approaching treatable capacity

The exposure function is $A(c)=1-0.5^c$. At one, two and four turnovers it is 0.5, 0.75 and 0.9375. These are not automatically removal percentages for all COD: they act on an effective ceiling dependent on the parameter and conditions.

With fixed ceiling θ , removal is $r(c)=\theta*(1-0.5^c)$ and concentration before the software floor is $C_{out}=C_{in}*(1-r)$. Its asymptotic residual is $C_{in}*(1-\theta)$. Calling it operational means that it describes stage conditions, not that the remaining mass is chemically impossible to treat by another process.

The equivalent exponential form is $A(c)=1-\exp(-\ln(2)*c)$. In an ideal mixed-tank balance the effective coefficient would be $\ln(2)=0.693147$, not a physical fraction of 0.5 per reactor visit. Estimating that coefficient experimentally requires fitting under stated hydraulics and residual assumptions, rather than importing it from an algebraic identity.

Base ceilings and concentration

For BOD5, COD, TSS and P, the code interpolates a base ceiling $B(C)$ between two concentrations. Below C_OK it retains the first ceiling; above C_BAD it retains the second. Within that range:

$$u = (C - C_OK) / (C_BAD - C_OK)$$

$$B(C) = B_OK + u * (B_BAD - B_OK)$$

Parameter	B_OK to B_BAD	C_OK to C_BAD, mg/L	TMAX / floor
BOD5	0.72 to 0.55	1200 to 7000	0.90 / 3
COD	0.64 to 0.55	2000 to 12000	0.80 / 15
TSS	0.67 to 0.58	800 to 5000	0.84 / 5
P	0.88 to 0.78	20 to 90	0.94 / 0.2

BOD5 and COD are expressed as O2, and P as P. TMAX is a fraction while the floor uses the parameter's concentration unit. These are adopted model values rather than universal constants extracted from the references. Effective parameter files override fallback values in JavaScript.

For COD of 7000 mg/L, the position between 2000 and 12000 is 0.5 and the base ceiling is 0.595. This alone does not calculate the outlet: difficulty, configuration, exposure and potentially stages still apply.

Matrix difficulty

The combined factor is $f=f_ratio*f_N*f_pH$. The code uses:

```
f_ratio = clamp(1 - 0.2*(COD/max(1,BOD)-2.4), 0.4, 1)
f_N = clamp(1 - 0.4*max(0,N-50)/150, 0.6, 1)
f_pH = 1 from pH 6.5 to 8.5
f_pH = clamp(1 - 0.5*d/3, 0.55, 1) outside that range
```

Here d is distance to the nearest range boundary. Each parameter responds through $1-S*(1-f)$, with sensitivities 0.25 for BOD and COD, 0.12 for TSS, 0.10 for P and 0.35 for N. This is a reduced representation: COD/BOD does not identify substances, and the same ratio may arise from differing toxicity, biodegradability or mixtures.

Synthetic example: COD/BOD of 4 gives $f_{\text{ratio}}=0.68$. With no N or pH penalty, the final COD factor is $1-0.25*(1-0.68)=0.92$. This does not mean literature measured a universal 8% loss at that ratio; it describes the model's correction.

Nitrogen and chemical options

The engine distinguishes ammoniacal fraction a , expressed as ammoniacal N divided by total N. Its base ceiling is $0.63*(1-a)+0.72*a$; with the oxidant option the second coefficient becomes 0.85. Maximum N removal is 0.79, or 0.90 with oxidant. N removal is not cascaded like COD.

This rule predicts aqueous concentration through a parameterisation; it does not establish whether N enters solids, gas or another species. Analytical interpretation must distinguish mg N/L from mg NH_4^+ /L. The calculation interface uses factor 1.2878 to convert ammonium-ion mass into nitrogen mass. A fraction must not be entered where a concentration is required.

With chemistry enabled, the factors for BOD, COD, N, P and TSS are 1.05, 1.06, 1.03, 1.12 and 1.15. For N, enabling oxidant as well replaces 1.03 with 1.10: the two factors are not multiplied together. Without chemistry, this N factor is 1 even if the oxidant option changes its specific ceilings. These bonuses specify neither reagent nor active dose and must not become dosing instructions.

Modules, turnovers and the global equation

The module factor is 1 below three modules, then grows as $\min(1.6, 1+0.1*(n-2))$. The turnover factor remains 1 until $c=12$, when it becomes 1.1. For non-N parameters, the effective maximum scales as $\text{TMAX}*\min(1, B/B_{\text{OK}})$.

The compact single-stage expression is:

```
r = min(B*F_chemical*F_modules*F_turnovers, cap)
* (1-0.5^c) * (1-S*(1-f))
Cout = max(floor, Cin*(1-r))
```

The N branch retains its specific denominator and rules in the code; it must not be reconstructed from the COD table. Options and version form part of every reproducible result.

Numerical stages and persistence

The engine groups modules using a minimum-exposure condition and a bonus rule. It recalculates BOD, COD, TSS and P on the preceding group's output, reassesses part of matrix difficulty and retains the better result of global and serial formulations. N does not receive successive reduction.

For stages removing r_1 and r_2 from their respective incoming loads, $r_{\text{total}}=1-(1-r_1)*(1-r_2)$. Applying a ceiling again to the residual assumes that residual can still respond. A permanently untreatable fraction should not restart as susceptible at every stage. Distinguishing an operational ceiling from persistent residual is therefore a physical condition, not merely a label.

Two hypotheses are proposed: extra exposure continues acting on susceptible material, and separation or matrix changes renew treatment conditions. Dose- and energy-matched comparisons with and without intermediate separation distinguish them. The benchmark does not turn a numerical envelope into proof of both.

Inverse calculation and marginal yield

While θ is fixed and no branch changes, target r_{target} requires:

```
c_target = -ln(1-r_target/theta)/ln(2)
condition: 0 <= r_target < theta
dr/dc = theta*ln(2)*2^(-c)
```

At $\theta=0.64$, 60% removal requires four turnovers. A 75% target has no finite solution in that branch because it exceeds the ceiling. This does not make the water untreatable; extending the same formulation does not solve the target. A new configuration needs its own justification.

Marginal yield falls as c rises while energy typically increases approximately linearly at constant power and flow. Extra operating hours can therefore become unproductive. This does not guarantee improved energy performance from another stage: its consumption and separations must be counted.

Features that technical users need to know

The factor change at twelve turnovers creates a programmed jump, not a demonstrated chemical transition. Floors can exceed very low inlet concentrations, producing a numerical outlet above the inlet; this domain has no direct physical interpretation. Initial equipment selection by minimum turnovers is also not optimisation against all analytical targets.

These features remain in the frozen core to support reproducibility. Correcting them requires a new version and regression tests rather than silently changing code within a book. The method becomes more useful by exposing these decisions and specifying experiments capable of testing them.

04. Electrocoagulation: From Electrical Charge to Separation

One Operation, Two Different Outcomes

Electrocoagulation, EC, generates metallic species through consumable electrodes and promotes aggregation or incorporation of water constituents into a separable phase. Its assessment must distinguish coagulant production from subsequent removal. Producing flocs does not mean extracting them from the circuit. A sample collected before settling, flotation or filtration may contain solids originating from the electrode itself and show more suspended solids than the feed, even though their separability has improved.

Within Aguas SB's proprietary commercial T1 method, this distinction leads to an operational question: how much improvement comes from transforming the dispersion, and how much from removing material? Answering it requires examining both water and residue. A decrease in chemical oxygen demand, COD, in the supernatant does not, by itself, identify oxidation, much less mineralization. It may represent organic matter incorporated into sludge, a useful outcome that needs the correct name.

Faraday's Law and Units

For an ideal anodic reaction, each mole of metal released requires a defined amount of electrons. Accumulated charge is calculated by integrating the current actually measured:

$$Q_e = \int I(t) dt$$

$$m_{\text{theoretical}} = M * Q_e / (z * F)$$

$$D_{\text{electrical}} = Q_e / V$$

Q_e is electrical charge in coulombs, not flow rate; I is expressed in amperes and time in seconds. $F = 96485 \text{ C/mol}$ is the constant used here; z denotes electrons per atom released, and M is molar mass in grams per mole. Consequently, $M*Q_e/(z*F)$ has units of grams. At constant current, the integral becomes $I*t$. One ampere-hour equals 3600 C: omitting this conversion introduces an error of three orders of magnitude.

The mass-to-volume ratio also requires care. One gram distributed through one cubic metre corresponds to one milligram per litre. This result is an equivalent concentration of added metal, not necessarily dissolved metal at the outlet, active coagulant concentration or dry sludge mass. Precipitates incorporate other elements and may retain contaminants and water.

Current density, $j = I/A_{\text{active}}$, adds a different coordinate. Two cells operated at the same current for the same time receive equal total charge but may have different current densities, reaction distributions and surface responses. The definition of wetted active area must be stated, including participating faces and electrical connections. Multiplying power-supply current indiscriminately by the number of plates is incorrect.

Synthetic Example 1: 2 A for One Hour in 5 m3

Consider a purely stoichiometric balance, without assigning it to any equipment or actual water. Assume a constant current of 2 A, a duration of 3600 s, a volume of 5 m3 and ideal dissolution of the specified metal:

$$\begin{aligned}
 Q_e &= 2 \cdot 3600 = 7200 \text{ C} \\
 D_{\text{electrical}} &= 7200 / 5 = 1440 \text{ C/m}^3 \\
 m_{\text{Al}} &= 26.9815 \cdot 7200 / (3 \cdot 96485) = 0.67115 \text{ g} \\
 m_{\text{Fe}} &= 55.845 \cdot 7200 / (2 \cdot 96485) = 2.08366 \text{ g}
 \end{aligned}$$

Anodic assumption	Theoretical mass	Water equivalent
Al, $z = 3$	0.67115 g	0.13423 mg/L
Fe, $z = 2$	2.08366 g	0.41673 mg/L

The difference follows from M/z , not superior treatment performance by iron. The Fe calculation assumes release as Fe(II); it does not establish subsequent speciation. Nor does it select an optimum dose: composition, treatment target, chemical availability, capture and separation are still unknown. The decimal places make the arithmetic auditable but do not represent precision achievable in a weighing campaign.

When current varies, its recorded history must be integrated; the setpoint is not a substitute. When sampling or purging changes volume, the relevant mass and volume must be reconstructed before reporting an equivalent concentration.

Aluminium, Iron and Matrix

The schemes $\text{Al} \rightarrow \text{Al(III)} + 3e^-$ and $\text{Fe} \rightarrow \text{Fe(II)} + 2e^-$ count electrons. The species interacting with colloids cannot be reduced to those symbols: hydrolysis, solid formation, complexation and local chemical evolution are involved. For iron, transformation between oxidation states also matters. Tank pH does not necessarily describe the immediate environment of each surface.

Selecting aluminium or iron should be treated as a process comparison. Relevant outcomes include residual metal, sludge volume and handling, consistency of separation and compatibility with downstream operations. Matching amperes alone does not match metal mass or chemistry. An informative comparison states what is held constant: charge, moles of metal, equivalent concentration or final treatment outcome.

The matrix can simultaneously change conductivity, coagulation demand and surface condition. A lower voltage after changing the water therefore does not demonstrate better coagulation; it may reflect lower electrical resistance. An experimental study using formulated water and Al/Fe electrodes found different passivation responses to carbonate, chloride and polarity reversal. It supports investigating matrix dependence, not prescribing a universal addition. [Passivation study, 2025](#).

Measured Efficiency and the Meaning of Weighing

Indicators should be defined without combining different observables:

$$\begin{aligned}
 \eta_{\text{loss}} &= \text{electrode_mass_loss} / \text{theoretical_mass} \\
 \eta_{\text{recovered}} &= \text{corrected_recovered_metal} / \text{theoretical_mass}
 \end{aligned}$$

The second ratio requires subtracting metal initially present and adding the phases included within the boundary. The first may include detached material, chemical corrosion and errors associated with deposits or cleaning. A ratio above one therefore does not prove that more electrons were generated than supplied; it indicates that weighing does not represent the selected Faradaic reaction exclusively. An experimental study of cork-boiling wastewater compared observed electrode loss with Faraday's prediction and identified a chemical dissolution contribution. [EC in a real matrix, 2022](#).

Calling a ratio “Faradaic efficiency” requires defining the mass and mechanism being counted. Total loss matters for maintenance engineering; explaining the process additionally requires knowing which fraction enters the liquid, precipitates or remains attached. No single indicator answers both questions.

Synthetic Example 2: Reconciling Loss and Recovery

Assume a theoretical mass of 10.0 g, an electrode mass loss of 12.0 g and 9.0 g of recovered metal, corrected for the initial background, across liquid and solids. Then $\eta_{\text{loss}} = 1.20$ and $\eta_{\text{recovered}} = 0.90$. These invented calculation inputs do not demonstrate a chemical efficiency of 120%.

The 3.0 g gap between loss and recovery calls for examination of deposits, unsampled fractions or cleaning and digestion biases. It must not automatically be assigned to dissolved metal or an unknown reaction. Repeating the balance with conditioned electrodes and deposit recovery can distinguish these explanations. The testable prediction is that a more complete boundary will reduce the discrepancy if retained material was its main cause.

Mini-Protocol 3: Surface and Separation

A practical comparison starts with a homogenized batch divided between EC treatment and a hydraulic control without current. Current, voltage, temperature, conductivity and pH are recorded over time; electrode area, initial condition and cleaning procedure are documented. Weighing must follow a reproducible procedure with a blank that estimates losses caused by cleaning itself.

Samples are then collected before and after a defined separation, using identical settling time or filtration procedure in both arms. Relevant metal, solids and COD fractions are analysed, and the residue is retained to close the balance. Analytical filtration must not be presented as an installed industrial separation. If the advantage appears only after separation, the conclusion concerns EC plus separation, not the isolated cell.

A voltage rise at constant current guides inspection but does not alone diagnose passivation: changes in conductivity, temperature, connections and geometry must be excluded. As an inferred recommendation, successive operating cycles should also be compared, because an initial test with freshly prepared surfaces can conceal operational drift.

Evidence and Design Questions

The 2011 thesis by Pablo Santiago Hernández Lehmann describes a 144 L/h plant in its abstract and addresses treatment, separation and energy. The record and abstract were consulted here, not the complete equations or full experimental conditions. The supervisor must not be confused with the author. [UPM thesis](#).

For T1, testable questions are whether recovered mass follows charge, whether the surface retains its response, and whether contaminants removed from water appear in a controlled phase. Changing pH, material or cleaning may justify another experiment; it does not automatically change the engine's rules. EC's contribution is better described through charge, metal, surface condition and separation than through a single percentage.

05. Electrooxidation: Electrons, Transformation and Selectivity

Defining What Changes

Electrooxidation, EO, seeks to transform substances through electrochemical reactions and reactive species generated within the system. Unlike electrocoagulation, its principal description is not the production of a coagulant mass. Nevertheless, an installation can combine both functions, and a concentration decrease at its outlet cannot retrospectively allocate their contributions without controls.

For the proprietary commercial T1 method, three questions should be separated: does the analysed substance decrease, does the water's oxidant demand decrease, and is its organic carbon transformed into inorganic carbon? The answers can diverge. A molecule may become undetectable because it turns into another molecule; a fraction may enter solids; partial oxidation can lower COD while preserving organic carbon. Mineralization requires additional evidence of fate, not a label attached to a COD percentage.

Direct and Mediated Pathways

In a direct pathway, the contaminant exchanges electrons at the electrode interface. In a mediated pathway, electrochemically generated species react with it at the interface or in the liquid. Both can coexist with reactions that consume current without producing the intended analytical outcome. Oxygen evolution is one example of competition that requires distinguishing total current from useful current.

Transport to the surface matters because a reaction cannot sustainably consume more substrate than is available nearby. A conceptual representation is $J = k_m(C_{\text{bulk}} - C_{\text{surface}})$, where molar flux J depends on the transfer coefficient k_m and the concentration gradient. This is not a T1 kinetic equation: it explains why raising current need not deliver a proportional improvement as concentration falls or transport becomes limiting.

Hydroxyl radicals are not assumed always to dominate. Material, potential, water composition, pH and competing species determine plausible pathways. Identifying a pathway requires specific measurements and interference controls; observing decolourization, bubbling or a redox-potential change is insufficient. Redox potential is a combined signal from the medium, not a universal radical counter.

Zou and colleagues studied EO using a boron-doped diamond, BDD, anode in real textile wastewater and observed dependence on current, pH and chloride. Their work supports this experimental sensitivity; neither the material nor its operating conditions transfer to T1 by identity. [EO study, 2017](#). Citing BDD does not establish that the commercial equipment contains it or reproduces its mechanisms.

The Electron Equivalent of COD

COD is expressed as an equivalent mass of oxygen. Complete reduction of one mole of oxygen involves four moles of electrons. A stoichiometric representation in acidic medium is:

$$\text{O}_2 + 4 \text{H}^+ + 4 \text{e}^- \rightarrow 2 \text{H}_2\text{O}$$

$$Q_{\text{equivalent}} = (4 * F / 32) * \Delta m_{\text{COD}}$$

$$m_{\text{COD}_{\text{equivalent}}} = (32 / (4 * F)) * Q_e$$

Here Δm_{COD} is in grams of O₂ equivalent, Q_e in C and $F = 96485 \text{ C/mol}$. The factor $32/(4 \cdot F)$ is approximately $8.2914 \times 10^{-5} \text{ g O}_2/\text{C}$, or $0.29849 \text{ g O}_2/\text{Ah}$. This conversion counts equivalents; it does not assert that molecular oxygen is injected or reproduce the mechanism of the COD assay.

At constant volume, with concentrations in mg O₂/L, $\Delta m_{\text{COD}} = V_L \cdot (C_0 - C_t)/1000$. When volumes differ, initial and final masses must be calculated, adding inputs and sample withdrawals. Concentration differences alone are insufficient where dilution, evaporation or purging occurs.

Synthetic Example 1: An Attribution Bound

At 2 A for one hour, $Q_e = 7200 \text{ C}$. Its equivalent is 0.59698 g O_2 . Across 5 m³, this corresponds to $0.11940 \text{ mg O}_2/\text{L}$. These are ideal calculations, not a prediction of T1 performance or a universal limit for a train that receives other oxidants or separates solids.

Their purpose is to detect incomplete attribution. If an aqueous COD decrease requires substantially more equivalents than the electricity supplies, it cannot be explained entirely as net oxidation driven by that charge alone within the proposed boundary. Separation, external oxidants, supplied oxygen, biological processes and analytical biases must be investigated. The comparison does not invalidate the observed decrease; it challenges the exclusive explanation assigned to it.

Nor does it turn all current into treatment. The ideal value assumes complete utilization of electrons for the selected COD change. In an actual experiment, parallel reactions and mediator fate require measuring how much of that equivalent appears in the target outcome.

Apparent Efficiency and Its Limits

An apparent current efficiency relative to COD can be defined:

$$\eta_{\text{COD_apparent}} = 4 \cdot F \cdot \Delta m_{\text{COD}} / (32 \cdot Q_e)$$

“Apparent” is an essential qualification: the numerator comes from an analytical difference and the denominator from an electrical measurement. The fraction of current following each reaction is not necessarily known. Only within a boundary without other oxidant sources or material removals, with appropriate analysis and a compatible balance, can it approximate an electrochemical efficiency for the target.

A value above one requires reviewing those conditions. It must not be capped at one hundred percent to conceal the discrepancy or advertised as extraordinary electron production. A small value does not necessarily prove poor overall operation either: charge may act on substances poorly represented by COD or serve a different objective, which must be measured separately.

Synthetic Example 2: Interpreting a Ratio

Assume an idealized 10 L experiment receiving 10 Ah. The electrical equivalent is 2.9849 g O_2 . A hypothetical COD decrease of 100 mg/L represents 1.000 g O_2 equivalent, giving $\eta_{\text{COD_apparent}} = 0.3350$. This is neither measured performance nor a current recommendation.

If the same difference is calculated after filtering only the final sample, the ratio loses its interpretation as oxidation: it potentially includes material retained by the filter. If water was also added, the comparison must be recalculated using masses. The example shows that a dimensionally correct formula can answer the wrong question when sample preparation changes.

Chloride, Chloramines and Byproducts

Conductivity does not capture chloride's full role. Under some electrochemical conditions, chloride can generate active chlorine species and mediated oxidation pathways. In the presence of nitrogen compounds, the chemistry includes possible chloramines. A study of electrochemical ammonium treatment with BDD examined formation of chloramines, chlorate and perchlorate in chloride-containing media, including leachates. The coverage used here is its abstract, not a reproduction of its protocol.

[Primary study, 2012.](#)

A separate investigation using latrine wastewater examined inorganic and organic byproducts under different electrochemical conditions and anode materials. It demonstrates that assessment must include unwanted products, not only disappearance of pollutant load. Its abstract was consulted; its concentrations are not imported as predictions for T1. [EO byproducts, 2017.](#)

The inferred practical consequence is to define an analytical panel appropriate to the matrix and intended water use, with laboratory advice and risk assessment. No recipe for chlorination, acid adjustment or oxidant mixing is provided here. Lower COD or an oxidant residual establishes neither drinking-water safety nor absence of byproducts. Similarly, ammonium disappearance does not prove exclusive conversion to nitrogen gas: the other nitrogen forms are required.

Mini-Protocol 3: Attribution Without Mechanistic Promises

A homogenized batch is compared between a hydraulic control and an energized arm, maintaining temperature, contact time and sample preparation. Actual electrode material, area, integrated current, voltage and surface condition are documented. Samples are obtained before any separation and, where relevant, after an identical separation in both arms.

The laboratory agrees in advance on preservation, residual-oxidant handling and COD interferences. COD and organic carbon are measured where the question requires them; when investigating a specific substance, relevant products are also sought. Blanks must check that preservation or quenching does not create the difference attributed to the reactor. Surface inspection complements the balance: a pilot urban-wastewater EO study reported nonconductive films and additional energy losses. [Continuous EO, 2013.](#)

The final questions are whether the change follows useful charge, whether it persists under equivalent analytical preparation, and whether the products meet the treatment objective. The T1 engine does not automatically identify these mechanisms. Its assessment improves when transformation, phase transfer and outlet safety are evaluated as distinct outcomes.

06. Hydrodynamic Cavitation: Pressure, Cavities and Exposure

What Forms in the Liquid

Hydrodynamic cavitation, HC, occurs when liquid motion creates regions of sufficiently low pressure to favour cavity formation and growth. Subsequent evolution depends on pressure recovery and flow history. The engineering interest concerns local effects and how they modify transport, dispersion or transformation, not simply whether the circuit has a powerful pump.

A cavity is not synonymous with an air bubble. It may contain vapour and noncondensable gas in varying proportions; a bubble introduced through aeration has a different formation history and may persist as pressure changes. Both populations can interact, but photographing bubbles at a Venturi outlet does not by itself demonstrate cavitation or collapse intensity. This conceptual separation prevents attributing the entire response of a gas-liquid system to one phenomenon.

Within the proprietary commercial T1 method, HC is treated as an operation whose contribution must be identified for a defined geometry and hydraulic condition. The number of recirculated volumes expresses accumulated circuit exposure; it does not directly measure the number of collapses or their spatial distribution.

Flow and Pressure: Related, Not Interchangeable

Flow rate Q_r describes the volume passing through the device per unit time. Pressure drop Δp is a difference between measurement points. Neither quantity alone determines the local pressure minimum. One geometry may concentrate acceleration in a throat; another may distribute it through a vortex field. Pressure taps, backpressure and reading type, absolute or gauge, must therefore be identified.

A common expression for organizing conditions is the cavitation number:

$$\sigma = (p_{\text{reference_absolute}} - p_{\text{vapour}}) / (0.5 * \rho * u_{\text{reference}}^2)$$

Density ρ is in kg/m³, velocity $u_{\text{reference}}$ in m/s and both pressures in Pa; the ratio is dimensionless. Values are comparable only when the reference pressure and velocity definitions are retained. No universal threshold is provided here to certify the regime of every T1 device. Using gauge pressure without converting it to absolute pressure can even incorrectly change the numerator's sign.

For a conduit of known cross-section, $u_{\text{mean}} = Q_r/A$, using consistent units. This is a mean velocity, not the local maximum or a cavity's velocity. Flow regime also depends on geometry and liquid properties. Flow and pressure records should accompany each analytical series because obstruction, gas accumulation or valve changes can alter actual exposure without changing programmed operating time.

Vapour, Gas, Temperature and Viscosity

Vapour pressure depends on temperature. As liquid warms, the thermodynamic condition for vapour formation changes, but the amount of vapour within a cavity and its collapse dynamics may also change. A monotonic improvement in treatment cannot be inferred simply from increasing temperature. Heating during recirculation is an experimental variable to record, not a detail that can be omitted because volume remains unchanged.

Noncondensable gas participates in nucleation and modifies compressibility and cavity evolution. More gas may facilitate some interactions and damp others; observing greater gas volume does not identify which effect dominates. Viscosity affects flow and dissipation and can vary with temperature and composition. A fit obtained with a model compound in water therefore does not automatically characterize a concentrated suspension or a surfactant-containing liquid.

Sarvothaman, Nagarajan and Ranade investigated pressure, temperature, aeration and scale using model contaminants and vortex devices. They found the per-pass factor to depend on conditions and compound. Their work provides an experimental basis for selecting variables to investigate, not universal values for the T1 reactor. [Primary study, 2018](#).

Size and Distribution: Avoiding a Single Criterion

Cavity size is dynamic: it changes during formation, growth and collapse. Furthermore, an image records a distribution conditioned by position, instant, lighting and resolution. The observed diameter of persistent bubbles should not be confused with the initial size used in a cavity-dynamics model.

The assertion “smaller is always better” combines different objectives. Greater interfacial area may favour transfer, but it does not alone determine collapse intensity, residence time or chemical performance. Two devices with the same mean diameter can have different distributions, gas fractions and trajectories. A useful description states which population is measured and by which technique, preserving the distribution instead of reducing interpretation to an average.

The model developed by Sarvothaman, Simpson and Ranade integrates per-pass performance, flow calculations and cavity dynamics, assessed using acetone in water. It provides a precedent for connecting descriptive scales; it does not identify T1’s cavity distribution. [Model in the 2019 volume, available online in 2018](#).

Synthetic Example 1: Hydraulic Power

Power transmitted to the flow across a pressure drop is calculated as:

$$P_{\text{hydraulic}} = Q_r \cdot \Delta p$$

$$P_{\text{input_estimated}} = Q_r \cdot \Delta p / \eta$$

With Q_r in m³/s and Δp in Pa, the result is W. Consider a hypothetical circuit operating at 15 m³/h, with a total pressure drop of 280000 Pa and an assumed overall efficiency of 0.65 between electrical input and hydraulic power:

$$Q_r = 15 / 3600 = 0.0041667 \text{ m}^3/\text{s}$$

$$P_{\text{hydraulic}} = 0.0041667 \cdot 280000 = 1166.7 \text{ W}$$

$$P_{\text{input_estimated}} = 1166.7 / 0.65 = 1794.9 \text{ W}$$

These are not measured T1 powers. If 280 kPa refers only to the device, losses in the rest of the circuit are missing from the pump-input estimate. If efficiency refers only to pump hydraulic efficiency, motor and drive losses remain unaccounted for. The boundary and efficiency definition are part of the calculation, not optional notes.

Synthetic Example 2: Equal Power, Different Conditions

A second hypothetical circuit operates at 30 m³/h and 140 kPa. It also supplies approximately 1.167 kW to the flow. This does not establish equivalent cavitation: it doubles flow, halves pressure drop and may create a different distribution of velocities and pressure minima.

In a 5 m³ tank, one hour would represent three recirculated tank volumes in the first case and six in the second. Equal power does not mean equal exposure, and greater exposure does not demonstrate greater transformation. The example poses a specific experimental question: which result persists when hydraulic loading, duration and mean number of visits are matched separately? It does not propose an alternative engine formula.

What Scale Evidence Contributes

The study by Ranade, Sarvothaman and colleagues on vortex devices compared throats of 3, 6, 12 and 38 mm, at flow rates from 1.3 to 247 L/min and a pressure drop of 280 kPa, using 2,4-dichloroaniline in water. Per-pass performance decreased with scale and approached a plateau. This is specific evidence, not a general law for all HC. [Scale-up study, 2021 volume; online publication 2020](#).

The nominal flows of 15, 30 and 60 m³/h used for T1 modules correspond to 250, 500 and 1000 L/min. These are nominal design data, not measurements from this account. The proximity of 250 to 247 L/min establishes no equivalence; nor does it justify extending the experiment to 1000 L/min. Geometry, matrix, gas, temperature and the definition of a pass remain decisive. This comparison delimits the precedent without repeating the general scale-up chapter.

Mini-Protocol 3: Testing the Hydraulic Contribution

A circulation control and a technically characterized HC condition are proposed for comparison using the same homogenized batch. Actual flow, relevant absolute pressures, temperature, aspirated gas and configuration are documented. If changing the cavitating condition changes mixing or heating, those differences are quantified: the control no longer isolates a single factor if they are ignored.

Sampling distinguishes whole samples from separated fractions. A decrease in particle size may change turbidity, filterability or soluble COD without mineralizing matter. Interpretation therefore relies on relevant balances and analyses, not appearance alone. Deposits and device condition are also recorded to avoid attributing hydraulic drift to chemical exhaustion.

The inferred recommendation is to retain a hydraulic record with each sample. Testable questions are whether the response persists at comparable temperature, whether it changes when gas is modified while hydraulics remain characterized, and whether the effect concerns transformation or separation. Neither observed bubbles nor a pH correction automatically updates T1 coefficients; they provide variables against which to test them.

07. Venturi Aeration: From Gas Flow to Transferred Oxygen

Aspiration, Dispersion and Transfer

A Venturi can aspirate gas when its pressure field and connection conditions allow it. The liquid transports and disperses that gas, and some oxygen enters the aqueous phase. These are three different operations: admitting air, creating gas-liquid contact and transferring oxygen. Observing bubbles or reading an air flowmeter establishes only part of that chain.

Suction pressure, backpressure, liquid level and losses in the gas line influence operation. A nominal water flow does not establish actual air flow. A circuit modification can simultaneously alter mixing, aspiration and bubble residence time; attributing the result to “more oxygen” requires measuring transfer.

Within the proprietary commercial T1 method, aeration is described as a potential oxygen input and a modification of phase contact. It is not, by itself, mineralization. Transferred oxygen may accumulate, be consumed biologically, react with reduced species or leave the water again. Its fate requires a time-dependent balance.

Driving Force and kLa

In a well-mixed tank representation, transfer is expressed as:

$$\begin{aligned} \text{OTR}_{\text{vol}} &= kLa * (C_{\text{star}} - C) \\ dC/dt &= kLa * (C_{\text{star}} - C) - \text{OUR} \end{aligned}$$

C is dissolved oxygen, DO, in mg O₂/L; C_star is the equilibrium concentration corresponding to the gas and liquid conditions; kLa is a volumetric coefficient, for example in h⁻¹. OTR_vol is the volumetric transfer rate in mg O₂/L/h, and OUR is the volumetric oxygen uptake rate in the same units. The equation assumes that inflows, outflows and other contributions are zero or accounted for separately.

The product kLa combines a transfer coefficient and an interfacial area per unit volume. A single DO curve cannot identify these factors separately. A larger apparent area does not guarantee an equivalent increase in their product either: interface mobility, coalescence, mixing and liquid conditions also change.

For volume V in m³, total transfer in kg O₂/h is $\text{OTR} = V * kLa * (C_{\text{star}} - C) / 1000$. Near saturation, the driving force decreases even though gas continues to flow. An almost constant DO record can mean little transfer or substantial transfer balanced by uptake. Without additional information, the curve alone does not distinguish those situations.

Clean Water and Matrix: Alpha and Beta

The factor alpha is defined here as the ratio between kLa in the matrix and in clean water under comparable conditions. The factor beta is the ratio between the corresponding equilibrium concentrations. Their operational definitions must state temperature, pressure, gas composition, geometry and flow rates; comparing incompatible experiments produces factors without transferable meaning.

$$\begin{aligned} \alpha &= kLa_{\text{matrix}} / kLa_{\text{clean}} \\ \beta &= C_{\text{star}_{\text{matrix}}} / C_{\text{star}_{\text{clean}}} \end{aligned}$$

No universal alpha is assigned to wastewater, and beta is not selected by visual inspection. Interfacial properties and dissolved composition justify measuring them or explicitly declaring the uncertainty of estimating them. An actual operating transfer rate must not be mixed with a standardized oxygen transfer rate, SOTR, without stating the latter's reference conditions.

A study of Venturi and Venturi-Vortex systems quantified kLa , SOTR and efficiency under experimental configurations. It supports evaluating transfer with defined quantities, not automatically transferring its coefficients to another matrix. [Aeration study, 2022](#).

Synthetic Example 1: Demand and Saturation

Assume, solely to illustrate the balance, a 5 m³ tank, $kLa_{clean} = 4 \text{ h}^{-1}$, $\alpha = 0.60$, $C_{star_clean} = 8 \text{ mg/L}$, $\beta = 0.95$ and $C = 2 \text{ mg/L}$. These values are hypothetical inputs, not measured T1 parameters. Then:

```
kLa_matrix = 0.60 * 4 = 2.4 h-1
C_star_matrix = 0.95 * 8 = 7.6 mg/L
OTR_vol = 2.4 * (7.6 - 2) = 13.44 mg/L/h
OTR = 5 * 13.44 / 1000 = 0.0672 kg/h
```

If OUR = 10 mg/L/h, the initial slope is 3.44 mg/L/h. With constant uptake and the other assumptions maintained, equilibrium would be $C_{equilibrium} = 7.6 - 10/2.4 = 3.433 \text{ mg/L}$, not 7.6 mg/L. Aeration does not imply saturation when demand exists.

If the target is to maintain 4 mg/L, available transfer would be $2.4 * (7.6 - 4) = 8.64 \text{ mg/L/h}$, below the assumed uptake. That condition could not sustain the setpoint. The conclusion is an incompatibility between demand and transfer under those assumptions, not an observed equipment failure. If the calculation produces negative DO, the constant-OUR model becomes physically inadmissible near depletion; a negative concentration must not be published as an operational prediction.

Synthetic Example 2: Incoming Air and Retained Oxygen

Consider 1 m³/h of dry air measured under conditions for which an ideal molar volume of 24.5 L/mol and an O₂ mole fraction of 0.2095 are adopted. Incoming oxygen mass would be:

```
n_air = 1000 / 24.5 = 40.816 mol/h
m_O2_input = 40.816 * 0.2095 * 32 = 273.63 g/h
```

If, as a second synthetic assumption, an independent balance assigns 40 g/h to net gas-liquid transfer, the ratio would be $40/273.63 = 0.1462$. This ratio is not proposed as Venturi performance or a T1 effectiveness figure. It shows that 273.63 g/h introduced does not mean 273.63 g/h transferred.

Standardized and actual gas flow cannot be interchanged without correcting conditions. Closing the gas-side balance requires the relevant outlet flow, composition and humidity; closing the liquid side requires accumulation and uptake. Furthermore, accumulated DO is not total transfer: when OUR exists, part of the transferred oxygen disappears from the reading through consumption during the test.

Mini-Protocol 3: Reoxygenation in Clean Water and Matrix

First, the DO sensor's response, calibration and measurement-point representativeness are verified. Effective volume, temperature, pressure and liquid and gas flow rates are characterized. In clean water without appreciable uptake, with constant kLa and C_{star} , integrating the balance gives:

```
ln[(C_star - C_t)/(C_star - C_0)] = -kLa * t
```

The slope estimates kLa provided the assumed mixing holds and sensor response time is considered. Points very close to saturation amplify the influence of error in the concentration difference; they should not be treated as equally robust information. The procedure for establishing initial DO must be assessed by competent personnel and must not introduce an unnoticed residual demand.

The test is then repeated with the matrix under comparable conditions. If uptake occurs, OUR is estimated in a compatible supplementary experiment or a balance including it is fitted with sufficient information. Forcing the clean-water equation onto a curve with respiration would assign uptake effects to transport. A Jetventurimixer study using water and mixed liquor, with an effective volume of 1.5 m³, illustrates the importance of interpreting transfer and uptake together. Its device is not interchangeable with every external injector. [JVM study, 2022](#).

If an aeration pause is used to estimate uptake, sufficient mixing must be maintained and residual surface transfer accounted for. The constant-OUR assumption is checked over the interval used; it is not automatically extended over hours of biological evolution. As an inferred recommendation, DO should be recorded at more than one position during initial characterization to detect gradients before fitting a single tank coefficient.

Interpretation Within the Train

Oxygenation supplies oxygen to the liquid; oxidation transfers electrons in a transformation; mineralization converts organic matter into inorganic products. These operations may be related, but they are not equivalent. A reduction in odour or an improved appearance likewise does not replace the analyses needed to distinguish them.

Testable questions are whether additional gas increases OTR at matched hydraulics, whether the matrix changes α , and whether observed demand explains DO evolution. Bubble size helps describe contact but does not automatically update the engine response. The useful input for integrating aeration into T1 is documented transfer and demand, together with their measurement conditions, not the visible presence of air.

08. Interactions: Sequence, Balances and Causality

Integration Is Not Adding Removal Percentages

The T1 train brings together electrocoagulation, electrooxidation, hydrodynamic cavitation and aeration. Its value as a proprietary commercial method lies in organizing operations that can change one another's working conditions. An operation's outlet is not necessarily the same matrix at lower concentration: it may contain new species, different particle sizes, altered oxygen demand and solids generated during treatment.

A library of published results therefore does not constitute a formula adding four percentages. Studies may use different matrices, doses, materials, times and sample preparations. Even with the same feed, the response of an isolated operation does not automatically determine its response after another operation. Integration requires describing what reaches each stage and what leaves the process boundary.

Complementarity, intensification and synergy should be distinguished. Complementarity means that different operations address different fractions or functions. Intensification denotes improvement in a defined metric, such as required time under comparable conditions. Synergy requires exceeding an explicit no-interaction reference; it is not established merely because the complete train improves on each individual operation.

Order Changes the Question

In an EC, separation and EO sequence, removing solids can reduce the material reaching the subsequent cell. A favourable hypothesis is that this releases capacity to treat another fraction; an alternative is that substances contributing to transport or particular pathways are removed. The net direction of the effect cannot be decided from the diagram.

When HC precedes EC, modified particles or dispersion may change subsequent coagulation. When HC follows floc formation, it may alter floc integrity and separation. Both are engineering hypotheses requiring measurements of size, separable fraction and pollutant-load fate. HC is not declared always to improve or destroy flocs.

Aeration introduces another dependency: it can change DO, mixing and gas-liquid contact simultaneously. When coupled with HC, attributing every change to oxygen is incorrect unless the hydraulic modification is controlled. When combined with EO, oxygen presence likewise does not demonstrate dominance of a particular electrochemical pathway. Variables capable of distinguishing explanations must be observed.

Proposed sequence	Causal question	Decisive observation
EC, separation, EO	Does accessible load change?	Fractions before EO
HC before EC	Does aggregation change?	Final separability
HC after EC	Does the floc change?	Solids and distribution
HC with air	Gas or hydraulics?	OTR and pressures

These questions do not prescribe a universal sequence. They help select an experiment whose outcome can refute the designer's preferred explanation.

Water, Solids and Gas Within One Boundary

The balance starts with water. Feed, added water, samples, purges, sludge moisture and relevant losses must be counted. Otherwise, a concentration decrease may reflect dilution. For each conserved component, the structure is:

$$\text{accumulation} = \text{inputs} - \text{outputs} + \text{generation} - \text{consumption}$$

For an element, such as total carbon, net generation and consumption vanish when all its forms are included and no nuclear reactions occur. For a chemical species, transformation and formation do occur. COD is not a conserved elemental mass: it is a property expressed as oxygen equivalents. An elemental closure must not be forced using COD alone.

For carbon, the liquid can contain organic and inorganic fractions; solids retain both, and gas can carry inorganic carbon or volatile organic compounds. Detected CO₂ does not alone demonstrate contaminant mineralization: it can also originate from initial inorganic carbon released as conditions change.

Background corrections and a coherent boundary are required.

EC introduces metal from the electrode; aeration introduces gas; any dosing introduces additional matter. A balance cannot treat these operations as boxes that only remove material. Sludge samples must likewise refer to dry mass or declared moisture, avoiding comparisons between wet kilograms and water concentrations as though they were equivalent quantities.

Synthetic Example 1: Following Carbon, Not a Label

Imagine a batch with 1.00 kg of initial organic carbon and no other carbon inputs. At the end, a hypothetical inventory identifies 0.55 kg of organic carbon in water, 0.30 kg in solids, 0.10 kg of additional recovered inorganic carbon and 0.05 kg unaccounted for. All figures are teaching assumptions, not T1 measurements.

The decrease in aqueous organic carbon is 0.45 kg. This does not equal 0.45 kg mineralized: 0.30 kg is assigned to solids. The 0.10 kg of inorganic carbon is compatible with transformation only after correcting the background and excluding alternative sources; the remaining 0.05 kg is still a discrepancy, not a demonstrated reaction.

The practical decision is to improve recovery and sampling before attributing the unaccounted term. Had only water been measured, interpretation would have confused separation with transformation. This reasoning also explains why intermediate separation can improve outlet quality without necessarily increasing mineralization.

Additive Reference and Synergy

For two hypothetically independent stages acting on the same fraction, with reductions r_A and r_B defined relative to their own inlets, sequential combination is:

$$\begin{aligned} C_{AB} &= C_0 * (1-r_A) * (1-r_B) \\ r_{AB_reference} &= r_A + r_B - r_A * r_B \end{aligned}$$

It is not $r_A + r_B$, because the second stage receives less mass. Nor is this a law for actual operations: it assumes that r_B remains applicable after A and that the analytical variable and boundary remain unchanged. That transferability is precisely a hypothesis requiring testing.

For effects on removed mass, a contrast can be defined as $I = Y_{AB} - Y_A - Y_B + Y_0$, with Y the response and Y_0 the control. A favourable value only indicates interaction on that response scale and within that design; it does not identify a chemical mechanism. The contrast requires matching A's dose between A and AB, and B's dose between B and AB, while controlling time and hydraulic conditions. AB consuming the sum of both resources does not itself invalidate the contrast; changing those component doses between arms confounds interaction and dose. The reference model must be written before interpreting the result, not selected afterwards to manufacture an advantage.

Synthetic Example 2: A Comparable Budget

Assume a per-batch budget of 12 Ah total charge and 1.20 kWh total measured energy. A hypothetical train allocates 4 Ah to EC and 8 Ah to EO; energy includes pumps, power supplies, aeration and separation within the agreed boundary. These numbers are solely an accounting exercise, not operating setpoints.

Comparing this train with EC at 12 Ah and EO at 12 Ah matches total charge but does not guarantee equal energy: voltages and auxiliaries may differ. Comparing it with each process at 1.20 kWh does not guarantee equal charge either. Both quantities must therefore be recorded, and the budget defined as either an equality or a limit.

One methodological solution is to investigate feasible conditions under the same limits and report the resources each actually consumes. To isolate local interaction, another comparison preserves each component's dose and uses time and circulation controls; it answers a different question from the fixed-budget economic comparison. Energy should not be artificially wasted to feign equivalence. If both constraints cannot be matched, the unresolved question must be stated.

Mini-Protocol 3: Distinguishing Sequence and Separation

A homogenized batch is divided between a hydraulic control, EC with separation, EO alone, and EC with separation followed by EO. Where the question requires it and operation is technically safe, an EC-to-EO arm without intermediate separation is added. Waiting time, sampling and analytical preparation remain comparable; resources for each stage are recorded.

The comparison with and without separation investigates whether phase removal explains the difference. To test order, another arm applies EO followed by EC, preserving each operation's dose and observing its actual inlet. If switching an operation off changes the circuit, that change is characterized: "without current" does not necessarily mean "without interaction with the electrode".

HC and aeration are incorporated through specific controls, not assigned the unexplained remainder of a balance. A circulation control characterizes mixing and temperature; a transfer experiment distinguishes aspirated air from transferred oxygen. The questions are whether the fraction available to the next stage changes and whether the advantage persists when sample preparation and relevant resources are matched. Replication design belongs to the statistical chapter; this chapter establishes the causal comparison to be replicated.

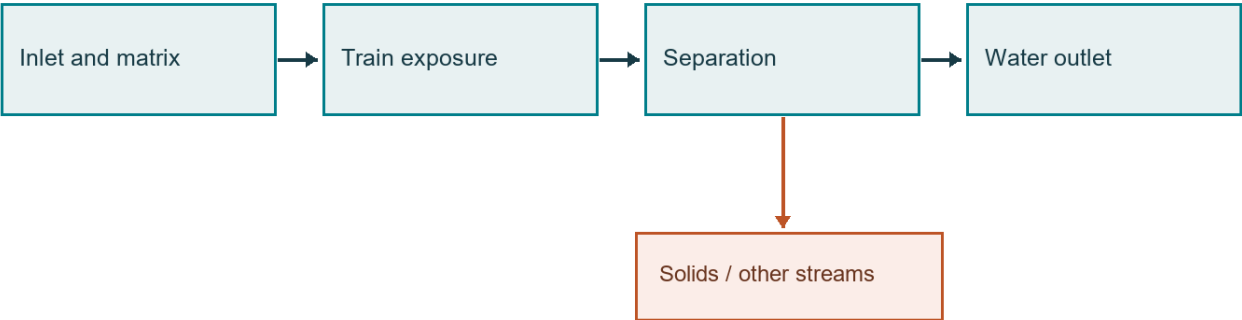
Precedents Without Appropriating Results

Paramanik and colleagues studied EC before HC with variants including air and oxidants in rice-mill effluent. The abstract confirms that related hybrids exist; it does not establish the exact EC, EO, HC and Venturi combination or a joint T1 curve. The coverage used is the abstract, not the full text. [Hybrid study, 2026](#).

Amaral-Silva, Martins, Castro-Silva and Quinta-Ferreira integrated physical separation, coagulation/flocculation and Fenton treatment in olive-mill wastewater. Their abstract provides a different example of integration and separation after oxidation. It does not investigate T1 or demonstrate recirculation-induced cavitation; scale is not inferred from the title. [Integration study, 2016](#).

These precedents are useful for formulating comparisons, not importing performance. A defensible interaction claim preserves traceability of matter, exposure and resources, admits unfavourable results, and explains which observation would distinguish rival hypotheses. This can improve the method without presenting the literature library as automatic validation of its coefficients.

Combined-treatment boundary



Aqueous removal is not mineralisation. Balance all outputs.

09. Scale-Up: Preserve Conditions, Explain Differences

The transfer question

Scaling the proprietary commercial Aguas SB T1 method means transferring an operation to another capacity while preserving what determines its response, or measuring how those determinants change. It does not mean multiplying volume while retaining a removal percentage. The comparison concerns a defined system: water, equipment, hydraulic regime, exposure, dose, separation and measurement boundary. Before asking whether a plant reproduces a pilot, the transferable outcome must be specified: outlet concentration, mass removed from water, specific consumption or stability over an operating campaign.

T1 2.3 remains frozen in this edition. Its rules provide sizing hypotheses, not a publicly calibrated scale-up correlation. A difference between prediction and observation may reflect poorly represented inputs, unequal conditions or an insufficient model structure. Immediately attributing it to size would obstruct investigation of these alternatives. Agreement does not prove physical similarity either: different mechanisms can produce the same final COD while leaving different amounts of solids, organic carbon or nitrogen.

Five similarities worth separating

Hydraulic similarity describes flow paths, mixing and residence-time distribution. It requires identification of feed, recirculation, working volume, pressure and connections. Matching the flow-to-volume ratio does not ensure the same exposure distribution when a dead zone or preferential bypass develops. Parallel branches allow independently measured flows to be added; in series, the same flow crosses several modules. Counting module contacts does not turn that series into a multiplied tank flow.

Exposure similarity concerns how much water circulates and for how long. For a constant-volume batch, $c = Q_r \cdot t / V_b$; with variable flow, $c = \int (Q_r(t) / V_b(t)) dt$. The latter expression also requires volume changes to be recorded. Continuous operation additionally involves Q_r / Q_f and V_b / Q_f . The configurator's daily ratio, $c = \sum (q_i \cdot h_i) / V_d$, uses daily treated volume; it does not itself establish a distribution of individual passes.

Dose similarity distinguishes electrical charge per volume, active reagent, metal supplied and oxygen transferred. Energy similarity adds total energy and its allocation to pumping, electrical conversion and auxiliaries. Finally, matrix similarity requires composition and physical state: waters with identical COD can differ in soluble fraction, particles, conductivity, alkalinity or oxidant demand. These five similarities form a checklist, not five numbers that must be maintained simultaneously at any cost.

Example 1: Equal exposure, different operation

Consider an entirely synthetic calculation. A pilot batch of $V_b = 0.5 \text{ m}^3$, recirculated at $Q_r = 3 \text{ m}^3/\text{h}$ for $t = 1 \text{ h}$, has $c = 6$. Another batch of $V_b = 5 \text{ m}^3$, recirculated at $Q_r = 15 \text{ m}^3/\text{h}$ for $t = 2 \text{ h}$, also has $c = 6$. The second receives the same relative recirculated volume but takes twice as long. Equality of specific electrical charge, temperature, aeration or electrode ageing cannot be inferred.

If both hypothetically operated at constant current $I = 10 \text{ A}$, electrical dose would be $D = I \cdot t_s / V_b$: 72000 C/m³ in the pilot and 14400 C/m³ in the larger batch. These are invented design quantities illustrating a balance, not recommended conditions or T1 measurements. Matching c has left a fivefold difference in

specific electrical charge. If outcomes differ, this design cannot attribute the difference exclusively to hydraulic scale.

A useful comparison would establish which quantity is held constant: c , electrical dose or energy. When all cannot be preserved, a second comparison should decouple the variables. This constraint is engineering information: it reveals which similarities the architecture prevents, instead of concealing that limitation within a single correction factor.

From mechanisms to defensible extrapolation

In cavitation, geometry and pressure fields affect local exposure; a vapour cavity is not an aspirated air bubble. Visible gas does not establish cavitation intensity. A primary study of vortex devices found scale-dependent degradation per pass within its tested geometry and compound. That finding justifies measuring response transfer, not imposing the same penalty on T1. [Vortex scale-up study](#).

Multi-mechanism extrapolation requires recognition that each operation may have a different dominant variable. Electrocoagulation requires metal dose and fate; electrooxidation requires electrical conditions and mass transfer; aeration requires gas actually transferred; separation requires solids capture and evacuation. A design preserving total energy can redistribute it between operations. Equal energy therefore does not establish equivalent treatment either.

A practical strategy compares the complete architecture first and investigates discrepancies through partial controls afterwards. Disabling an operation can change pressure losses or mixing; the control must measure those changes. A perfect decomposition is not necessary for useful learning, but unresolved confounding must be declared. Experimentally observed pH and bubble effects are recorded as findings; they do not automatically modify constants or branches of the frozen engine.

Operational plateau and persistent residual

An observed plateau indicates that increasing exposure within the tested conditions barely changes the resolvable response. It does not by itself identify an untreatable fraction. It may reflect limitations in dose, transfer, separation or analytical resolution. Formulating a persistent-residual hypothesis requires asking whether the remainder retains its behaviour when conditions are renewed and its composition is measured.

In a stage approximation, $r(c) = \theta(1 - \exp(-k \cdot c))$. Here θ is an operational amplitude and k is an exposure sensitivity. Interpreting θ as an immutable susceptible proportion assumes more than fitting a curve. Repeating fractional removal on the entire residual allows continued removal in the calculation; if a genuinely persistent mass exists, it must be explicitly preserved between stages. These hypotheses cannot be exchanged after the outcome becomes known.

Example 2: Three tests of a plateau

A proposed mini-protocol splits the same batch into three branches after reaching a plateau defined beforehand through analytical precision and a minimum relevant change. The first branch continues under the same conditions. The second introduces intermediate separation and continues operating. The third renews a limiting condition selected in advance, such as electrode condition, while keeping the other quantities recorded. Removed volumes and masses are accounted for.

If only the second branch improves, the evidence supports a separation-related limitation, not definitive proof of a unique mechanism. If the third recovers a response, the residual was not immutable under that intervention. If none changes, several explanations remain, including inadequate experimental sensitivity.

Final interpretation should compare whole-water and soluble measurements, additional energy and generated residues. Removal from water and mineralization remain different outcomes.

Example 3: Comparing pilot and plant

The proposed transfer record starts with a characterized batch or feed window, without publicly identifying facilities. Each scale requires measurement of effective volume, flows, tracer behaviour where necessary, integrated energy, doses and separation conditions. Inlet and outlet samples must correspond appropriately to residence times. Responses are then compared in physical units before percentages or performance ratios are calculated.

Dimension	Comparison variable	Testable question
Hydraulics	RTD and flows	Is there short-circuiting?
Dose	C/m3 and active mass	Is it comparable?
Resources	kWh/m3 and residues	Does allocation change?
Matrix	Total and soluble	Does substrate change?

A condition excluded from the initial interpretation should be reserved for testing an explicit prediction. For example, if a hypothesis attributes the discrepancy to electrical dose, it should predict which comparison ought to converge when that dose is matched, without anticipating an efficacy value. New agreement would support the explanation within the tested domain; a persistent discrepancy would require another similarity to be reconsidered.

Decisions without a universal penalty

A scale-up report should conclude with a domain, not a magic coefficient: represented matrices, operating ranges, preserved variables and observed limitations. A plant may perform better, equally or worse than a pilot for measurable reasons. Commercial decisions also require capacity, maintainability and final quality, not merely maximum removal per pass. The reproducibility bank allows verification of what T1 2.3 calculates; the proposed experimental comparison investigates when those calculations transfer. These tasks complement each other but cannot replace each other.

10. Energy, Materials and Economic Comparison

Define consumption and the comparison boundary

A resource balance turns a treatment proposal into an assessable operation. Its first decision is not the electricity price but the boundary: which equipment, schedules, volumes and residues are included. Module consumption is not necessarily treatment-train consumption; train consumption does not always equal the increment attributable to adding it to an existing facility. Mixing these boundaries can produce apparent savings even when every individual reading is correct.

For the proprietary commercial Aguas SB T1 method, preliminary calculations use the declared T1 2.3 values. These values support a reproducible estimate but do not replace campaign submetering. Comparisons must retain the same useful treated volume and comparable final quality. Lower expenditure achieved by missing the treatment objective does not constitute an energy improvement in the service delivered.

From power to specific energy

At constant power, $E=P \cdot t$, with P in kW, t in h and E in kWh. When power varies, $E=\int P(t) dt$; an integrating meter avoids replacing a variable load with a single reading. For several consumers, energies over equivalent intervals are added and divided by the net volume actually treated, not by the volume passing repeatedly through the pump.

For identical modules, with flow q and exposure $c=n \cdot q \cdot t/V$, the result is $E/V=n \cdot P \cdot t/V=(P/q) \cdot c$. Cancelling n and t is algebraic, not a claim that every arrangement has identical performance or actual power. It requires q and P to correspond to the operating condition and no additional consumption to be omitted. In hydraulic series, c may count contacts with units; that definition must be preserved when interpreting the result.

Equipment	Declared P, kW	Nominal q, m3/h	P/q, kWh/m3
T1-16	1.925	15	0.12833
T1-32	2.425	30	0.08083
T1-50	3.850	60	0.06417

The final column corresponds to one unit of c . It is not a universal efficiency ranking: equipment must also be compared through achievable exposure, obtained quality, capacity and auxiliaries. A larger machine may have a lower nominal ratio yet be unsuitable for the required schedule or flow.

Example 1: Estimate and meter reading

At four cycles, the declared calculation gives 0.5133, 0.3233 and 0.2567 kWh/m3, respectively. These are arithmetic model outputs, not new measurements of efficacy or actual consumption. In a synthetic 10 m3 scenario using T1-16 at $c=4$, equivalent operating time is $t=4 \cdot 10/15=2.6667$ h; estimated energy is $1.925 \cdot 2.6667=5.1333$ kWh.

Suppose, solely to illustrate the boundary, an independent auxiliary consumes 0.25 kW over that interval. It would add 0.6667 kWh, giving a synthetic total of 5.8 kWh, or 0.58 kWh/m³. Before adding it in a real project, its exclusion from the declared power must be confirmed. Double-counting and omission are symmetrical errors.

The verification mini-protocol records initial and final meter readings, net volume, starts, stops and the state of each auxiliary. A second column retains the nominal estimate. The difference is not silently corrected: investigation asks whether it reflects schedule, load, flow, electrical efficiency or boundary. In a direct-current circuit, the corresponding voltage and current are measured; that current must not be multiplied by the alternating-current supply voltage.

What energy per kilogram removed means

With concentration in mg/L and volume in m³, equivalent mass removed from a closed aqueous phase is $\Delta_m = V \cdot (C_{in} - C_{out}) / 1000$, in kg. Mass-specific energy is $SEC = E / \Delta_m$. Where inflows, purges or volume changes exist, a load balance replaces that concentration difference. The denominator must be named: kg of COD equivalent removed from water, kg of nitrogen removed and kg of separated solids are not interchangeable.

When the concentration difference approaches analytical uncertainty, SEC can become unstable. A small denominator change produces a large ratio change. In that domain, energy per volume and load difference with uncertainty should be reported, without presenting an impressive ratio as an equipment property. Negative removal must not be converted to zero before the balance is examined either.

Gross savings, net savings and train order

Gross energy savings are consumption avoided in a reference operation. Net savings subtract added consumption: $S_{net} = E_{avoided} - E_{additional}$. Both quantities must preserve their sign and share a time horizon. Positive gross savings can coexist with negative net savings. Avoided energy also does not automatically equal bill savings, which depend on fixed charges, contracted power, time-dependent prices and other contractual items.

If T1 precedes biological treatment, reducing susceptible load may change aeration demand, but savings depend on actual blower and control responses. Mixing minima, oxygen maintenance, nitrification and load variation constrain a proportional conversion between COD removed and kWh avoided. Carbon removal can also change its availability for subsequent biological operations. The train and its objectives must be measured, not simply a COD decrease.

If T1 follows biological treatment, it may serve as a polishing operation and must not be retrospectively credited with upstream aeration savings. The core uses combo for conventional treatment followed by T1, whereas energy calculations may examine T1 before biology. These are different scenarios. The process diagram is part of the economic result and must accompany any comparative figure.

Example 2: Preserve negative savings

In a synthetic daily exercise, a reference operation consumes 120 kWh/day. Following an intervention maintaining the same service, that operation would consume 95 kWh/day, while the added treatment and its auxiliaries would consume 32 kWh/day. Gross savings would be 25 kWh/day; net savings would be -7 kWh/day. The complete system would move from 120 to 127 kWh/day. None of these figures describes a real installation.

The conclusion is not that the intervention has no value: it might pursue different quality or capacity objectives. The energy conclusion is that it consumes more under these assumptions. A savings claim

would require another verified scenario. A before-and-after trial should record flow, loads, temperature, final quality and control rules; without that comparability, consumption changes may reflect service changes rather than the added treatment.

Materials and maintenance as balances

Chapter 04 develops Faraday's law and its assumptions; the concern here is connecting that physical check to materials accounting without repeating the derivation. The theoretical electrode mass is neither an invoice nor necessarily the mass recovered in sludge. Electrodes should be weighed using a reproducible procedure, cleaning recorded, and lost material distinguished from dissolved metal and metal retained in solids.

Passivation and parallel reactions justify supplementing current and time with material observations. Experimental electrocoagulation studies show that actual wear and passivation response depend on tested conditions, so a universal efficiency correction is inappropriate. [Electrode dissolution, passivation and composition](#).

Example 3: Practical consumables accounting

The third mini-protocol weighs initial inventory, identifies replenishment and accounts for final inventory over a defined campaign. It records commercial reagent and active fraction separately, along with dilution water, wet sludge and dry matter. Specific consumption is divided by net treated volume. A moisture change must not be interpreted as additional dry-solids production, nor a charge per cubic metre as a measured metal dose.

Maintenance hours, cleaning, downtime and replaced parts should also be included. This distinguishes variable consumption from exceptional replacement. The record allows investigation of whether longer operation reduces available capacity or changes unit cost, even when electrical expenditure per volume remains similar.

Model cost and commercial decisions

T1 2.3 incorporates economic assumptions including electrode cost of 0.12 EUR/m³, activated chemistry at 0.22 EUR/m³, annual parts at 6% of CAPEX and eight-year depreciation. These are calculation inputs, not measured consumption or a binding quotation. Their use requires checking coverage and avoiding duplicate accounting. Taxes, financing, waste management and contractual conditions need their own boundaries.

The metric $\text{saving}_{M3} = \max(0, \text{reference} - \text{total})$ clips additional costs to zero. It must therefore be accompanied by the signed difference $\text{reference} - \text{total}$: zero in the first metric does not demonstrate break-even. A defensible decision compares alternatives delivering the same service, declares omitted items and preserves adverse scenarios. Reproducing a cost through the public bank demonstrates arithmetic traceability; verifying consumption and a quotation requires distinct operational and commercial evidence.

11. Measurement, Data and Material Fate

The unit of evidence

A useful datum for the proprietary commercial Aguas SB T1 method is more than a concentration. It is a concentration linked to a sample, location, time, matrix, analytical method, unit and operating state. The minimum evidence unit for a comparison is an identifiable test with its boundary and conditions. An isolated outlet result describes that sample; it cannot establish removal without a corresponding inlet. Two reports close in calendar time do not automatically form a pair either.

The data system should separate reported values, interpretation and derived calculations. The original transcription preserves signs, units and laboratory comments. A normalized layer converts quantities through explicit rules. An analytical layer calculates loads and comparisons without overwriting the earlier layers. This separation allows conversion errors to be corrected without reconstructing the test from scattered documents, and prevents a data-cleaning decision from retrospectively becoming a measurement.

Pairing influent and effluent

AF and EF here designate influent and effluent of the studied boundary. In a batch, the pair derives from the same initial inventory, corrected for withdrawn samples, additions and separations. In continuous operation, synchronization means relating inlet and outlet windows according to water transit; it does not necessarily mean collecting both samples at the same clock time. The residence-time distribution, RTD, determines how materials of different ages overlap.

A mean time can guide the offset but does not itself represent a broad RTD. When feed fluctuates, a grab sample can associate a high-load inlet with an outlet originating in another period. Flow-weighted composite samples better approximate a window's load when the protocol and preservation requirements permit. Increments, their volumes, duration and weighting criterion must be recorded.

Example 1: Two windows, two questions

In a synthetic scenario, a facility has an estimated mean residence time of two hours, but tracer measurements show an appreciable tail. Comparing AF from 08:00 to 10:00 with EF from 10:00 to 12:00 is an initial pairing hypothesis, not a guarantee of exact correspondence. The proposed mini-protocol measures the RTD, broadens windows where appropriate and documents which fraction of the feed may fall outside the comparison.

If the objective is to describe discharged quality, a representative EF sampling strategy under stated conditions is sufficient. If the objective is to attribute a reduction to the module, AF and EF at that module and its balance are required. Samples at the plant's endpoints include every intermediate operation. They cannot be reassigned to T1 alone merely because it belongs to the train. This distinction must be decided before statistical analysis, not when selecting the most favourable outcome.

Analytical censoring and units

A result $<L$ means the laboratory does not quantify or detect above the stated threshold according to its method. LOD and LOQ are not equivalent: the reported type must be preserved. The datum contains interval information, not an observation equal to L , zero or $L/2$. Substitution can support a declared sensitivity analysis but must not occupy the original-results column.

The minimum record includes analyte, value or limit, comparator, unit, method and qualifier. For nitrogen, mg N/L must be distinguished from mg NH₄⁺/L. The adopted conversion is $\text{NH}_4\text{_mg/L} = \text{ammoniacal_N_mg/L} \times 1.2878$; the inverse divides by that factor. The engine's nh4 input is the ammoniacal-N fraction of total N, not the ion concentration. Total nitrogen, Kjeldahl nitrogen and ammonium require different labels.

Example 2: A limit and a conversion

With a synthetic inlet of 100 mg/L and outlet <5 mg/L, assuming equal volume and corresponding samples, nominal removal is >95% and at most 100% when nonnegative concentration is imposed. Reporting 97.5% by substituting half the limit is inappropriate. Inlet uncertainty and threshold meaning must accompany that interval; no confidence interval has been calculated here.

In another synthetic record, 12.878 mg NH₄⁺/L equals 10 mg N/L. If total N is 20 mg N/L, the ammoniacal fraction is $a = 10/20 = 0.5$. Dividing 12.878 directly by 20 would produce an incorrect fraction by mixing reporting bases. Automated unit checks prevent this error before engine execution, and a fraction outside [0,1] triggers review rather than silent clipping.

Balances distinguishing transformation from transfer

For a conservable species, the structure is input+generation-output-consumption=accumulation. In an elemental carbon or nitrogen balance, internal generation and consumption are replaced by transfers and changes of species; water, solids and gas must be included where relevant. COD concerns oxidation equivalents, not elemental carbon mass. TOC and COD provide different information and cannot be converted through a universal factor.

Total COD and the operationally soluble fraction require comparable preparation procedures. Filtering one sample but not another changes the question. Cut-off size, colloid handling and recovery must be documented. A total-minus-soluble difference can inform the fraction retained by that procedure but cannot independently identify all particulate species.

A decrease in aqueous COD may accompany sludge accumulation, transformation or mineralization. Investigating mineralization requires evidence of carbon fate, not merely decolorization or a fall in aqueous TOC when transfer to solids was possible. Likewise, decreasing aqueous N does not prove conversion to N₂. Ammonium, nitrite, nitrate, organic N, solids and possible gaseous outlets should be investigated according to the hypothesis.

Example 3: Balance check and positive/negative analytical controls

A synthetic exercise considers 2 m³ of water at 600 mg COD/L: initial aqueous inventory is 1.2 kg of COD equivalent. After treatment and separation, 1.9 m³ remains at 400 mg/L, or 0.76 kg. The 0.44 kg difference does not demonstrate destruction: separated liquid and solids also carry load. Those streams must be analysed or the balance declared incomplete; the difference is not automatically assigned to oxidation.

The proposed quality-control procedure accompanies actual matrix samples with a procedural blank as a negative control and a control material or known spike as a positive control. The blank investigates contamination or spurious signal; the positive control investigates recovery within the method's scope. Acceptance criteria are agreed with the laboratory before tests are interpreted. No universal acceptable recoveries or actual control results are invented here.

A preparation duplicate is added to distinguish heterogeneity and handling from instrumental repeatability. If the blank fails or recovery conflicts with the predefined criterion, the affected analytical

batch is flagged and investigated. Values that worsen removal are not selectively deleted. Positive, negative and null treatment outcomes remain equally visible, together with their quality qualifiers.

Observable mechanisms and confounders

A measurement should be selected for the explanation it can distinguish. Flow and pressure inform hydraulic operation; current, voltage and electrode mass inform electrochemical conditions; dissolved oxygen and transfer inform aeration; solids and metals inform separation and fate. No single signal identifies the complete mechanism. Increasing dissolved oxygen can reflect greater transfer or lower consumption by the liquid.

Venturi studies have evaluated oxygen transfer using system-specific indicators, supporting measurement rather than inference from visible bubbles. They do not provide a universal T1 coefficient. [Transfer in Venturi configurations](#). A vapour cavity and an air bubble are different phenomena; a photograph cannot replace hydraulic characterization.

pH may vary together with temperature, composition or dosing. Attributing the entire change to pH requires a design that decouples these variables. Similarly, an improved outlet after solids separation may reflect the sampling procedure itself. Observations are recorded with times and operations; they do not trigger automatic pH or bubble adjustments in T1 2.3.

From notebook to reproducible dataset

The final table preserves identifiers for batch, independent replicate and analytical aliquot; inlets and outlets; timestamps; volume and flows; limits and units; incidents and exclusion reasons. Missing data remain missing. Adverse results are not errors by definition. Corrections retain traceability allowing recovery of the earlier value and the reason for change.

Publication uses non-reversible identifiers and reviews possible indirect identification through dates, composition or facility descriptions. This chapter contains no private analytical results. The public dataset unambiguously distinguishes observed data, synthetic calculations and model outputs. Only then does comparison between measurement and prediction become meaningful: the quality of that comparison depends as much on the meaning of each row as on the equation used.

12. Calibration, Identifiability and Uncertainty

What is calibrated and what remains frozen

Calibration means estimating parameters from a defined set of observations, an objective function and declared assumptions. It does not mean selecting constants until a favourable case is reproduced. Validation requires evaluating predictions against information that did not influence those decisions. In this edition, the proprietary commercial T1 2.3 engine remains frozen: the alternatives in this chapter are research proposals, not executed adjustments or publicly verified calibration of its constants.

The first step would not be opening an optimizer but building a correspondence table linking each parameter, proposed mechanism and identifying observation. A parameter may be computable yet unidentifiable from the available observations. When different combinations produce responses indistinguishable within experimental error, publishing more decimal places does not resolve ambiguity. The useful conclusion is to design the next comparison or reduce the number of free parameters.

Ceiling and rate: Structural confounding

To examine identifiability, consider the proposed family $r(c) = \theta(1 - \exp(-\beta c))$. θ represents operational amplitude and β controls the approach with exposure. Here β is not the recirculation ratio used in other hydraulic balances. In T1, the approach term corresponds algebraically to $\beta = \ln(2)$ while the other rules remain constant. Allowing a free β would be a calibration alternative, not a description of an implemented modification.

If βc is small, a first-order expansion gives $r(c) \approx \theta \beta c$. Early points mainly inform the product of θ and β . A high ceiling with slow approach can resemble a low ceiling with fast approach. Distinguishing them requires a broader exposure range while maintaining comparable conditions affecting θ . An apparent plateau helps only when it exceeds resolution limitations and cannot be explained by dose or matrix changes.

The sensitivities are $dr/d\theta = 1 - \exp(-\beta c)$ and $dr/d\beta = \theta c \exp(-\beta c)$. Near the origin both contain c and provide similar information; at high exposure, sensitivity to β declines. Concentrating all samples at the beginning or all at the end can therefore waste identification capacity. Point placement should address the question, not just sampling convenience.

Example 1: One datum, several curves

In a synthetic exercise, the algebraic response $r(2) = 0.30$ is specified without attribution to any experiment. With $\theta = 0.60$, the result is $\beta = -\ln(1 - 0.30/0.60)/2 = 0.3466$; with $\theta = 0.80$, it is $\beta = -\ln(1 - 0.30/0.80)/2 = 0.2350$. Both curves pass through the same point. This equality shows that one observation cannot identify amplitude and approach simultaneously, even when the fitted residual is exactly zero.

The resulting mini-protocol adds different exposure conditions and independent replicates, preserving dose and matrix or recording their variations. Before measurement, it defines which divergence between curves would be resolvable. If the feasible operating range cannot distinguish them, a set of compatible parameters is reported or one is fixed through an explicit hypothesis. A parameter selected by numerical convenience is not declared identified.

Removed fraction, concentration or load

Fitting $r=1-C_{out}/C_{in}$ facilitates fraction comparison but places C_{in} in the denominator and shares its error with the response. At low inlet concentrations, the ratio can amplify uncertainty. Fitting C_{out} in physical units changes weighting: the same absolute deviation has different relative meanings across matrices. Fitting loads incorporates flow and volume but also their errors. No transformation automatically eliminates all these problems.

The objective function must correspond to intended use. If final quality is the prediction target, concentration error deserves prominence. If removed mass and specific consumption matter, comparable loads are required. Both outcomes should be reported when adequate data exist, without changing metrics after discovering which favours the model. Uncertainty-based weights require justified uncertainties; they must not be invented to improve the appearance of a fit.

Example 2: Same percentage, different mass significance

Assume two synthetic scenarios with the same net flow of 10 m³/day and inlet concentrations of 100 and 1000 mg/L. A ten-percentage-point removal error corresponds respectively to 10 and 100 mg/L outlet error, or 0.1 and 1 kg/day load error. An unweighted fraction regression would assign them the same squared error although their mass differences are tenfold apart.

This exercise does not prescribe always favouring the larger load: a low-concentration objective could make the first scenario more important. It requires the purpose of the statistical loss to be declared. Cross-matrix comparisons should retain error tables by concentration, load and group instead of summarizing the entire campaign with a single coefficient of determination.

Separating training from evaluation

Rows from the same facility, batch or campaign share characteristics. Randomly distributing aliquots from the same batch between training and validation causes leakage: during fitting, the model sees part of what it was supposedly expected to predict. Splitting should use groups consistent with future use. For transfer between facilities, facilities are held out; for new batches at a known facility, complete batches or periods are reserved.

Variable selection, normalization, imputation and hyperparameter choice take place within the training set. If validation results repeatedly inform decisions, that set ceases to be an independent final assessment. A final reserved group can protect evaluation, provided its size and diversity address the question. With few groups, transfer variability may remain highly uncertain.

A proposed grouped validation could leave each facility out in turn to explore transferability, keeping its campaigns together. This is a possible design, not an analysis performed here. The report should explain whether the objective is interpolation within known conditions or extrapolation to new matrices and scales; good interpolation does not automatically establish the latter capability.

Conditional uncertainty, not invented intervals

Uncertainty arises from analysis, sampling, operating inputs, parameters and structure. An interval propagating only flow and concentration errors does not cover the possibility that the equation is inappropriate. It must be labelled as conditional on the version, assumptions and distributions used. Deliberately varying inputs over a grid produces sensitivity scenarios, not probabilities or confidence intervals.

Censored results must retain their limits in proposed fitting, through a censoring-compatible objective or justified interval analysis. Replacing all such values with zero artificially changes the residual. Grouped resampling could evaluate variability between independent units, but it cannot create nonexistent groups or correct missing coverage. Without sufficient data, the honest outcome is unquantified uncertainty, accompanied by the measurement that could reduce it.

Sensitivity and discontinuous code rules

A local derivative can be calculated within a smooth branch. T1 2.3 contains rule changes requiring a different interpretation: the exposure multiplier changes at $c=12$, stage groupings may change discretely and outputs apply floors. A finite difference crossing these boundaries combines local sensitivity with a programmed jump. It must not be interpreted as a kinetic constant or an observed physical transition.

The floors are 3 for BOD, 15 for COD, 5 for TSS, 2 for N and 0.2 for P, using each parameter's corresponding units. They are not analytical limits. When an inlet lies below its floor, the calculated outlet can exceed it; this behaviour is retained as a code limitation and excluded from physical interpretation, without modifying the engine for this chapter.

Example 3: Audit boundaries without recalibration

The third mini-protocol runs the same scenario at $c=11.999$, 12 and 12.001, keeping all other inputs fixed. It records output, active branch and differences without fitting a smooth curve through the three points. Another series places concentrations on either side of each floor and checks whether the calculation represents interpretable removal. These cases are software tests, not water experiments.

Next, one input at a time is varied within interior regions, supplemented by selected combinations because interactions may exist. The effective configuration is preserved and outputs compared with the reproducibility bank. Any future alternative, such as a smooth approach or explicit residual model, would require a new version, prior criteria and held-out evaluation. This chapter proposes how to learn from data; it does not attribute a calibration to T1 2.3 that is not yet publicly documented.

13. A Reproducible Protocol for Researchers and Engineers

Ask a question the experiment can answer

The protocol turns a design uncertainty into an interpretable comparison. Its purpose is to test the proprietary commercial Aguas SB T1 method, not to present the activity as a university programme or turn the experiment into a promotional demonstration. A campaign should begin with one primary question: transfer across scales, exposure response, separation effects or predictive capability of a model version. Accumulating objectives without prioritization often produces many measurements and few identifiable conclusions.

The question becomes a primary outcome, comparison and acceptance criterion before responses are observed. For example, investigating intermediate separation requires configurations with equivalent exposure and records of removed material. Investigating prediction requires inputs, version and rules to be frozen before held-out results are opened. Criteria should express engineering relevance and required precision, not merely statistical significance selected afterwards.

Operational preregistration

The prior record identifies the responsible person, date, T1 2.3 version, effective configuration, units, question, hypotheses, and primary and secondary variables. It describes batches, treatment allocation, replicates, sampling points, permitted exclusions and handling of censored values. It includes the analysis plan and conditions that would make the test inconclusive. It may remain under commercial document control; its purpose is establishing precedence and traceability, not disclosing confidential information.

Three forms of acceptance should be separated. Operational acceptance confirms that the setup functioned within permitted limits. Analytical acceptance confirms that laboratory controls met agreed criteria. Hypothesis acceptance uses valid comparison results. Failure of the first or second may prevent evaluation of the third; it does not demonstrate that treatment works or fails. Deviations are recorded and analysed according to their implications.

Inlet water, batch and preparation

Each batch needs an identifier, an origin description without publicly identifying details, and collection, storage and preparation conditions. Initial characterization follows the question: total and soluble COD, TOC, solids, total N and nitrogen species, P, pH, conductivity, alkalinity and temperature where relevant. Measuring everything in every test is unnecessary; justifying that omitted variables do not prevent interpretation of the primary outcome is essential.

Homogenization should produce comparable aliquots without unnecessarily changing the matrix. Prior settling, sieving, filtration, dilution and additions are recorded. Differently prepared samples constitute different conditions even when they originate in the same container. Synthetic water helps isolate factors; real water supports transferability investigations. Neither universally replaces the other. The selected composition and its limitations are part of the evidence.

Hydraulics and exposure before treatment

The circuit is drawn with tank, feed, recirculation, purges, modules and separators. Working volume and actual flow are measured under operating conditions. Parallel branches and flow distribution are identified; in series, common flow is retained and module contacts counted separately. Batch exposure is $c=Qr \cdot t/Vb$ under constant conditions; changes in flow, volume or active periods require integration and time records.

Where sample correspondence depends on mixing and residence, a tracer experiment compatible with the installation and matrix is proposed following a safety assessment. RTD informs AF/EF sampling windows; it is not a retrospective correction for every discrepancy. Nominal time V/Q does not itself demonstrate the absence of short-circuiting. Hydraulic and chemical tests must be distinguished if the tracer changes relevant conditions.

Example 1: A batch exposure series

The first proposed design uses a homogenized batch and points $c=0,1,2,4,8$, adding others where the question requires. This series is neither universally optimal nor a dose recommendation. In a synthetic setup with $Vb=0.75 \text{ m}^3$ and $Qr=3 \text{ m}^3/\text{h}$, corresponding times are 0, 0.25, 0.5, 1 and 2 h. These are scheduling calculations, not efficacy results.

A baseline is taken before treatment and each sample volume is recorded. If withdrawals materially change Vb , integrated exposure is updated or independent reactors are used for each point. Successive observations from one batch form a correlated series, not five independent replicates. If the programmed twelve-cycle jump is investigated, points near that boundary are added without assuming a physical threshold.

Energy, electrical charge and material

The time record includes power or integrated energy, current and voltage in the electrochemical circuit, electrode condition, temperature, pressures, gas flow and reagents where present. An explicit auxiliary boundary is retained. Specific energy uses net treated volume; electrical charge uses integrated current and coherent units. Faraday's law and its material interpretation are developed in Chapter 04 without turning theoretical mass into measurement.

Residual liquid, samples, sludge, foam, replenishment and separations are accounted for. Before the experiment, the protocol defines which streams can be analysed and which balance closure will be possible. Useful aqueous removal does not require proof of mineralization, but it must be named correctly. A mineralization or nitrogen-transformation hypothesis requires specific fate observables, not only percentages disappearing from water.

Example 2: Hydraulic control and dose-matched separation

The second design divides comparable batches between recirculation without intermediate separation and two treatment periods with solids removal between them. As far as the setup permits, total exposure, electrical charge, active dose and thermal conditions are matched. Any energy or hydraulic difference introduced by separation is measured. An additional hydraulic control preserves circulation without activating the investigated operation, whenever technically feasible and safe.

If matching every dose is impossible, the actual comparison is declared: complete configurations, not a pure separation effect. Whole-water and soluble analyses, separated material and resources are examined. Branch differences may support an operational hypothesis but do not establish synergy

across every mechanism. An interaction requires a design also capable of estimating the relevant contributions under comparable conditions.

Replicates, order and practical statistics

An independent replicate repeats the relevant experimental unit; a second reading of the same aliquot evaluates another source of variation. Batch, reactor, run, sample and reading must be labelled separately. A pilot with, for example, three independent runs per condition can inform variability and feasibility but does not guarantee statistical power or sufficient precision. The eventual number depends on the minimum relevant effect, variability and dependence structure.

Order is randomized where possible and blocked by batch or day where those differences matter. This avoids confounding treatment with progressive heating, wear or sample ageing. Analysis reports effect magnitude, dispersion, sample size and relevant individual outcomes. An isolated p-value does not replace technical relevance or matrix coverage. Losses and failures remain in the tracking record.

Example 3: Held-out prediction and acceptance

The third design separates complete batches for development and evaluation. Before the held-out group is revealed, inputs, outputs predicted by T1 2.3 and acceptable-error criteria for the engineering decision are archived. Concentration, load where relevant and energy are compared while preserving analytical limits. No universal tolerance is set here: it must reflect the measurement method and intended use.

If prediction fails, data quality, hydraulic correspondence and model domain are examined. A subsequent explanation may generate a new hypothesis but does not turn the same held-out set into independent validation of a refit. Any future calibration is versioned and requires another evaluation. An inconclusive test is reported as such, without selectively retaining favourable analytes or conditions.

A bounded first comparison and decision criterion

The first comparison can combine the preceding designs without attempting to validate every mechanism at once. Select a matrix, configuration and primary response; record a development batch and reserve another independent batch to evaluate the prediction before refitting. Compare circulation control, activated train and matched separation only where the equipment can safely distinguish them. Do not construct nominal controls that change every condition simultaneously.

Define the decision in advance: reproducing the curve supports that representation only under tested conditions; material bias requires restricting the domain or proposing another parameterisation; insufficient hydraulic, analytical or energy data make the question inconclusive. A concentration pair may show removal but cannot simultaneously identify rate, ceiling and separation effects. Do not fit every factor to that same pair.

This comparison does not validate all matrices, sizes, chemical options or serial configurations by extension. Its value is resolving a priority uncertainty and providing a transferable result with limits, not turning a favourable pilot into universal validation.

Safety, quality and reproducible delivery

Operation requires competent assessment of electrical, pressure, gas, chemical and waste hazards. The protocol does not prescribe improvised reactive mixtures or atmospheres. The laboratory defines preservation, oxidant neutralization and interference handling according to its methods; blanks, positive controls and duplicates check analytical quality. Vapour cavities and air bubbles are characterized differently, and pH observations do not automatically change the engine.

The delivery includes protocol and deviations, schematic, original and normalized data, unit dictionary, configuration, energy and material records, exclusion rules and comparison results. Public reporting separates synthetic scenarios, authorized measurements and model outputs. The reproducibility bank verifies frozen execution; the experiment tests hypotheses under specific conditions. The valuable outcome is a repeatable conclusion, even when it refutes a commercial expectation or defines a smaller domain than anticipated.

14. From laboratory analysis to a valid comparison

A laboratory analysis can rigorously establish a concentration while still not allowing equipment removal efficiency to be calculated. The difference is the question being asked. An outlet sample describes that sample; a properly linked pair supports change estimation; a time series helps identify response; controlled comparison supports attribution to an operation.

The method uses application evidence to guide hypotheses and design. This public edition does not reproduce commercial case files or identify installations. Examples here are invented to explain the procedure, not disguised customer results. Published references retain attribution and their authors' conditions.

Internal measurements and public examples

Preparation of the method located laboratory inlet/outlet pairs, plant-application records and other outlet results without comparable inlets. Their existence is distinct from the published synthetic examples. Nor is the collection presented as engine calibration: batch, train, separation, dose and exposure correspondence require case-by-case examination.

The priority real comparison is a recoverable analytical pair associated with a combined-treatment experiment. It remains in the internal file until permission, identifiability and conditions required for comparison are resolved. This public edition uses neither its concentrations nor an alias to imply validation a reader cannot reproduce. A historical case already examined will not constitute an independently held-out test of future calibration.

Four useful forms of evidence

An **isolated outlet** can demonstrate a particular quality at one point. It matters operationally and helps decide what to investigate next. Without a comparable inlet it cannot yield removal, nor establish year-round quality.

An **inlet/outlet pair** supports calculation when it represents the same batch or a hydraulically matched period. Units, methods, preservation and separation must be consistent. Where water addition changes volume, the concentration percentage needs a mass balance.

A **response series** includes several times or exposure levels. It helps separate fast and slow responses and investigate a plateau. If every point uses different water, however, the curve confounds matrix variation with exposure.

An **independent test** evaluates a prediction fixed before observing held-out results. Independence is not established solely by an external laboratory: a result used to select coefficients does not become independent validation through remeasurement of the same case.

System boundary

Plant influent and final effluent include everything between those points: equalisation, upstream operations, internal recycles, separations and downstream treatment. The pair's performance belongs to that plant boundary. Attributing a contribution to T1 requires sampling around the unit or controls separating its effect.

This distinction retains the value of a good result without exaggeration. Saying an installation achieved an outlet while operating the train differs from saying the module alone caused all removal. The latter needs more information.

Synthetic example: overall inlet 800 mg COD/L, module inlet 300 and final outlet 80. The complete train removes 90% relative to 800, but that 90% cannot be assigned to the module. Even the change from 300 to 80 may include downstream separation. The process diagram determines each percentage's boundary.

Concentration and mass

A stream with volume V in m³ and concentration C in mg/L carries $M = V \cdot C / 1000$ kg. If 10 m³ enters at 1000 mg/L and 12 m³ leaves at 500 mg/L, concentration falls 50%, while aqueous load changes from 10 to 6 kg: a 40% decrease. The added 2 m³ explains part of the concentration reduction.

For multiple outlets, sum their loads. A purge does not leave the balance simply because it is not the main stream. Solids and foam require masses and composition, not just apparent volume. Report imperfect closure rather than automatically assigning unmeasured material to mineralisation.

COD is an operational measure of oxygen-demand equivalent, not a direct carbon weighing method. Its fall can combine material removal, changes in oxidisability and oxidation. TOC adds another perspective but also requires the analysed phases to be known.

Values below a reporting limit

An outlet reported as <20 mg/L is neither exactly 20 nor zero. With a measured inlet of 500 mg/L, matched sampling and the same analytical basis, concentration removal exceeds 96%. Input and analytical uncertainty can require further interpretation.

A graph can show an interval or censoring symbol. Statistical fitting should accommodate censored observations or show sensitivity to their treatment. Replacing every value with half the limit is an analytical choice, not recovery of an unmeasured concentration.

A simulator floor differs from an analytical quantification limit. A programmed 15 mg/L minimum does not mean a laboratory cannot measure below 15. Confusing these produces apparent agreement rather than a real comparison.

Comparing prediction and observation

First define the endpoint: outlet concentration, load removed, specific energy or a combination. Then assemble equivalent inputs and conditions. If actual operating hours are absent, do not select the hours that best fit the result and subsequently present them as observed.

Unknown operating hours may be represented through a labelled sensitivity range. Its purpose is to identify which missing record would most reduce uncertainty. It is not a statistical confidence interval or a proven reconstruction of the test.

Complete comparisons retain unfavourable results. Falling COD with increasing TSS before separation may be consistent with floc formation; increasing TSS in final effluent is an operational issue that a COD percentage must not conceal. Interpretation depends on sampling location and time.

Prediction residuals should retain physical units and sign. In a synthetic example, predicting 100 and measuring 180 mg/L underpredicts the outlet by 80 mg/L, even if both appear low relative to the inlet. An overall average can conceal systematic error near the target range.

Evidence that changes a decision

Before requesting another analysis, ask what decision it could change. A response series may be more useful than another isolated outlet when considering extra time. Phase closure matters for sludge transfer; submetering at equal quality matters for savings; splitting one batch between configurations helps distinguish geometry from matrix.

This approach avoids large but uninformative campaigns. It does not require measuring everything in every trial: measurements should answer the question. Missing information becomes a specific task rather than a general doubt about previous work.

Commercial records can contain valuable observations without a complete original experimental design. Retaining the right scope allows use as feasibility evidence, achieved quality or plausible mechanism. The next step is a targeted test rather than inventing information that was not recorded.

Publication and traceability

Publishing results requires permission and assessment of identifiability. Removing a name does not necessarily prevent identification from sector, location, dates and distinctive values. Public and internal records can retain different detail without losing consistency.

An authorised public case should distinguish what was tested, measured, inferred and reproduced by the engine. Recoverable references may include a shareable technical report, dataset or paper. An attractive image of water does not replace those relationships, although it may usefully describe the setup.

The strongest evidence is not evidence without qualifications. It enables calculation to be reconstructed and explains why the result belongs to that system under those conditions. This allows the corpus to grow without making every case universal.

15. Worked examples and reproduction

All cases in this chapter are synthetic. Some execute the T1 2.3 core directly; others are independent balances used to interpret inputs and outputs. Keeping them separate helps locate errors in the model, units or layout without conflating them.

Example 1: four turnovers do not mean 94% COD removal

Assume COD 500, BOD5 250, TSS 220, N 40 and P 8 mg/L; pH 7.2 and ammoniacal fraction 0.8. COD/BOD=2, so the matrix receives no penalty in this scenario. For one T1-16 at four turnovers without chemical options, the COD ceiling is 0.64 and exposure factor 0.9375.

```
r_COD = 0.64 * 0.9375 = 0.60
COD_out = 500 * (1-0.60) = 200 mg O2/L
r_BOD = 0.72 * 0.9375 = 0.675
BOD_out = 250 * (1-0.675) = 81.25 mg O2/L
```

These results are checked by executing frozen JavaScript. The 93.75% describes approach to the ceiling, not removal of all inlet concentration. Confusing them would materially overstate proposed capacity.

Example 2: one additional turnover

Within the same branch, five turnovers give A=0.96875, COD removal 62% and outlet 190 mg/L. Relative to four turnovers, additional exposure improves the outlet by ten mg/L. The energy cost does not fall merely because the benefit is smaller.

At declared power 1.925 kW and nominal flow 15 m3/h, each turnover costs P/q=0.128333 kWh/m3. Moving from four to five adds that energy to remove another 0.010 kg COD/m3: marginal consumption is 12.8333 kWh/kg. This does not contradict lower average consumption for the complete treatment; it answers a different question.

Example 3: operating hours and production

For 75 m3/day, a 15 m3/h unit operating 20 h/day provides c_d=15*20/75=4. Estimated energy is 1.925*20=38.5 kWh/day, or 0.513333 kWh/m3.

If production rises to 100 m3/day without changing equipment or hours, the index falls to three. Maintaining four would require 26.6667 hours from that unit within the same day, which is impossible. Capacity, storage strategy, period or configuration must change. More than 24 operating hours per day is not an acceptable operating schedule.

Example 4: three sizes at equal exposure

Using the core's declared powers and nominal flows, four turnovers require:

Model	q, m3/h	P, kW	E/V, kWh/m3
T1-16	15	1.925	0.513333
T1-32	30	2.425	0.323333
T1-50	60	3.850	0.256667

The difference follows from P/q without establishing equal chemistry across sizes. Performance comparison requires other exposures to be measured or maintained. External auxiliaries are not automatically included in declared power.

Example 5: attainable target and target beyond a branch

At fixed ceiling 0.64, reducing 500 to 250 mg/L requires 50% removal. Inversion gives $c = -\ln(1-0.5/0.64)/\ln(2) = 2.192645$. The unit's indicative minimum-turnover rule may require more exposure than that mathematical solution. The mathematical target and operating-selection criterion are separate checks.

Reducing 500 to 125 mg/L requires 75%, above the fixed ceiling. There is no time solution within that branch. The complete engine contains bonuses and stages, so the actual configuration must be executed; the inverse calculation cannot be extended across rule changes. Another configuration predicting success is not experimental validation.

Example 6: equal concentration, different load

Two waters contain 500 mg COD/L. At 30 m3/day incoming load is 15 kg/day; at 300 m3/day it is 150 kg/day. Equal percentage removal requires ten times the removed load. With one unit's time and current unchanged, electrical dose per volume falls as production rises.

This explains why the same composition does not mean the same installation. Composition and quantity differ. It also explains why both treated flow and circulation must be reported: a 15 m3/h pump does not automatically produce 360 m3/day at the target quality.

Example 7: two interpretations of a second stage

From 500 mg/L, a first stage removing 60% leaves 200. A second removing 50% of that residual leaves 100: 80% overall. This is a correct balance under those efficiencies, not a T1 experimental prediction.

If instead a persistent residual of 180 mg/L is assumed, repeating the same mechanism cannot reach 100 under that hypothesis. The disagreement defines a useful test: determine whether the second stage acts on still-susceptible material or the first plateau was persistent. Solids separation and dose controls help interpret the result.

Example 8: signed net energy savings

For balance illustration alone, suppose aeration avoids 6000 kWh/year while added treatment uses 9000 and auxiliaries 500. Net savings are $6000-9000-500 = -3500$ kWh/year. Energy rises even if there is another benefit, such as achieving a quality target.

If later optimisation avoids 14000 kWh/year with unchanged added consumption, savings become 4500. The second figure cannot replace the first without supporting operating conditions. Neither is a measurement of a particular treatment plant.

Example 9: a censored result

With inlet 500 and outlet <20 mg/L, removal exceeds 96%; it is neither exactly 96% nor 100%. A simulator outlet of 19 is compatible with the censored measurement, but does not establish an error of only 1 mg/L. Actual concentrations of 2 or 18 would also be compatible.

Example 10: a known discontinuity

For the first scenario, executing 11.999 and 12 turnovers reveals the bonus change. COD removal jumps by approximately 6.40 percentage points. Physical testing on either side could investigate real continuity, but the software already explains the table's jump: a discrete condition changes branch.

This behaviour is retained as a regression test rather than a promotional result. If a future release smooths the transition, change the version, record the reason and repeat comparison cases.

Reproducing and submitting a comparison

The package contains captured code, parameters, public inputs and results. Local Node.js execution requires no AI API and sends no data to a server. `reproduce.cjs` checks the version and four-turnover COD/BOD outputs through three assertions. `book_checks.cjs` adds 33 specific checks of examples, conversions and numerical balances, identified in `BOOK_CHECKS.json`. It is not a universal unit or balance validator: the assertions establish computational consistency for those cases, not scientific validation.

For a comparison, retain input JSON, asset names and hashes, configuration and outputs. Then add measurements, provenance and experimental boundary. Do not change constants before calculating error on held-out results. This sequence separates reproduction, evaluation and model updating.

Opening the benchmark from this PDF

This PDF embeds `T1_REPRO_2_1.zip` as a file attachment. A viewer supporting attachments can extract it; some browser viewers do not expose that feature. The same ZIP is supplied separately within this edition's package. The benchmark needs no network or API and does not execute when the PDF opens. Reproduction requires an installed Node.js runtime and voluntary execution of the commands in its README.

The `FILES_SHA256.json` file identifies the benchmark contents. SHA-256 hashes of the captured core assets are:

```
t1_parametros.js
24f0d7e82a97efdc1c6310e35845e243225f2536ff9021d820fc10b8d970fc25
t1_motor_v2.js
5e306ae6953271efed422eccd9664b7a1d5c2353f6f552bb73e43556f888527d
```

Matching hashes establish identical bytes, not measured performance. The benchmark loads parameters then engine, without external `T1_CONFIG`. Website configuration changes must be recorded as differences; the frozen edition does not automatically follow the live site.

16. Design decisions and difficult questions

A useful method does more than calculate an outlet: it helps choose the next action. This chapter turns model limitations into specific decisions, distinguishing input corrections, additional measurements and interpretation questions that should be resolved before sizing.

More turnovers or a different configuration?

When the target is below the effective ceiling and away from discontinuities, curve inversion gives an initial exposure. Available hours, hydraulic capacity, energy and quality must then be checked. If the target exceeds the ceiling, the same calculation has no solution; extra hours under unchanged conditions do not resolve it.

A new stage can be reasonable if it changes a limiting condition, but it must be described physically. Are solids removed? Does the matrix change? Is total dose increased? Is flow unchanged? These answers distinguish an installation change from numerical repetition of a percentage.

Is the model conservative?

Parameters may have been chosen with prudent intent. That does not turn every prediction into a guaranteed lower performance bound. An unrepresented matrix, inadequate separation or different flow may perform worse. Establishing conservatism requires a distribution of validation errors within a defined domain.

The appropriate operational description is a design estimate under stated conditions. Any margin should identify whether it concerns target concentration, exposure, load or uncertainty. A 25% margin on one variable does not automatically transfer to the others.

Why does lower power not always save energy?

Because the balance includes consumption actually avoided. A wastewater plant may retain minimum aeration for mixing or nitrification even after some organic load is removed. If avoided consumption is below added treatment consumption, net savings are negative. Quality, capacity or material benefits may still exist and should be evaluated separately.

Savings need equivalent periods or configurations in flow, load and final quality, with consistent energy boundaries. The reference must not be redefined retrospectively until the result becomes positive.

Does falling COD establish mineralisation?

Not alone. Material may enter flocs, foam or another stream. Improved biodegradability also does not mean all material has already been biologically consumed. The next measurement depends on the claim: phase balance, organic and inorganic carbon, species or biological monitoring.

Removing pollutants from water can be valuable for discharge design even when they remain in sludge. The issue is not to deny aqueous removal but to budget and manage material fate. Omitting residues can displace costs and risks beyond the chosen boundary.

Can four mechanisms be added together?

Operations can be integrated; their removal percentages cannot be added as though acting on independent masses. Each stage changes the next stage's feed, and interactions may help or hinder. Synergy needs a defined reference and comparable controls rather than merely a functioning combination.

A more productive question asks which operation changes a variable limiting the next. Particle removal might alter transport or chemical demand, for example. This is testable through controls, not a numerical improvement to insert automatically into a simulator.

Is a paper with a similar equation sufficient?

Algebraic similarity guides comparison without establishing physical equivalence. Concentration, exposure and regime definitions must align. A coefficient for a model contaminant does not become an industrial-water COD coefficient because both use an exponential.

A reference can also be useful because it shows differences: another scale, energy requirement, persistent residual or adverse response. A bibliography retaining counterexamples is more valuable for engineering than one selecting only high removal percentages.

What if bubble size changes?

First identify the bubble: aspirated gas used for transfer or a transient cavity whose collapse contributes to cavitation. Size distribution, gas content, pressure and residence can affect different processes. This edition has no measured T1 coefficient supporting a universal diameter correction.

The immediate decision is to record relevant geometry and conditions. A model change should follow a test varying that feature without simultaneously changing every other factor. This incorporates literature knowledge without inventing unsupported precision.

What should trigger a sizing review?

Significant changes in composition, solids, pH, salinity, temperature, actual flow or separation can alter applicability. Changing the target also matters: a result acceptable for one use does not establish suitability for another. Review should start with the changed variable rather than necessarily repeating every calculation.

Observation	First check	Possible decision
Lower actual flow	Exposure and pressure	Recalculate hours
More outlet solids	Sampling point and separation	Review floc removal
Early plateau	Dose, phases and matrix	Design a limiting-factor test
Negative savings	Boundary and avoided consumption	Optimise or retain another objective

When is a result ready to communicate?

When it is clear what was calculated or measured, under which conditions, what it means and what it does not. Communication can be brief without hiding decisive information. Reproducible results allow configuration and sources to be recovered; decimal places alone do not provide that assurance.

For researchers, communicate the open question and proposed comparison first. For operators, identify the next measurement or adjustment. For customers, explain the indicative scope and information needed to confirm a solution. These are different detail levels of the same knowledge, not incompatible factual accounts.

What counts as method improvement?

Improvement may correct units, identify a limit or remove a redundant variable rather than increase removal percentages. Preserve a regression case detecting the original problem and explain the change. Once new data recalibrate a version, they are no longer independent validation for that version.

The corpus is strongest when a precise criticism can become a test and then an improved release. Retaining relevant open hypotheses does not weaken the proposal; it prevents a local error from invalidating an architecture that remains useful for sizing and learning.

17. Contribution and evolution of the method

T1 contributes a reproducible engineering proposition: connecting recirculation, composition, configuration and resources of a combined train, and specifying observations that could improve that connection. A model release is presented alongside assumptions, examples and open questions. This allows scientific discussion without equating it to acceptance of a commercial offer.

What a reduced formulation can contribute

A reduced model does not resolve every reaction or all flow dynamics. It selects variables useful for estimating a response within an operating domain. It can be useful without uniquely mechanistic parameters provided its scope, errors and conditions remain visible.

The practical benefit is coherent decisions: how production changes exposure, what another turnover costs, when a target falls outside a branch and what information is missing for installation comparison. These questions prevent decisions based only on rated power or a remembered percentage.

The trade-off is that an aggregate parameter may absorb several mechanisms. Adding an untested bubble or temperature factor may count an effect already contained in the aggregate response twice. Model expansion should demonstrate predictive utility, not merely add a plausible explanation.

Three hypotheses organising the experimental programme

H1, conditional exposure. Under stable matrix and configuration, response may be represented by an exposure curve with effective parameters. Time series and dose controls test it; systematic variation unexplained by the curve defines its domain.

H2, renewable operational capacity. Part of a plateau may depend on separation, reagent availability or transport and change when stage conditions are renewed. Compare equal total exposure with and without that renewal. This does not assume all residual material is treatable.

H3, multivariable scale-up. Equal turnovers are insufficient when matrix, energy, charge, pressure, aeration or residence changes. Transfer improves by recording those differences and identifying which predict deviations. A curve remaining stable despite major changes is also an important result.

These hypotheses are not three new coefficients already inserted into the engine. They form a testing programme starting from the current formulation while retaining alternatives.

Discussing the method with a researcher

An initial comparison should answer a bounded question. For example: a study describes per-pass yield while our core uses effective exposure; what regime and measurements permit comparison without equating fraction removed per visit to an exponential coefficient? This is more useful than requesting general endorsement.

A second discussion might focus on scale: select a published result with known conditions, reproduce its balance using the original definitions and identify T1 variables lacking correspondence. Where equivalence fails, retain the difference. An imperfect match informs experimental design rather than justifying forced fitting.

A researcher need not accept every component to contribute. They can examine hydraulics, dose, separation or statistical treatment. Identifying a non-identifiable parameter advances the method even without producing a higher removal percentage.

From feedback to a new release

A proposed change should state observation, possible mechanism, expected effect and test. Better fit to previously used data does not establish improved generalisation. Reserve a case or condition before fitting and evaluate error without retrospectively changing success criteria.

New versions should retain previous configuration, motivating data and output comparisons. Interface changes must not silently alter units or parameters. Translation must not change the described regime or turn estimated into demonstrated.

Knowledge continuity depends on that discipline rather than duplicated text volume. The same chapter supports human reading, retrievable records and simulator explanations. Equation changes should regenerate examples and derived documents from the same editorial source.

What closing this edition means

Closing an edition means delivering consistent definitions, complete content, repeatable calculations and clear limits for available evidence. It does not mean ending research permanently. An applied method can be editorially complete while remaining open to data changing its interpretation.

The most valuable next improvement is not undifferentiated extra pages. It is a comparison separating currently confounded hypotheses: exposure from dose, separation from oxidation, and operational plateau from persistent residual. The corpus allows that work to begin with a common language and preserves its results beyond any one person's memory.

18. Glossary and unit equivalence

Notation must retain its meaning across the book, simulator and laboratory data. Spanish and English terms are paired here so translation does not change the quantity. Concentrations require both a unit and a chemical basis.

Water and load

COD / DQO. Chemical oxygen demand, commonly mg O₂/L. It describes response under an analytical oxidation method. It is neither carbon mass nor direct identification of individual compounds.

BOD5 / DBO5. Biochemical oxygen demand measured under the method's five-day conditions. Its ratio to COD is an aggregate descriptor rather than an inventory of each compound's biodegradability.

TSS / SST. Total suspended solids. Sampling and prior separation determine what is quantified. A settled sample differs from a mixed-tank sample.

TOC / COT. Total organic carbon under the selected method. It differs from COD; discussing mineralisation requires the included phases and carbon forms to be known.

Total N. Concentration expressed as elemental nitrogen. It cannot be exchanged for ammonium-ion mass without conversion. Kjeldahl nitrogen is not automatically total N when oxidised species occur.

Total P. Concentration expressed as elemental phosphorus. Phosphate reported as ion mass retains a different basis and must be explicitly converted before comparison.

Load. Quantity per period or batch. For m³ and mg/L, $\text{kg} = V \cdot C / 1000$. Using m³/day gives kg/day. Concentration and load answer different questions.

Hydraulics and exposure

Qr. Recirculation flow through the circuit, normally m³/h. Measure it at the operating point rather than inferring it solely from a pump rating.

Qf. Net feed flow. At steady state without volume change or other flows it equals net effluent, not circulation.

Vb and Vd. Useful tank volume and daily treated volume. Both have volume dimensions but different meanings.

c. Dimensionless exposure ratio: $Q_r \cdot t / V_b$ for a closed batch and $\sum(q \cdot h) / V_d$ for the daily index. Declare the definition used.

Pass. Exposure of a portion to a unit, not necessarily one mean tank turnover. This book preferably reserves turnover for the hydraulic ratio.

RTD. Residence-time distribution. It describes distributed retention and helps investigate short-circuiting and slowly exchanging regions.

Model and measurement

theta. Effective ceiling of the branch being analysed. It remains constant for inverse calculation only while rules and conditions remain unchanged.

phi. Fraction removed per physical visit in a specified balance. An effective exponential coefficient must not receive the same value merely because notation looks similar.

Floor. Numerical lower bound in software, not a laboratory quantification limit or demonstrated residual concentration.

Calibration. Selecting parameters using data. **Independent validation.** Comparing with results not used to select them, under a defined question and domain.

Sensitivity. Output variation under changing inputs or parameters. It is not probabilistic unless an explicit probability model describes those changes.

Uncertainty. Limited knowledge of a quantity or prediction. It can involve sampling, analysis, parameters and model structure; decimal places do not automatically summarise it.

Energy and materials

Electrical P. Power in kW. Distinguish it from P for phosphorus through context and subscripts. Energy is integrated power, in kWh.

Electrical charge. I*t, in coulombs when time is seconds. One hour is 3600 seconds. This differs from pollutant load.

Specific energy. kWh/m3 or kWh/kg removed, stating pollutant and boundary. The denominators differ and concentration is needed for conversion.

Faradaic efficiency. Charge associated with the reaction of interest relative to supplied charge under the stated definition. Electrode loss may include chemical corrosion and cannot automatically replace this ratio.

kLa. Volumetric transfer coefficient, normally h-1 or s-1. Convert units before comparison. It is neither air flow nor oxygen concentration.

OTR and OUR. Oxygen transfer and oxygen uptake rates. Dissolved-oxygen increase follows their balance together with other inputs and outputs.

Common conversions

From	To	Operation
L/min	m3/h	multiply by 0.06
mg/L	kg/m3	divide by 1000
m3/h maintained for 24 h	m3/day	multiply by 24
mg NH4+/L	mg N/L	divide by 1.2878 in this core
kPa	Pa	multiply by 1000
kW times hours	kWh	multiply

Hourly-flow conversion to daily volume applies only to the stated operating period. A plant operating for twenty hours uses twenty in its volume calculation. An interface multiplying by 24 must be checked against the original data definition.

19. Bibliography and consultation scope

Twenty selected scientific and technical sources, not a worldwide systematic review. Coverage distinguishes selected sections, abstracts and institutional descriptions. Bibliographic identity does not validate T1 parameters.

R01 Modelling of vortex based hydrodynamic cavitation reactors

2019. [10.1016/j.cej.2018.08.025](https://doi.org/10.1016/j.cej.2018.08.025). Metadata, abstract or extracts.

R02 Scale-up of vortex based hydrodynamic cavitation devices: A case of degradation of di-chloro aniline in water

2021. [10.1016/j.ultsonch.2020.105295](https://doi.org/10.1016/j.ultsonch.2020.105295). Sections of full text.

R03 Performance evaluation of a novel pilot-scale pinned disc rotating generator of hydrodynamic cavitation

2021. [10.1016/j.ultsonch.2020.105431](https://doi.org/10.1016/j.ultsonch.2020.105431). Sections of full text.

R04 Treatment of Solvent-Contaminated Water using Vortex-Based Cavitation: Influence of Operating Pressure Drop, Temperature, Aeration, and Reactor Scale

2018. [10.1021/acs.iecr.8b01688](https://doi.org/10.1021/acs.iecr.8b01688). Metadata, abstract or extracts.

R05 Electrocoagulation and Hydrodynamic Cavitation, a Hybrid Process for Efficient COD Removal From Rice Mill Effluent

2026. [10.1002/wer.70555](https://doi.org/10.1002/wer.70555). Metadata, abstract or extracts.

R06 Intensification of industrial wastewater treatment using hydrodynamic cavitation combined with advanced oxidation at operating capacity of 70 L

2019. [10.1016/j.ultsonch.2018.12.016](https://doi.org/10.1016/j.ultsonch.2018.12.016). Metadata, abstract or extracts.

R07 Design and experimental evaluation of a Venturi and Venturi-Vortex microbubble aeration system

2022. [10.1016/j.heliyon.2022.e10824](https://doi.org/10.1016/j.heliyon.2022.e10824). Metadata, abstract or extracts.

R08 Application of jetventurimixer for developing low-energy-demand and highly efficient aeration process of wastewater treatment

2022. [10.1016/j.heliyon.2022.e11096](https://doi.org/10.1016/j.heliyon.2022.e11096). Sections of full text.

R09 Uncovering the key determinants of electrode passivation and faradaic efficiency in electrocoagulation: Depassivation and sustainable performance via polarity reversal

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A DOI year may differ from the volume year. Hernández Lehmann authored the UPM thesis; Aurelio Hernández Muñoz supervised it. The 2006 report has a 2007 institutional review. Chapters connect claims to the relevant process and conditions; citation does not turn a study into a T1 equipment test.