Supplementary Material

Supplementary Material S1: Structured Search, Evidence Classification, and Interpretation Framework

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S1. Structured Search Concepts

Structured searches were conducted in Scopus, Web of Science Core Collection, and PubMed. Google Scholar was used as a complementary source for literature discovery and citation tracing. The search initially focused on publications from 2000 to 2025 and was subsequently updated during manuscript preparation to include relevant publications available through 2026. Seminal studies published before 2000 were retained when they provided foundational evidence directly relevant to nutrient-solution formulation, salinity management, or recirculating soilless systems. Search concepts were combined iteratively because the review was designed as a structured critical synthesis rather than an exhaustive systematic review.

Table S1. Structured search concepts used to organize the literature search.

Evidence domain	Core search concepts
Crop and production system	tomato; *Solanum lycopersicum*; greenhouse; soilless culture; substrate culture; coir; coconut coir; rockwool
Drainage recovery and recirculation	drainage; drain water; nutrient solution; recirculation; recycling; reuse; closed-loop fertigation; closed system; semi-closed system
Nutrient and salinity management	electrical conductivity; pH; sodium; chloride; ion accumulation; nutrient balance; uptake concentration; nutrient replenishment
Sanitation and pathogen risk	disinfection; UV-C; ultraviolet; ozone; hydrogen peroxide; heat treatment; slow sand filtration; *Pythium*; *Phytophthora*; *Fusarium*; ToBRFV
Digital monitoring	sensor; ion-selective electrode; Internet of Things; IoT; automation; decision-support system; predictive model; smart fertigation
Sustainability	water-use efficiency; nutrient-use efficiency; nutrient discharge; circular economy; environmental impact; life-cycle assessment

S2. Evidence Classification Criteria

Table S2. Evidence-directness classification used in the review.

Class	Definition	Use in synthesis
Direct evidence	Tomato grown in solid soilless substrate with drainage recovery or recirculation.	Primary basis for crop-specific and operational conclusions.
Related evidence	Tomato grown in other recirculating hydroponic configurations.	Used when mechanisms or management principles were relevant but substrate context differed.
Transferable evidence	Other horticultural crops used to evaluate a directly relevant treatment or monitoring technology.	Used to characterize technological performance; not treated as equivalent to tomato-specific evidence.
Contextual evidence	Reviews, books, proceedings, or technical reports used to explain principles or identify primary studies.	Background and interpretive support; not treated as independent experimental evidence.

S3. Evidence-Extraction Fields

Table S3. Evidence-extraction fields used during manuscript preparation.

Domain	Fields considered
Bibliographic/context	Publication year; country when reported; experimental or commercial context; crop/cultivar.
Cultivation system	Substrate; system type; drainage fraction; recirculation approach; crop stage or duration.
Water/nutrients	Source-water quality; irrigation and drainage EC/pH; individual ions; nutrient formulation; water/fertilizer use.
Sanitation	Target organism; treatment technology; wavelength/dose or concentration; contact time; flow; turbidity; pathogen reduction.
Crop response	Yield; fruit quality; salinity response; physiological or sanitary effects.
Digital monitoring	Sensor type; measured variable; calibration/validation; data frequency; model or decision-support function.
Environmental/operational	Resource savings; nutrient discharge; energy or cost information; commercial validation.

S4. Evidence Quality and Directness Framework

Table S4. Framework used to assess evidence quality and directness during interpretation.

Domain	Interpretive question
Experimental design	Is the study design sufficiently clear to support the reported conclusion?
Comparator	Is an appropriate control or comparison available when needed?
Replication	Is experimental replication described and appropriate?
Duration	Is the exposure/crop duration adequate for the conclusion being drawn?
Water and nutrient characterization	Are source water, nutrient solution, EC/pH, and relevant ions adequately reported?
Recirculation description	Is the hydraulic/recirculation configuration sufficiently described?
Measurement reliability	Are sampling compartment, treatment dose, sensor calibration, or analytical methods adequately specified?
Statistics and reporting	Are statistical methods and outcome reporting adequate for interpretation?
Commercial relevance	Can the finding reasonably be transferred to commercial greenhouse tomato, particularly coir-based systems?
Evidence directness	Is the evidence direct, related, transferable, or contextual relative to coir-grown greenhouse tomato?

These domains were used to qualify evidence interpretation and directness rather than to generate a composite methodological quality score. Studies were not excluded solely on the basis of these domains.

S5. Interpretation Rule

Quantitative findings were compared only when units, denominators, treatment conditions, and measurement compartments were sufficiently compatible. Electrical conductivity, pH, and ion concentrations measured in the applied nutrient solution, drainage, reservoir, root-zone solution, or substrate extract were not treated as interchangeable. Where methodological heterogeneity prevented meaningful quantitative comparison, the direction, consistency, and operational relevance of findings were emphasized rather than pooled estimates or universal thresholds.

S6. Key-Evidence Matrix

Table S5. Expanded key-evidence matrix linking representative studies, quantitative findings, and evidence directness.

Review question	Study/source	Crop/system and coir relevance	Water/drainage/treatment context	Key quantitative evidence	Evidence type	Transferability / limitation
System configuration; coir nutrient balance	Xiong et al. [10]	Tomato cv. Lucius F1; coir vs rockwool; closed system	Source-water EC 0.12 dS m^{-1}; Na 0.6 mmol L^{-1}; 20–50% drainage; reservoir solution replaced every 2 months	Coir initial K 1560 mg kg^{-1}; root-zone K/Ca 2.3 vs 1.6 in rockwool; K uptake 41.2 g m^{-2}; yield 84.9 t ha^{-1}	Direct	Direct coir–tomato comparison; periodic reservoir replacement means not permanent zero-discharge
Coir fertigation and crop response	Liu et al. [31]	Greenhouse tomato in coir; no drainage recirculation	Nutrient-solution application-rate treatments	70% application maintained yield close to the highest-input treatment while improving water/fertilizer-use efficiency and fruit-quality indicators	Related	Coir-specific fertigation evidence; no drainage recirculation
Coir substrate chemistry	Abad et al. [9]	Thirteen coir-dust sources; no tomato crop	Physicochemical characterization; no recirculation treatment	CEC 31.7–95.4 cmol(c) kg^{-1}; salinity 39–597 mS m^{-1}; available K 2.97–52.66 mol m^{-3}; high Na and Cl reported	Related	Direct coir-substrate evidence; not crop or recirculation performance
Coir ageing	Song et al. [11]	Greenhouse tomato; coir bag culture over three years	Repeated substrate use; no quantified closed-loop recirculation	Porosity 65.4–73.1%; EC 22.2–53.5 dS m^{-1} by the study extract method; CEC 71.0–191.7 cmol kg^{-1}; pore structure changed with use	Related	Direct coir-ageing evidence; extract values are not direct root-zone-solution concentrations
Nutrient uptake and discharge strategy	Signore et al. [15]	Cherry tomato; closed NFT	Replacement set-points 5, 7.5, 10 dS m^{-1}; uptake-concentration replenishment	Discharged water 842/420/181 m^3 ha^{-1}; Na 568/516/297 kg ha^{-1}; Cl 1146/821/614 kg ha^{-1}	Related	Strong tomato-recirculation evidence; substrate-free system
Tomato uptake benchmarks	Voogt [50]	Year-round greenhouse tomato; foundation-related evidence	Whole-cycle nutrient uptake concentration	N 9.6, P 1.1, S 1.2, K 6.1, Ca 2.2, Mg 0.9 mmol L^{-1}	Related	Foundational benchmark; varies with stage, climate, cultivar, and system
Sodium accumulation and predictive management	Varlagas et al. [45]	Tomato; closed-cycle hydroponics	Predictive Na/Cl uptake model across irrigation-water salinity	For cv. Formula, root-zone Na target <19 mmol L^{-1} implied irrigation-water Na ≤0.53 mmol L^{-1} under tested conditions	Related	Cultivar- and system-specific; not a universal coir threshold

Review question	Study/source	Crop/system and coir relevance	Water/drainage/treatment context	Key quantitative evidence	Evidence type	Transferability / limitation
Adaptive sodium management	Giannothanasis et al. [16]	Tomato; mineral wool; closed loop	Raw-water Na about 4 mmol L^{-1}; adaptive nutrient reduction	Drainage Na reached about 21 mmol L^{-1} without yield loss; nitrate losses reduced 25.5%	Related	Mechanistically relevant; mineral-wool substrate differs from coir
UV disinfection	Runia [44]	Recirculating nutrient solution; plant pathogens	UV after sand filtration; benchmark doses for fungal vs viral targets	Runia recommended UV doses of about 100 mJ cm^{-2} for pathogenic fungi and 250 mJ cm^{-2} for complete disinfection including viruses	Transferable	Transferable UV-design evidence; reported doses are technology- and matrix-dependent and are not direct ToBRFV validation
ToBRFV sanitation	Zhou et al. [22]	Tomato greenhouse hydroponics; ToBRFV	Cold-plasma ozone; inoculum- and exposure-dependent	At 1:1000 inoculum, 48 min suppressed infectivity; at 1:10,000, 24 min achieved complete inactivation under tested conditions	Related	Tomato/hydroponic evidence; direct validation in recirculating coir drainage remains needed
Ozone/H_2O_2 treatment	Langlais et al. [35]	Greenhouse soilless effluent; coir not specified	O_3 ~10 g m^{-3}; H_2O_2/O_3 0.15 g g^{-1}; ~1–2 s	Atrazine ~90%; Clavibacter 3.5–4 log; Pythium 1–1.5 log; Fusarium 2–4 log; Fe/Mn decreases reported	Transferable	Technology evidence; conditions are not universal coir-tomato recommendations
Fe-chelate stability under UV	Acher et al. [58]; Arcas et al. [46]	Nutrient-solution / hydroponic chemistry; transferable	254 nm UV in Acher et al.; UV-chelate stability assessment in Arcas et al.	Fe-chelate response depended on chelator and UV exposure; repeated treatment can alter Fe availability	Transferable	Supports post-UV Fe verification; direct commercial coir-drainage validation remains limited
Substrate-associated pathogen risk	McGehee & Raudales [57]	Coir and rockwool; non-tomato crop	Substrate-associated isolates; not liquid recirculation	Pathogenic Pythium/Globisporangium and Fusarium isolates recovered from used coir/rockwool	Transferable	Supports non-liquid sanitary reservoirs; does not demonstrate ToBRFV adsorption to coir
Circularity and environmental performance	Elvanidi et al. [78]; Rufí-Salís et al. [79]	Greenhouse hydroponic/cascade systems; transferable	Recovered drainage and nutrient-recovery scenarios	Reported reductions in freshwater/nutrient disposal and environmental impacts under evaluated scenarios	Transferable	Supports circularity rationale; local technical–economic validation remains necessary

Interpretation note: Evidence type indicates directness to coir-grown greenhouse tomato drainage recirculation, not an absolute methodological quality score. Numerical values should be interpreted within the measurement compartment, crop, water matrix, treatment, and system conditions reported by the original study.