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Review

Reclaimed Water and Biochar in Southern Highbush Blueberry Production: A Review of Root-Zone Chemistry, Growth, and Solute Dynamics

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Abstract

Sustainable southern highbush blueberry production in Florida is increasingly constrained by freshwater competition, variable rainfall, and the chemical vulnerability of coarse-textured and organic-based production media. Reclaimed water irrigation and biochar amendment are promising strategies for improving water use efficiency and root zone function, but their combined implications for blueberry systems remain insufficiently understood. This review synthesizes the current knowledge on blueberry production requirements, the regulatory and operational context of reclaimed water use, and the physical and chemical roles of biochar in sandy and pine bark-based substrates relevant to horticulture in Florida. Particular emphasis is placed on mechanistic links among reclaimed water chemistry, substrate properties, and root zone processes that govern salinity, pH drift, nutrient retention, and solute leaching. The literature indicates that reclaimed water can improve irrigation reliability and provide supplemental nutrients, but may also introduce sodium, chloride, boron, and other constituents, as well as alkalinity, which alter substrate chemistry and increase the risk of salinity stress and nutrient imbalance. Biochar may enhance water retention, cation exchange, and sorption capacity, but its effects are strongly dependent on feedstock, production conditions, aging, application rate, and substrate context. Overall, successfully integrating reclaimed water and biochar into blueberry systems requires substrate-specific and constituent-resolved evaluation under production conditions relevant in Florida.

Keywords: reclaimed water; biochar; southern highbush blueberry; pine bark substrate; root-zone chemistry; salinity; nutrient leaching; sustainable irrigation

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Academic Editor: William Frederick Ritter

Received: 31 March 2026
Revised: 29 April 2026
Accepted: 7 May 2026
Published: 11 May 2026

1. Introduction

The sustainability of horticultural production systems in Florida is increasingly challenged by intensifying competition for freshwater resources, variable rainfall patterns, and the vulnerability of coarse-textured soils and soilless substrates to nutrient loss and salinity accumulation. These constraints are particularly important for high-value crops such as the southern highbush blueberry, which is highly sensitive to root zone chemical imbalances, elevated salinity, and suboptimal substrate conditions. As pressure on conventional water supplies increases, management strategies that maintain crop productivity while reducing environmental impacts have become increasingly important.

Two approaches receiving growing attention are the agricultural reuse of reclaimed water (RW) and the use of biochar as a soil or substrate amendment. Reclaimed water can reduce dependence on freshwater resources and may provide supplemental nutrients; however, it may also introduce salts and other constituents that alter substrate chemistry, nutrient availability, and plant performance [1,2]. Biochar has been widely studied for its ability to modify physical and chemical properties, enhance sorption capacity, and influence nutrient retention and water dynamics; however, its effects are highly context-dependent and vary with feedstock source, pyrolysis conditions, aging, application rate, and the characteristics of the receiving substrate environment [3,4].

Southern highbush blueberry provides a particularly relevant system for evaluating these issues because of its shallow root system, preference for acidic media, and sensitivity to salinity and poor drainage. In Florida production systems, where pine bark-based substrates and alternative irrigation sources are especially relevant, the combined use of reclaimed water and biochar provides a useful case for examining broader interactions among water quality, substrate buffering, crop sensitivity, and leaching risk in acid-sensitive horticultural systems.

This review addresses these challenges by moving beyond a descriptive summary of reclaimed water and biochar use in blueberry production to a comparative and mechanism-oriented synthesis. Although Florida pine bark-based systems are used as a primary case context because of their strong relevance to southern highbush blueberry production, this review also considers broader implications for acid-sensitive horticultural systems grown in low-buffering soils or organic-based substrates. Specifically, this review evaluates how reclaimed water chemistry, substrate properties, and biochar characteristics interact to influence root zone pH, salinity, ion accumulation, nutrient availability, plant stress responses, and solute leaching. It also examines where current evidence is consistent, where findings conflict, and which uncertainties remain unresolved, particularly with respect to long-term performance, biochar aging, and multi-season salt accumulation. By integrating the literature from both water-management and root zone process perspectives, this review aims to identify decision-relevant mechanisms, practical trade-offs, and priority research needs for more resilient blueberry production systems.

2. Conceptual Framework for Reclaimed Water–Blueberry Systems

This review is organized around two complementary analytical frameworks that link water-resource sustainability with mechanistic root zone processes. Integrated Water Resource Management (IWRM) is used to interpret reclaimed water adoption at the system level, including resource efficiency, water substitution, operational feasibility, and environmental trade-offs. The Soil–Plant–Environment framework is used to interpret how irrigation water quality and substrate amendments jointly regulate root zone chemistry, nutrient cycling, plant stress responses, and solute movement. Used together, these frameworks allow the literature to be evaluated not only in terms of whether reclaimed water or biochar is beneficial, but also in terms of why outcomes differ across studies, which processes are dominant under specific conditions, and how these interactions translate into management implications for blueberry production and related acid-sensitive horticultural systems.

2.1. Integrated Water Resource Management (IWRM)

Integrated Water Resource Management emphasizes the coordinated management of water and land resources to achieve economic and social benefits while maintaining environmental integrity. In Florida, increasing urban demand and climatic variability intensify pressure on freshwater supplies, motivating interest in alternative irrigation sources such as reclaimed water [5]. Reclaimed water supports circular water use and can offset freshwater withdrawals; however, its suitability for horticultural production depends on the magnitude and variability of salinity, ionic composition, nutrient loading, and potential biological constituents [1,2]. When coupled with substrate amendments such as biochar, reclaimed water irrigation may better align with IWRM objectives by improving water retention and sorption capacity, thereby moderating water-quality-driven risks such as salt accumulation and nutrient leaching [3,4].

From an IWRM perspective, the use of reclaimed water in specialty crop production should be evaluated not only for its water supply benefits but also for its agronomic and environmental impacts over time. In blueberry systems, this is particularly important because reclaimed water may alter root zone conditions through sodium loading, chloride accumulation, alkalinity effects, and changes in nutrient balance. These potential trade-offs highlight the need for management strategies that improve substrate buffering capacity and reduce off-site nutrient and solute losses.

2.2. Soil–Plant–Environment Interactions

The Soil–Plant–Environment framework emphasizes how substrate physical and chemical properties interact with plant physiological responses under prevailing environmental conditions to determine crop performance. In coarse-textured media typical of Florida horticulture, biochar has been reported to influence water retention and aeration-related properties, although the direction and magnitude of these effects depend strongly on feedstock, pyrolysis conditions, particle size, and application rate [6,7]. Biochar can also modify nutrient availability by altering pH, cation exchange capacity, and sorption behavior, thereby influencing nutrient acquisition and plant stress responses [8,9].

Under lower-quality irrigation water, these substrate-mediated effects may be especially important. By increasing sorption capacity and altering ionic interactions, biochar may reduce the mobility of certain ions and moderate salinity-related nutrient imbalances, although the outcomes remain highly context-dependent and vary with both water chemistry and substrate composition [10,11]. In this framework, crop performance is not determined by irrigation water quality or substrate amendment alone, but by the combined interaction of water composition, substrate buffering capacity, plant sensitivity, and environmental conditions.

2.3. Remaining Challenges

Despite these potential benefits, adoption of reclaimed water and biochar in Florida horticultural systems remains constrained by uncertainty in performance and implementation. Biochar varies widely in ash content, surface functional groups, and liming potential, which can generate inconsistent outcomes across crops and substrates and may complicate pH management in acidophilic systems such as blueberry. Reclaimed water quality also varies spatially and temporally, and its ionic composition, including Na^+, Cl^-, and alkalinity, can increase the risk of salt accumulation and nutrient imbalance in low-buffering, highly leachable substrates. In addition, economic considerations, infrastructure requirements, and regulatory constraints may limit reclaimed water delivery and on-farm integration at a commercial scale [4,5].

Continued research is therefore needed to establish water quality- and substrate-specific best management practices and to quantify longer-term effects on substrate chemistry, leaching losses, and blueberry performance under Florida-relevant production conditions. In addition, the limited availability of long-term and multi-season datasets restricts confidence in predicting cumulative salt loading, biochar aging effects, and persistent changes in nutrient cycling under commercial production conditions.

3. Southern Highbush Blueberry Production Constraints Relevant to Water Quality

Southern highbush blueberry (SHB) cultivars are low-chill Vaccinium corymbosum hybrids adapted to Florida's subtropical production region and are typically harvested earlier than northern highbush cultivars, enabling access to premium early-season markets. Optimal growth occurs under acidic conditions, commonly pH 4.5–5.5, with high organic matter and well-drained moisture-retentive substrates. However, Florida's sandy soils and many production media are characterized by low buffering capacity and limited nutrient- and water-holding capacity, increasing susceptibility to drought stress, nutrient leaching, and variable plant performance. Southern highbush blueberry is also sensitive to salinity and ion-specific effects, particularly those associated with elevated electrical conductivity and increased Na^+ and Cl^-, which can disrupt water uptake and nutrient balance. These risks may be amplified when alternative irrigation sources are used and when salts accumulate over time in low-buffering substrates. Accordingly, management practices that stabilize substrate moisture, maintain acidity, and limit salt accumulation are critical for sustained productivity in Florida blueberry systems.

Florida's blueberry industry has expanded rapidly over the past two decades, driven by the development of low-chill southern highbush blueberry cultivars and Florida's subtropical climate, which enables early-season production and favorable market timing [12,13]. Efficient irrigation is essential because SHB has a shallow, fibrous root system and requires consistent moisture during flowering and fruit development. Drip irrigation is widely adopted to improve application efficiency and support fertigation, while reducing non-target water losses and the risk of nutrient leaching below the effective root zone compared with less targeted irrigation methods [14]. Florida's warm and humid climate also heightens pest and disease pressure, underscoring the importance of integrated pest management strategies that incorporate monitoring, cultural practices, biological controls, and judicious pesticide use [13,15].

Breeding efforts at UF/IFAS have produced southern highbush blueberry cultivars with improved yield potential, fruit quality, and adaptation to Florida production conditions, including cultivars such as 'Arcadia', 'Kestrel', 'Emerald', and 'Farthing' [12,16]. While 'Arcadia' and 'Kestrel' exhibit strong self-compatibility, cross-pollination can still increase fruit mass and total yield in many SHB systems [17,18]. In addition to yield, cultivar selection is guided by market-relevant quality traits, including firmness, soluble solids, and phytochemical composition, which influence both consumer acceptance and postharvest performance [19,20]. To improve drainage and root health in coarse-textured environments, many Florida producers rely on amended-bed or soilless production systems that incorporate pine bark-based substrates. Although these systems can improve aeration, they often have a low buffering capacity and may be prone to nutrient leaching and salt accumulation depending on irrigation water quality and management [14].

From an economic perspective, blueberry production is an important and growing specialty crop sector within Florida agriculture. Recent UF/IFAS reporting based on USDA statistics indicates that Florida produced approximately 22.3 million pounds of blueberries in the 2023 season, with an associated value of about USD 75 million, grown on roughly 5700 acres [21]. At a broader scale, UF/IFAS economic impact analyses show that Florida's agriculture and food system supports substantial statewide sales revenue and employment when multiplier effects are included, underscoring the importance of improving production resilience under increasing land use pressure and competition for freshwater resources [22]. Despite continued expansion, the industry faces persistent constraints, including price volatility, market saturation risk, labor availability, competition, salinity stress, and climate variability [13,23]. In this context, strategic investment in resilient production practices, including careful evaluation of reclaimed water and biochar as integrated water–substrate management tools, may be critical for maintaining productivity while protecting environmental quality.

3.1. Root Structure and Irrigation Needs

Southern highbush blueberry cultivars are interspecific hybrids developed for warm-climate production regions, combining the fruit quality traits of northern highbush blueberry (Vaccinium corymbosum) with low-chill adaptation, in part derived from southern species such as Vaccinium darrowii [24]. SHB is widely grown in Florida, where mild winters and coarse-textured soils and production media create distinct constraints for water and nutrient management. Its root system is typically shallow and fibrous, increasing sensitivity to short-term fluctuations in root zone moisture and heightening the importance of precise irrigation scheduling to minimize stress and sustain nutrient uptake [25]. Because effective rooting depth is limited, frequent irrigation and careful selection of soil or substrate conditions are critical for maintaining stable root zone water status.

Irrigation requirements vary seasonally and are influenced by cultivar, weather conditions, and the hydraulic properties of the soil or substrate. Reported crop coefficient (Kc) values range from 0.59 to 1.10, with an annual mean of approximately 0.84, reflecting changes in canopy development and water demand across phenological stages [26]. In Florida production systems, both micro-sprinkler and drip irrigation are used, with peak water demand commonly occurring during fruit development and harvest in spring and, under warm conditions and active canopy growth, extending into early summer [27]. Mulching and organic amendments, including peat-based materials, can improve moisture retention and plant performance, particularly under high-frequency irrigation regimes [25]. Pine bark-based beds, which are frequently used to improve aeration and drainage, may require more frequent irrigation because of rapid drainage and limited buffering capacity, although water-holding behavior varies with bark particle size, compaction, and substrate blends [27].

Collectively, these characteristics make SHB systems highly responsive to irrigation management and particularly vulnerable to both solute leaching and salt accumulation when irrigation water chemistry differs, including under reclaimed water use. This sensitivity underscores the importance of evaluating irrigation not only in terms of water supply but also in terms of its effects on root zone chemical stability and nutrient dynamics.

3.2. Soil pH and Salinity Tolerance

The southern highbush blueberry exhibits a narrow tolerance range for root zone pH and salinity, both of which strongly influence nutrient availability, root function, yield, and fruit quality. Blueberries generally perform best under acidic conditions, with an optimal pH range of approximately 4.2 to 5.5, in part because acidic conditions enhance the solubility of micronutrients, particularly Fe, Mn, and Zn, and are consistent with the physiological traits of blueberry roots and the preferred nitrogen form [28,29]. Elevated pH can reduce micronutrient availability and has been associated with delayed flowering, reduced ripening, and poorer fruit quality. Cultivar differences in pH response have also been reported; for example, ‘Chaoyue No. 1’ showed greater tolerance to higher pH than ‘Climax’, indicating genetic variability that may be relevant for cultivar selection under marginal conditions [30]. In soilless or amended substrates, liming agents such as calcium carbonate may be used cautiously to reduce excessive pH fluctuations; however, maintaining the acidic range required for blueberry root function remains a primary management objective [31].

In addition to pH sensitivity, SHB is susceptible to salinity stress, which can restrict water uptake and disrupt physiological and biochemical processes essential for growth and productivity. Salinity exposure has been associated with altered metabolism and reduced performance, including effects on stress-response pathways [32,33]. Cultivar variation in salt tolerance has also been documented. For example, 'Duke' demonstrated greater tolerance than 'Sweetheart', which was associated with lower Na accumulation in leaves and higher expression of the Na^{+} transport-related gene VcHKT1;1 [34]. These findings underscore the importance of ion exclusion and stress-response traits in breeding and cultivar selection for saline environments [32]. Additional mitigation strategies, including beneficial symbioses and rhizosphere-based approaches, may improve nutrient uptake and stress resilience under salinity, although their effectiveness remains context dependent [35,36]. Rootstock strategies involving sparkleberry (Vaccinium arboreum) germplasm may also improve adaptation to suboptimal soils, including elevated pH and salinity [28].

Together, these characteristics confirm that SHB is particularly sensitive to root zone chemical perturbations. This sensitivity is central to evaluating reclaimed water irrigation and biochar amendment, because both practices can alter pH behavior, salinity dynamics, and ion availability in ways that may either mitigate or intensify production constraints depending on substrate conditions and management.

3.3. Florida Blueberry Substrates and Implications for Reclaimed Water Chemistry

Florida blueberry production commonly relies on pine bark-based substrates, often blended with sand, in amended raised beds or containerized systems to maintain aeration, drainage, and acidic conditions favorable for southern highbush blueberry. These organic-dominant media differ fundamentally from mineral soils in hydraulic behavior, buffering capacity, and solute-retention mechanisms, with direct implications for how reclaimed water alters root zone chemistry. In pine bark–sand systems, rapid percolation and short residence times can accelerate the transfer of irrigation-water chemistry into the root zone solution and leachate, particularly under the frequent irrigation regimes typical of blueberry production. In addition, pine bark substrates can release substantial dissolved organic carbon (DOC) and exhibit appreciable cation exchange behavior associated with oxygen-containing functional groups. As a result, early leaching patterns may reflect both external loading from reclaimed water and internal mobilization of labile substrate pools.

Evaluating reclaimed water in Florida blueberry systems, therefore, requires a substrate-aware perspective, because pine bark–sand media respond differently to mineral soils. Owing to comparatively limited carbonate buffering, the repeated application of alkaline or bicarbonate-rich irrigation water can induce faster pH drift than would be expected in many field soils, with downstream consequences for nutrient availability in calcifuge crops such as blueberry [37,38]. These risks may be compounded by confined root zone volumes and limited dilution capacity in raised-bed or containerized production, which can accelerate salinity accumulation when irrigation water contains elevated Na and Cl and when leaching fractions are insufficient to export salts [39,40]. Consequently, management thresholds for pH and salinity may be reached more rapidly in pine bark–sand systems, and findings from mineral-soil irrigation studies may not translate directly without accounting for rapid transport and limited buffering in the substrate environment [41,42].

4. Reclaimed Water Use in Agriculture and Blueberry Production

4.1. Reclaimed Water Use in Agriculture and Horticulture

Reclaimed water has been used in Florida agriculture and horticulture for more than five decades as a strategy to conserve freshwater resources while improving wastewater management efficiency. Florida has become a national leader in water reuse, and the Florida Department of Environmental Protection (FDEP) reports that approximately 958 million gallons per day of reclaimed water were beneficially reused in 2024, illustrating the scale of nonpotable reuse statewide [43]. Reclaimed water use is governed by an established regulatory framework, with reuse and land application requirements maintained in Chapter 62-610, Florida Administrative Code, and implemented through FDEP's comprehensive reuse program [44,45].

For edible crops, Florida regulations distinguish between processed and nonprocessed commodities. In general, direct-contact irrigation with reclaimed water is permitted for edible crops that will be peeled, skinned, cooked, or thermally processed before consumption, whereas crops consumed raw are allowed only under indirect application methods that preclude direct contact, such as drip or subsurface irrigation; direct-contact methods, including spray or overhead irrigation, are prohibited [46]. This distinction is particularly relevant for berry systems because blueberries are typically consumed without peeling or thermal processing. As a result, adoption of reclaimed water in blueberry production requires irrigation designs and operational practices that prevent contact between reclaimed water and fruit or foliage, and this requirement may constrain uses such as overhead frost protection where direct contact could occur.

Documented benefits of reclaimed water include improved water supply reliability during drought, supplemental nutrient inputs in some cropping systems, and reduced irrigation costs in regions where reuse infrastructure is already available [47–50]. However, important management challenges remain. Elevated salinity and sodicity in some reclaimed water sources can increase the risk of nutrient imbalance and crop salinity stress if water quality is not carefully monitored and managed [51]. In addition, statewide planning priorities and sectoral competition can influence the availability of reclaimed water for agriculture as urban and public access uses continue to expand [43]. Overall, reclaimed water represents a promising resource for more sustainable irrigation in Florida, but its long-term viability depends on continued monitoring and adaptive management tailored to crop sensitivity and site-specific soil, substrate, and water quality conditions.

4.2. Public Perception and Social Adoption

Public perception and social acceptance remain important determinants of reclaimed water adoption in Florida agriculture, even when the technical feasibility and water-supply benefits of reuse are well established. Although reclaimed water has a long history of use in the state, broader adoption depends on trust in treatment performance, confidence in monitoring and enforcement, and a clear understanding of how reclaimed water is applied in ways that protect human health and environmental quality [49]. Florida's regulatory framework reflects these concerns by restricting irrigation practices for nonprocessed crops and requiring application methods that preclude direct contact between reclaimed water and edible portions [46].

Expansion of reclaimed water reuse has been driven in part by recurring droughts and the growing value of reliable nonpotable supplies, particularly in regions with existing reuse infrastructure [47]. Early resistance among some growers, often linked to concerns about pathogens, trace constituents, and the reliability or consistency of reclaimed supplies, has generally declined as long-running reuse programs have demonstrated stable operation and as regulatory oversight and routine monitoring have become more established [47]. Nevertheless, consumer skepticism can still constrain broader social acceptance, particularly when the public is unfamiliar with reclaimed water treatment processes and the standards governing agricultural use [52].

Public attitudes toward recycled water also vary with perceived risk from the source. In some contexts, gray water is viewed more favorably than reclaimed water derived from municipal wastewater streams, reflecting differences in perceived contamination pathways and trust in treatment [53]. Using Q-methodology, studies have identified stakeholder discourses that frame reclaimed water primarily as (i) a guarantee of water supply, (ii) a sustainability solution, or (iii) a potential environmental risk. Although these findings are context-specific, the underlying narratives parallel themes commonly raised in water reuse debates and may be informative for stakeholder engagement in Florida [52]. Even where grower perceptions become more favorable after adoption, economic barriers, especially those related to treatment level, distribution infrastructure, and on-farm system compatibility, can remain significant constraints and may require cost-sharing mechanisms or public investment to support broader implementation [54]. Across stakeholder groups, government agencies are commonly viewed as central actors in the adoption of reclaimed water through regulation, infrastructure planning, and public education [52].

Advanced treatment technologies can substantially reduce pathogens and many chemical contaminant risks when paired with appropriate irrigation methods and site-specific management; however, caution is still warranted in settings where monitoring and oversight are limited, such as residential or home gardening contexts [2,55]. Overall, expanded reclaimed water use in Florida agriculture will depend not only on regulatory compliance and agronomic performance, but also on sustained efforts to build public trust through transparent communication, stakeholder engagement, and long-term outreach [49,52].

4.3. Reclaimed Water Constituents of Concern and Mechanistic Links to Root Zone Processes

Reclaimed water quality is often summarized using electrical conductivity (EC) as an integrated indicator of salinity; however, the agronomic significance of EC depends on which ions dominate and how they interact with root zone exchange processes and plant uptake. In salt-sensitive, calcifuge crops such as southern highbush blueberry, sodium, chloride, alkalinity (often expressed as bicarbonate, HCO_3^-), and boron are key constituents of concern because they can impose osmotic stress, drive specific-ion toxicities, and indirectly alter nutrient availability through pH shifts and competitive uptake effects [56,57]. Evidence from reclaimed water irrigation studies indicates that sustained inputs of these constituents can increase root zone salinity over time, with outcomes governed by site conditions and the balance between irrigation loading and leaching or export [58,59]. Accordingly, interpreting the impacts of reclaimed water in blueberry systems requires linking ion-specific contributions to EC with mechanistic pathways in the root zone, rather than treating EC alone as a universal predictor of crop response.

4.3.1. Sodium-Driven Cation Exchange Displacement

Elevated Na+ can influence nutrient dynamics through cation exchange displacement. Sodium can compete for exchange sites and displace nutrient cations such as K^+, Ca^{2+}, and Mg^{2+}, thereby increasing their mobility and potential leaching, even when changes in bulk salinity, as reflected by EC, appear modest [60,61]. Although Ca^{2+} and K^+ are often preferentially retained on exchange complexes relative to Na^+, sustained Na^+ loading and elevated Na^+ activity in the root zone solution can shift exchange equilibria and redistribute cations: effects that may be amplified in systems characterized by rapid solution turnover [62,63]. These processes are especially relevant in pine bark-dominant media, where oxygen-containing functional groups contribute appreciable exchange capacity and the exchange complex may respond rapidly to repeated ionic inputs [64].

https://doi.org/10.3390/w18101141

4.3.2. Chloride as a Generally Conservative Tracer

Chloride is widely used as a generally conservative tracer because it is typically weakly retained relative to many cations, making it a practical indicator of salinity loading and transport through the root zone. In column and leaching studies, Cl^- is therefore useful for evaluating breakthrough behavior, cumulative export, and the degree to which irrigation water salinity is transmitted through soils or soilless substrates [65]. However, Cl^- is not universally conservative. Net retention or release can occur depending on ecosystem conditions and internal cycling, indicating that biological and site-specific factors may influence chloride behavior [66–68]. Accordingly, Cl^- should be interpreted as a generally conservative tracer, the behavior of which must still be evaluated within the specific production system and substrate context.

4.3.3. Alkalinity Effects on pH Drift and Micronutrient Availability

Irrigation water alkalinity can increase pH drift in pine bark-based substrates, particularly when carbonate buffering is limited, leading to a progressive increase in substrate pH over time. For blueberries, which perform best under acidic conditions, this shift can reduce the availability of key micronutrients, particularly Fe, Mn, and Zn, thereby increasing the likelihood of nutrient limitation even when osmotic salinity stress is not severe [69,70]. Because this pathway is mediated primarily through acid–base chemistry and micronutrient solubility, alkalinity-driven pH effects are mechanistically distinct from salinity effects captured by EC. Where alkalinity is elevated, acidification approaches that neutralize bicarbonate or carbonate alkalinity have been reported to mitigate pH rise and help maintain micronutrient availability in container or soilless media systems [71,72].

4.3.4. When EC Is Informative Versus Potentially Misleading

Electrical conductivity is a rapid screening tool for total dissolved salts and is useful for tracking water-quality trends, but it cannot determine whether salinity is dominated by Na–Cl versus Ca-, Mg-, or sulfate-associated salts, which have different implications for cation exchange, nutrient balance, and plant response [73,74]. Moreover, the relationship between EC and individual ion concentrations is not fixed because it depends on ionic composition and temperature; therefore, EC should not be treated as a substitute for ion-specific analysis [75,76]. Accordingly, EC is most informative when interpreted alongside measurements of key ions, particularly Na and Cl in salt-sensitive blueberry systems, and in conjunction with alkalinity and Ca supply, which can modulate exchange behavior and influence pH stability in the root zone [74,77].

5. Biochar as a Root Zone Amendment in Blueberry Systems

5.1. Physical and Chemical Properties

Biochar is a carbon-rich material produced by pyrolysis of biomass under limited oxygen and is increasingly being evaluated as a multifunctional amendment to improve soil function, crop performance, and environmental resilience. Its pore structure, particle morphology, and surface chemistry can influence soil water retention and solute transport, with reported benefits including increased water-holding capacity, improved nutrient retention, and reduced leaching losses under conditions where coarse texture and low organic matter limit retention processes [78,79]. Across cropping systems, positive agronomic responses have been attributed to changes in soil physical conditions and nutrient use efficiency, including improved soybean productivity and structural improvements that support root zone functioning [80]. Positive effects of spent-grain-derived biochar on hop growth and cone production have also been reported under horticultural conditions, supporting the broader view that biochar may improve plant performance in some systems, although outcomes remain crop- and context-dependent [81]. Enhanced plant growth has also been reported in contaminated soils where sorption and immobilization processes may reduce contaminant bioavailability [82].

Biochar's effects on physical properties are frequently reported as increases in porosity and decreases in bulk density, although the magnitude and direction of these changes depend on feedstock, pyrolysis temperature, particle size distribution, soil texture, and incorporation method [80,83]. Chemically, biochar can increase soil pH and reduce aluminum toxicity in acidic soils, reflecting its ash content, surface functional groups, and liming potential [80,83]. In addition to nutrient-related functions, biochar can also act as a sorbent for some organic pollutants, supporting applications in pollution control and soil remediation [79,83].

5.2. Effects on Soil Fertility and Biological Activity

From an environmental perspective, biochar may contribute to carbon sequestration and greenhouse gas mitigation because its carbon often includes relatively recalcitrant aromatic structures that can persist in soil over extended periods [83,84]. Biochar can also influence soil biological activity by altering habitat structure, including the formation of protected microsites, as well as moisture dynamics and nutrient availability. Reported effects range from enhanced microbial activity and diversity to neutral or variable outcomes depending on biochar properties and site conditions [85,86].

Agronomic responses to biochar are not uniformly positive. Outcomes depend strongly on feedstock type, pyrolysis conditions, particle size, aging, soil properties, climate, and management practices, leading to inconsistent performance across studies and production contexts. To improve predictability, the '3R' framework—right biochar source, right application rate, and right placement—has been proposed as a practical decision-making structure to align material properties and application methods with site needs [87]. Potential ecological risks should also be considered, including the introduction of contaminants and phytotoxic compounds in some materials, particularly under repeated or long-term application scenarios [86]. Consequently, biochar benefits are best interpreted as context-dependent and should be evaluated using site-specific performance metrics and longer-term monitoring of soil and crop responses.

5.3. Application in Blueberry Production

Biochar has shown potential in blueberry production by modifying physical and chemical conditions that regulate root function, nutrient availability, and yield, particularly in acidic or low-organic-matter systems. Reported benefits include increases in cation exchange capacity (CEC), improved retention of nutrient cations, and reduced leaching losses, effects that may be especially relevant in coarse-textured soils and low-buffering substrates used in many blueberry systems [88,89]. Biochar has also been associated with improved soil aggregation and structure, which may support root development and plant vigor [90]. Field evidence further suggests that biochar can increase blueberry biomass and fruit yield relative to unamended controls, although responses vary with amendment characteristics, baseline soil constraints, and local environmental conditions [91].

Biochar may also influence symbiotic interactions, including mycorrhizal colonization, that affect nutrient uptake, although these responses can be moderated by pathogen pressure and field variability [90]. From an implementation standpoint, localized placement, such as banding or planting hole amendment, can reduce material requirements and application costs relative to full-row incorporation, thereby improving feasibility for commercial adoption [91]. At the same time, limitations and trade-offs have also been reported, including reduced magnesium uptake, reflected in lower leaf Mg concentration in some cases, and

https://doi.org/10.3390/w18101141

limited suppression of root rot pathogens such as Phytophthora cinnamomi [90,91]. Overall, evidence supports biochar as a promising amendment in blueberry systems, but optimal outcomes require matching biochar chemistry and placement strategy to site constraints and production goals, with additional field-based work needed to refine best practices and minimize unintended nutrient- or disease-related effects.

5.4. Biochar Aging and Time-Dependent Changes in Surface Chemistry

Biochar properties are not static after incorporation into substrates; aging processes can substantially alter surface chemistry and, in turn, sorption behavior over time. Oxidative aging commonly increases the abundance of oxygen-containing functional groups, including carboxyl and carbonyl moieties, thereby increasing pH-dependent negative charge and enhancing cation exchange capacity and nutrient retention potential [92,93]. Aging can also modify ancillary properties, including pH and apparent surface reactivity, through interactions with minerals, dissolved organic matter, and microbial activity, with outcomes dependent on the surrounding medium and exposure conditions [94,95]. This time dependence is particularly important in systems where irrigation and leaching progressively reshape root zone chemistry. As a result, a biochar that initially contributes alkalinity may later exhibit stronger exchange and sorption behavior, implying that net effects on nutrient retention and ion mobility can evolve over the growing period [92,93].

5.5. DOC Interactions and Potential Mobilization of Trace Constituents

Dissolved organic carbon (DOC) is an important control for the speciation, mobility, and bioavailability of trace metals because dissolved organic ligands can form complexes with metals and shift partitioning between solution and solid phases. In pine bark-based substrates, DOC is already substantial, and biochar additions can further modify DOC concentrations and composition, thereby altering complexation behavior and metal mobility in metal-specific ways [96,97]. For example, biochar-associated DOC has been reported to decrease the mobility of some metals, such as Cu and Pb, through the formation of stable metal–organic associations, while increasing the mobility of others, such as As, under certain conditions [96,97]. These outcomes are strongly conditioned by pH and ionic strength, which influence biochar surface charge, sorption equilibria, and competition among ions and ligands [98,99]. This issue is especially relevant under reclaimed water irrigation because reclaimed sources may introduce trace elements and elevate ionic strength, potentially shifting complexation–sorption balances relative to low-salinity water sources [99,100]. Accordingly, biochar should be treated as a targeted substrate-design variable, the benefits and risks of which must be evaluated in the specific water chemistry and substrate context.

6. Combined Effects of Reclaimed Water and Biochar: Root Zone Drivers, Solute Dynamics, and Management Trade-Offs

6.1. Dominant Drivers of Reclaimed Water Effects in Blueberry Root Zones

The combined effects of reclaimed water and biochar in southern highbush blueberry systems are governed less by the simple presence of either input than by the interaction among irrigation water chemistry, substrate buffering capacity, and crop sensitivity. In blueberry production, the most influential reclaimed-water-related drivers are generally salinity load, alkalinity, and the accumulation of Na^+ and Cl^-, because these factors directly affect osmotic conditions, root zone pH, nutrient availability, and long-term substrate suitability [1,2,13,14,101–103].

Across the reviewed studies, salinity, alkalinity, and Na^+/Cl^- accumulation emerge as dominant first-order drivers of system response, whereas biological processes and traceelement mobility appear more context-specific and secondary in reclaimed water-irrigated blueberry systems.

In contrast, nutrient inputs supplied by reclaimed water may be beneficial in some situations, but these benefits are typically secondary to the need to maintain an acidic, low-salinity root environment suitable for blueberry growth [1,2,101,102].

These interactions are especially important in coarse-textured soils and pine bark-based substrates, where low buffering capacity and high leachability can amplify both short-term fluctuations and cumulative chemical change. Under such conditions, the response of the root zone depends on whether biochar improves water and solute retention without excessively increasing substrate pH or electrical conductivity. Thus, the agronomic outcome is determined not simply by whether reclaimed water or biochar is used, but by whether their combined effects remain within the tolerance limits of this calcifuge crop [13,14,91].

From a Soil–Plant–Environment perspective, reclaimed water acts primarily as an external chemical driver, whereas biochar modifies the internal buffering environment by altering sorption capacity, exchange behavior, porosity, and pH. From an Integrated Water Resource Management perspective, this interaction reflects a broader trade-off: reclaimed water can improve irrigation security and reduce freshwater demand, but its successful use depends on managing root zone consequences that may otherwise compromise crop performance or increase environmental risk [1,2,5,11,101]. The interaction hierarchy proposed in this review is summarized conceptually in Figure 1.

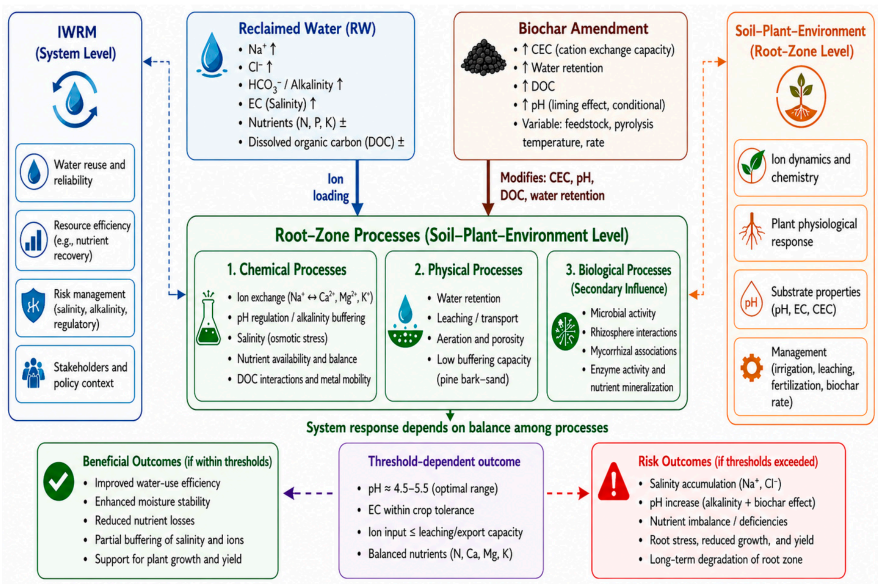

Figure 1. A conceptual model of reclaimed water–biochar–root-zone interactions in southern highbush blueberry systems. Reclaimed water acts as an external chemical driver by introducing salinity, alkalinity, and ion loading, particularly Na^+, Cl^-, and HCO_3^-, while biochar modifies internal root-zone conditions through effects on cation exchange capacity, dissolved organic carbon, pH, and water retention. These inputs interact within the root zone through chemical, physical, and biological processes that collectively determine whether system outcomes remain beneficial or shift toward risk. Beneficial outcomes are expected when pH, electrical conductivity, and ion loading remain within crop tolerance limits, whereas adverse outcomes arise when thresholds are exceeded, leading to salt accumulation, nutrient imbalance, and root-zone degradation. Solid downward arrows indicate direct effects of reclaimed water ion loading and biochar-mediated changes on root-zone processes. Dashed arrows indicate conceptual linkages between IWRM/system-level considerations, soil–plant–environment responses, and beneficial or risk outcomes. Curved arrows in the IWRM box represent water reuse and resource cycling.

6.2. When Biochar Mitigates Reclaimed Water Stress

Biochar can mitigate reclaimed-water-related stress by enhancing the retention of water and selected nutrients while moderating solute mobility in the root zone. In low-buffering systems, this may help reduce rapid nutrient loss, improve short-term moisture stability, and increase the retention of certain cations through additional exchange and sorption sites. Under these conditions, biochar may support more stable rhizosphere conditions and reduce the severity of some nutrient imbalances associated with reclaimed water irrigation [6,8,10,11,90,95,104,105].

Potential benefits may also extend to biological and rhizosphere processes. Biochar may provide microsites that alter microbial activity, nutrient mineralization, and possibly mycorrhizal interactions, with downstream effects on nutrient acquisition and plant stress responses [8–10,90,106,107]. However, these responses are not sufficiently consistent to be treated as universal benefits, especially in blueberry systems, where crop-specific evidence remains limited [89,101,102].

Accordingly, biological effects should currently be viewed as potentially important but secondary to the better-established chemical controls imposed by pH, salinity, and ionic composition [108]. Under suitable material–system matching, biochar may therefore function as a conditional buffering amendment rather than a universally beneficial input. Its most plausible role in reclaimed-water-irrigated blueberry systems is to reduce vulnerability to nutrient leaching and short-term root zone instability, provided that the amendment itself does not introduce excessive alkalinity or salinity [6,8,11,90,91,95,105].

6.3. When Biochar May Worsen or Fail to Mitigate Reclaimed Water Effects

Biochar does not uniformly reduce reclaimed-water-related risks and may, in some cases, worsen them. This is particularly important in blueberry systems, where substrate pH and salinity must remain within a relatively narrow range. Many biochars contain ash-derived alkalinity and soluble salts that can increase substrate pH and EC, potentially shifting root zone conditions outside the optimal range for blueberry [91,95,105].

This trade-off helps explain why biochar responses vary widely across studies. Differences in feedstock source, pyrolysis temperature, particle size, aging behavior, application rate, and baseline substrate properties can all alter the direction and magnitude of biochar effects [6–8,92–95,105]. Likewise, reclaimed water quality is not uniform; its electrical conductivity, sodium hazard, chloride concentration, alkalinity, and nutrient content can differ substantially among sources and over time [1,2,42,48,51,56,59,101,102].

As a result, biochar is most likely to fail when its liming effect, ash content, or soluble ion contribution adds to the same stress pathways already imposed by reclaimed water [91,95,103,105].

These context-dependent outcomes indicate that biochar should not be evaluated as a generic mitigation tool. Rather, its suitability depends on whether its sorptive and physical benefits outweigh its tendency to alter pH and ionic strength under a given irrigation chemistry and substrate condition. This balance is especially critical in acidophilic crops such as the blueberry, where relatively modest increases in pH or salt load may reduce nutrient availability, impair root function, and increase long-term management difficulty [13,14,91,108].

6.4. Implications for Solute Leaching, Nutrient Retention, and Management

The interaction between reclaimed water and biochar has direct implications for solute movement, nutrient retention, and off-site environmental losses. In principle, biochar may reduce leaching of selected nutrients or contaminants by increasing cation exchange capacity, providing additional sorption surfaces, and altering transport pathways. However, the magnitude and direction of these effects vary by constituent and depend on dissolved organic carbon release, pH shifts, ionic strength, competitive sorption, and water chemistry. This means that improved retention of one solute does not necessarily imply reduced mobility of all constituents [96–99,104,109–113].

Although biochar has been widely studied for the immobilization of trace metals and metalloids through adsorption, ion exchange, complexation, and precipitation-related mechanisms, the direct relevance of these pathways to reclaimed-water-irrigated blueberry systems is secondary to the more immediate challenges posed by salinity, alkalinity, and nutrient imbalance [101,102,104,109–113].

For blueberry production systems, the most decision-relevant issue is therefore not heavy-metal immobilization alone, but the broader balance among nutrient retention, salt accumulation, and maintenance of a chemically suitable root zone. Where reclaimed water increases Na^+, Cl^-, or alkalinity loading, management priorities should focus first on preserving acidity, limiting cumulative salt buildup, and preventing nutrient imbalance. Under such conditions, biochar may be useful only when selected and applied in ways that do not aggravate pH elevation or EC increases [1,2,13,14,91,101–103].

From a management perspective, maintaining substrate pH within the generally recommended blueberry range of approximately 4.5–5.5 and preventing sustained increases in EC are essential for preserving root function and nutrient uptake under reclaimed water irrigation [29–31,40,42,51,69,71].

Thus, in practical terms, the key question is not whether reclaimed water and biochar can be used together, but under which combinations of water chemistry, amendment properties, and substrate conditions their co-application remains compatible with blueberry root zone requirements. At the farm scale, these interactions support a management approach based on source-specific water testing; amendment characterization; and periodic monitoring of substrate pH, EC, and ion accumulation [1,2,14,101,102]. The trade-offs associated with reclaimed water–biochar integration, including threshold-dependent beneficial versus adverse outcomes, are summarized in Figure 2, whereas a practical decision framework for evaluating and managing this co-application under production conditions is presented in Figure 3.

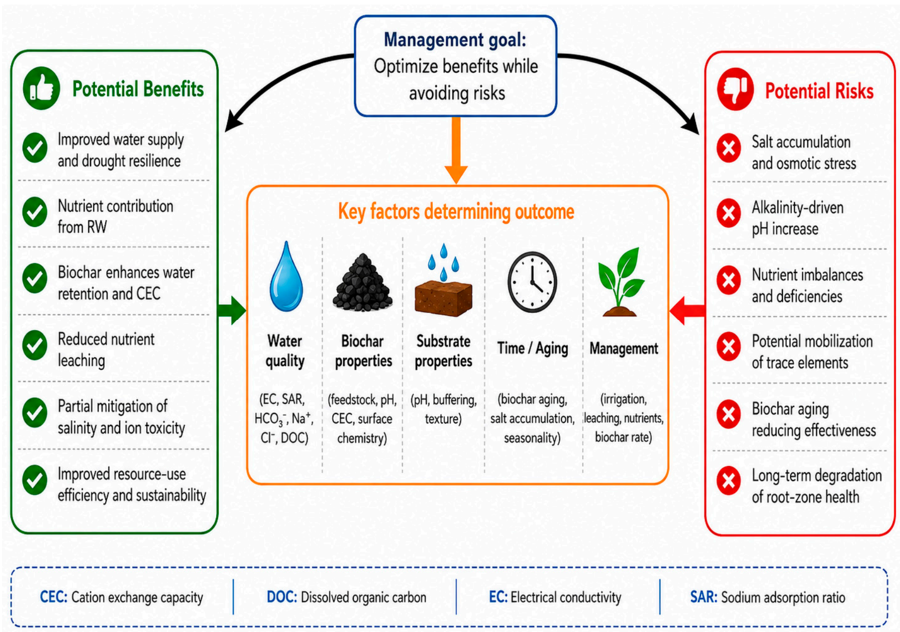

Figure 2. The trade-offs of integrating reclaimed water and biochar in southern highbush blueberry systems. The integration of reclaimed water and biochar may improve water supply reliability,

nutrient retention, moisture stability, and resource-use efficiency, but it may also increase the risk of salinity accumulation, alkalinity-driven pH increase, nutrient imbalance, and long-term decline in root-zone suitability. The overall outcome is threshold-dependent and is governed by interacting factors, including reclaimed water quality, biochar properties, substrate characteristics, exposure duration, and management practices. This framework highlights that reclaimed water–biochar co-application should be evaluated as a conditional management strategy rather than a universally beneficial practice. The orange arrow indicates the management goal of guiding outcome evaluation through the key determining factors. The green and red arrows represent the contributions of potential benefits and potential risks, respectively, to that evaluation. The black curved arrows emphasize the trade-off relationship between optimizing benefits and avoiding risks.

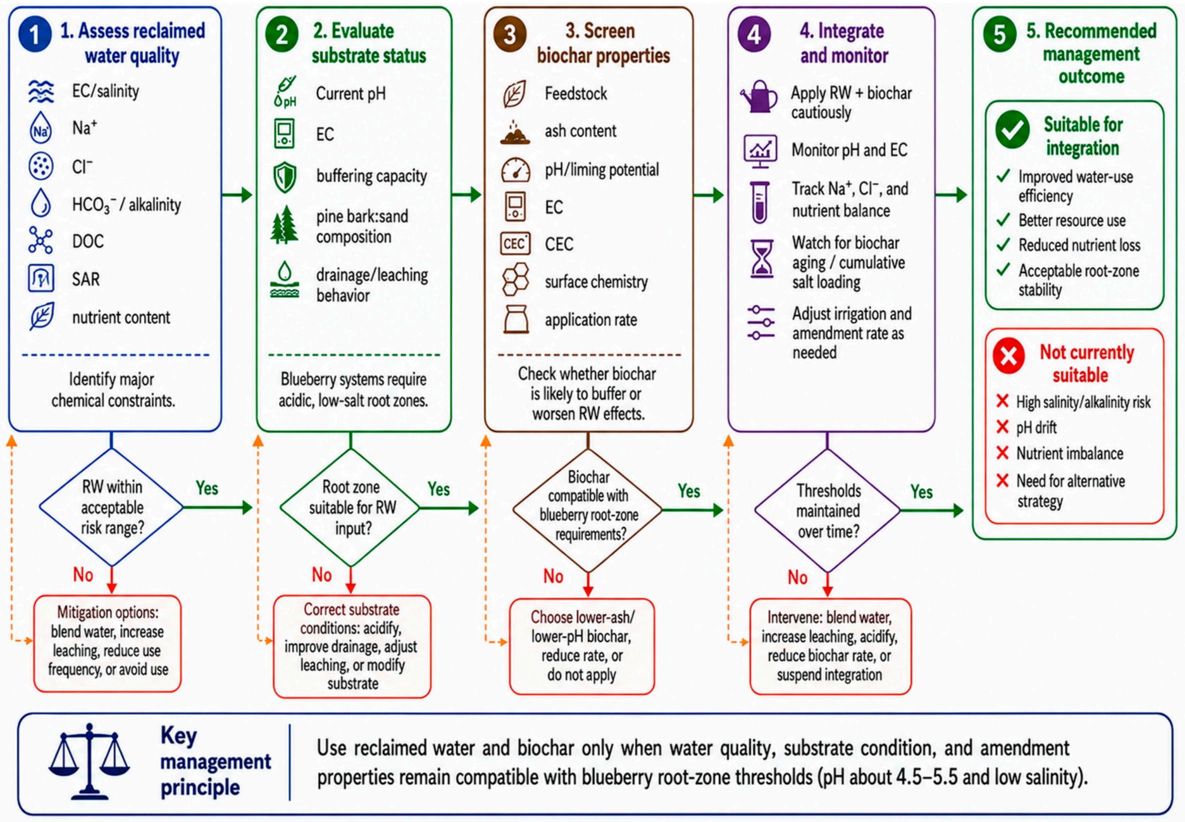

Figure 3. Decision framework for evaluating reclaimed water–biochar suitability in southern highbush blueberry systems. The framework outlines a stepwise approach for assessing whether reclaimed water and biochar can be integrated without compromising blueberry root-zone conditions. The evaluation begins with reclaimed water quality metrics, including salinity, Na^+, Cl^-, alkalinity, dissolved organic carbon, sodium adsorption ratio, and nutrient content, followed by an assessment of substrate condition and biochar properties. The framework then emphasizes integration with ongoing monitoring of pH, electrical conductivity, ion accumulation, and nutrient balance. The final outcomes depend on whether these factors remain within blueberry root-zone thresholds, leading to suitable integration or necessitating corrective management or alternative strategies. Green arrows indicate "Yes" pathways leading to continued evaluation or suitable integration, whereas red arrows indicate "No" pathways requiring mitigation, corrective management, or alternative strategies. Orange dashed arrows indicate feedback loops in which corrected conditions should be reassessed before proceeding.

7. Economic and Practical Considerations for Adoption

Economic viability is a primary determinant of the adoption of sustainable agricultural technologies, including biochar amendments, reclaimed water systems, and other resource-efficient practices. Adoption decisions are shaped by cost–benefit relationships in which up-front investment, operating costs, risk, and long-term returns must be weighed against environmental benefits and the costs of regulatory compliance. Accordingly, an economic assessment is necessary to identify implementation pathways that reflect farm-level constraints while clarifying how incentives, such as cost-sharing mechanisms, carbon markets, or infrastructure investments, may accelerate adoption.

For biochar specifically, commercial viability depends on production efficiency, feedstock availability, transport distance, and application practices optimized for the target crop and substrate. Feedstock choice can strongly influence production economics. For example, longan husks have been reported to yield higher energy efficiency and shorter payback periods than corncobs or rice husks under certain scenarios [114]. Integrated life cycle assessment (LCA) and cost–benefit analysis (CBA) frameworks also highlight trade-offs between production costs and the value of environmental co-benefits, particularly when carbon abatement or carbon credit revenue is considered [115]. In horticultural contexts, biochar has been associated with productivity gains and potential economic benefits when applied at rates aligned with agronomic response and cost constraints. In Mediterranean cropping systems, radish, lettuce, tomato, and sweet pepper showed increased fresh biomass when biochar was applied at an economically optimized rate of 1 kg m^{-2} [116]. Biochar has also been evaluated as a partial substitute for peat-based growing media, which may reduce greenhouse gas emissions associated with peat extraction while maintaining substrate function and, in some cases, improving economic competitiveness [117].

Despite these potential benefits, broader adoption remains constrained by high production and transportation costs, inconsistent feedstock supply, and limited standardization in biochar quality assurance, all of which can contribute to variable field outcomes [118]. In addition, the magnitude and persistence of economic benefits remain context dependent, varying with soil or substrate properties, crop type, climate, and management. Although many studies report improvements in soil function and crop performance, further work is needed to refine application protocols, quantify multi-year outcomes, and evaluate cumulative economic impacts under commercial production conditions [119]. Overall, the long-term economic sustainability of biochar in horticulture is closely tied to its broader environmental value proposition, reinforcing the need for integrated assessment approaches that jointly evaluate agronomic performance, economic returns, and environmental outcomes.

7.1. Economic Synthesis

Economic constraints are a consistent and often decisive barrier to the adoption of sustainable agricultural technologies, including biochar amendments, reclaimed water (RW) irrigation, and other sustainability-oriented management practices. Across these approaches, high up-front capital requirements are repeatedly identified as limiting factors. Required investments may include pyrolysis equipment and supply chain development for biochar, treatment and conveyance infrastructure for reclaimed water, and on-farm upgrades needed to integrate new water- and substrate-management practices. These costs can be prohibitive, particularly for small growers and beginners with limited access to credit.

Even after adoption, operating and transaction costs may remain higher than those associated with conventional alternatives. For biochar, these costs include feedstock procurement, processing, transportation, and application logistics, as well as uncertainty arising from variable product properties. For reclaimed water, treatment level, monitoring, distribution, and compliance requirements can remain persistent cost differentials relative to freshwater supplies. These economic realities are further complicated by externalities and market structures that often fail to compensate growers for broader public benefits such as water conservation, nutrient recycling, carbon sequestration, and reduced pollution risk. As a result, private incentives may continue to favor short-term conventional practices even when sustainable alternatives provide substantial long-term public value.

The economic literature suggests that large-scale adoption depends on coordinated policy and market interventions that address both structural barriers and incentive gaps. Financial instruments, including targeted subsidies, cost-share programs, low-interest credit, and payments for ecosystem services, may reduce transition risk and improve the near-term feasibility of capital investments. Standardization and quality assurance are particularly important for biochar, where inconsistent material properties and limited certification frameworks increase uncertainty and transaction costs for producers and end users. In parallel, integrated assessment approaches that incorporate life-cycle costs, environmental externalities, and social benefits can strengthen the case for investment by making the full value proposition more visible to policymakers, utilities, and producers.

Overall, the economic sustainability of reclaimed water and biochar depends on enabling conditions that recognize and compensate environmental and social benefits while also addressing the technical, social, and institutional constraints that amplify financial risk and slow adoption across diverse agricultural systems.

7.2. Adoption Barriers in Sustainable Agriculture

The adoption of sustainable agricultural practices, including reclaimed water (RW) irrigation, is constrained by the interaction of technical, economic, social, and institutional barriers that collectively limit implementation at scale. Technical constraints often include limited farmer knowledge and experience, which have been identified as key determinants in decision-support analyses [120]. Infrastructure limitations represent an additional and persistent barrier, particularly where storage, conveyance, and distribution capacity are insufficient to match reclaimed water supply with crop water-demand patterns [121]. Perceived operational complexity can further suppress adoption when growers view innovations as difficult to manage or incompatible with established routines and risk-management strategies [122]. Geographic constraints also shape feasibility; long distances and challenging topography between wastewater treatment facilities and agricultural areas increase conveyance costs and logistical complexity, as documented in Mediterranean case studies such as Sicily [123].

Economic factors are frequently central to adoption decisions. High up-front capital requirements for distribution infrastructure and on-farm system modifications can disproportionately affect smallholders and producers with limited access to credit [124]. Reclaimed water systems exemplify this challenge, as reuse may require additional treatment, delivery infrastructure, and monitoring and compliance activities that can increase operating costs relative to conventional water sources [125,126]. Market volatility and insufficient financial incentives can further reduce willingness to adopt sustainable practices, and cost-recovery policies that shift expenses to growers without compensatory mechanisms may erode profitability and discourage participation [125,127].

Social acceptance also influences adoption outcomes. Negative perceptions, particularly regarding the safety and quality of reclaimed water, can deter both producers and consumers, with concerns often centered on contamination pathways and perceived health risks [50,52]. Farmer attitudes and limited awareness of longer-term sustainability benefits can reinforce resistance to change, especially when benefits are delayed, uncertain, or difficult to quantify at the farm scale [124,128]. Cultural preferences for conventional production systems may further contribute to reluctance to adopt unfamiliar practices [129]. These factors highlight the importance of risk communication, stakeholder engagement, and outreach that clearly explain treatment processes and safety protocols in locally relevant terms [52,125].

https://doi.org/10.3390/w18101141

Institutional and policy constraints further shape adoption by determining access to information, financing mechanisms, and enabling infrastructure. Inadequate policy support, limited extension capacity, and restricted access to essential resources such as land and water can reduce farmers' ability to implement sustainable practices [127,130,131]. Regulatory challenges may arise where reclaimed water standards, particularly microbiological criteria and the monitoring and compliance requirements needed to demonstrate performance, are difficult to meet under local governance and infrastructure conditions [123]. In addition, limited political commitment and underinvestment can delay large-scale deployment despite growing environmental pressures that increasingly motivate reuse [125].

Overcoming these barriers will require coordinated, multi-stakeholder approaches that integrate education, financial support, and enabling policy design. Targeted training programs can build technical capacity, address knowledge gaps, and reduce perceived complexity [120,130]. Financial mechanisms such as subsidies, cost-sharing programs, and low-interest credit can offset transition costs and improve feasibility for growers [127]. Policy frameworks that embed sustainability goals within agricultural planning, supported by sustained political commitment, are also critical for establishing long-term enabling conditions [130,131]. Finally, community-based approaches and farmer cooperative networks can support cultural acceptance and peer-to-peer learning by strengthening trust and accelerating the diffusion of innovations [127]. Collectively, these interventions can reduce adoption barriers and support the broader implementation of sustainable agriculture, including the safe and effective integration of reclaimed water through coordinated engagement among policymakers, researchers, extension agents, and agricultural communities.

8. Knowledge Gaps and Future Research Needs

Although research on reclaimed water and biochar as individual management tools has expanded, relatively few studies have evaluated their combined effects in southern highbush blueberry systems in Florida, particularly in pine bark–sand substrates commonly used in commercial production. Much of the existing literature focuses on conventional mineral soils or on single-factor treatments, limiting their direct transferability to specialty crop systems, where substrate composition, irrigation-water chemistry, and fertilization practices interact strongly.

Important gaps remain in determining whether biochar-mediated benefits persist under reclaimed water irrigation across multiple seasons and in Florida-relevant production contexts, including amended beds, containerized systems, and high-density plantings. Additional uncertainty concerns how biochar type and application rate interact with reclaimed water ionic composition, especially Na^+, Cl^-, and overall electrical conductivity, with respect to cation retention, salinity buffering, dissolved organic carbon dynamics, and nutrient and trace-constituent leaching behavior in sandy and organic-based substrates.

Further research is also needed to clarify how reclaimed water and biochar jointly influence root zone pH regulation, nutrient availability, salt accumulation patterns, and the temporal stability of sorption processes under repeated irrigation. Because biochar properties change with aging, oxidation, and interaction with dissolved constituents, short-term studies may not adequately capture the evolution of substrate chemical behavior over time. This limitation is particularly relevant in blueberry production systems, where relatively small shifts in root zone chemistry can have disproportionate effects on nutrient uptake, plant stress, and yield.

Beyond technical uncertainties, adoption may also be constrained by regulatory and practical considerations. These include uncertainty in growers regarding reclaimed water allowances for specific crops and irrigation configurations; variability in water-quality monitoring requirements and implementation capacity across regions; and limited groweroriented guidance on biochar sourcing, quality assurance, application methods, and cost-effectiveness. Addressing these interconnected gaps will be essential to developing regionally tailored, operationally realistic strategies for integrating reclaimed water and biochar into Florida blueberry production systems.

9. Conclusions

This review synthesizes the agronomic, environmental, and management factors shaping the sustainability of southern highbush blueberry production in Florida, with particular emphasis on the integration of reclaimed water irrigation and biochar amendment in pine bark–sand substrates used in amended-bed and containerized systems. Due to the calcifuge nature of blueberry, crop performance is highly sensitive to salinity, pH shifts, nutrient imbalances, and fluctuations in root zone moisture, making irrigation water quality and substrate buffering capacity central determinants of production success.

The available literature indicates that reclaimed water can improve water supply reliability and contribute supplemental nutrients; however, these benefits are often constrained by increased salinity, alkalinity, and Na^+/Cl^- loading, which can progressively alter root zone chemistry when inputs exceed leaching or plant uptake capacity. Biochar amendments may enhance water retention, increase cation exchange capacity, and improve nutrient retention under certain conditions. Nevertheless, biochar effects are highly variable and dependent on feedstock, production conditions, application rate, and substrate characteristics, with particular concern for unintended increases in pH and electrical conductivity in acid-sensitive blueberry systems.

Overall, the combined use of reclaimed water and biochar should be viewed as a conditional management strategy rather than a universally beneficial practice. The literature suggests that system outcomes are governed primarily by the interaction between irrigation water chemistry (salinity, alkalinity, and ionic composition) and substrate buffering properties, with biochar acting as a modifier, the effects of which may either mitigate or exacerbate these stress pathways. In this context, the dominant challenge in blueberry production is not simply improving nutrient retention or water use efficiency but maintaining a chemically suitable root zone environment over time.

A key limitation across the current body of research is the scarcity of long-term, multi-season studies evaluating cumulative salt loading, biochar aging, and evolving substrate chemistry under reclaimed water irrigation. In addition, inconsistencies among studies highlight the need for more standardized evaluation of water quality, biochar properties, and substrate systems to enable meaningful comparison and synthesis.

Future research should therefore prioritize long-term and field-scale evaluations of reclaimed water and biochar interactions in blueberry systems; mechanistic studies linking ion transport, substrate buffering, and plant physiological response; the development of threshold-based guidelines for salinity, alkalinity, and pH management in substrate systems; and the assessment of practical management strategies, including water blending, amendment selection, and monitoring approaches, under real production conditions.

These conclusions should be interpreted as context-dependent because reclaimed water composition, substrate buffering capacity, biochar properties, and exposure duration can vary substantially across production systems. In Florida and similar production systems, successfully integrating reclaimed water and biochar will depend on aligning water quality, amendment properties, and substrate behavior within a framework that balances resource use efficiency with crop productivity and environmental protection.

https://doi.org/10.3390/w18101141

Author Contributions: Conceptualization, Y.S. and D.M.K.; methodology, Y.S.; software, Y.S.; validation, Y.S. and D.M.K.; formal analysis, Y.S. and D.M.K.; investigation, Y.S.; resources, D.M.K.; data curation, Y.S.; writing—original draft preparation, Y.S.; writing—review and editing, D.M.K.; visualization, Y.S. and D.M.K.; supervision, D.M.K.; project administration, D.M.K.; funding acquisition, D.M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Blueberry Project, project No. 00131246-212-2200; the USDA Hatch Program, project No. 006185; and the Soil, Water, and Ecosystem Sciences Department Matching Assistantship.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: During the preparation of this manuscript, the authors used ChatGPT, GPT-5.5 Thinking (OpenAI, accessed May 2026), where needed, to assist with language editing and manuscript organization. The authors reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

DOC	Dissolved Organic Carbon
RW	Reclaimed Water
LCA	Life Cycle Assessment
CBA	Cost–Benefit Analysis
CEC	Cation Exchange Capacity
HCO_3^-	Bicarbonate
FDEP	Florida Department of Environmental Protection
SHB	Southern Highbush Blueberry
Kc	Crop Coefficient
UF/IFAS	University of Florida Institute of Food and Agricultural Sciences
USDA	United States Department of Agriculture

References

1. Lewis, J.; Wright, A.L. Reclaimed Water Use for Edible Crop Production in Florida. *Ext. Data Inf. Source* **2011**, *2011*. Available online: https://journals.flvc.org/edis/article/view/119369 (accessed on 6 May 2026).
2. Freeman, T.L.; Silvasy, T.; Zhuang, Y.; Momol, E.A. Reclaimed Water in Your Florida-Friendly Edible Landscape. *Ext. Data Inf. Source* **2023**, *2023*, 1. [CrossRef]
3. Belmonte, B.A.; Benjamin, M.F.D.; Tan, R.R. Biochar systems in the water–energy–food nexus: The emerging role of process systems engineering. *Curr. Opin. Chem. Eng.* **2017**, *18*, 32–37. [CrossRef]
4. Fseha, Y.H.; Shaheen, J.F.; Sizirici, B. Revealing selected groundwater contaminants, risks, and sustainable solutions for safe drinking water through pristine and modified biochar. *J. Anal. Appl. Pyrolysis* **2023**, *176*, 106237. [CrossRef]
5. Abdellatif, W.A.; Abdel Kader, S.S. Integrated Water Resources Management (IWRM) plan as a tool to achieve sustainable water management: Applying on Fouka Basin. *MSA Eng. J.* **2023**, *2*, 28–45. [CrossRef]
6. Acharya, B.S.; Dodla, S.K.; Wang, J.J.; Pavuluri, K.; Darapuneni, M.K.; Dattamudi, S.; Maharjan, B.; Kharel, G. Biochar impacts on soil water dynamics: Knowns, unknowns, and research directions. *Biochar* **2024**, *6*, 34. [CrossRef]
7. Novak, A.; Li, L.; Wason, J.; Wang, J.; Zhang, Y.-J. Characterization and modification of biochar from a combined heat and power (CHP) plant for amending sandy soils collected from wild blueberry fields. *BioResources* **2024**, *19*, 228–244. [CrossRef]
8. Murtaza, G.; Ahmed, Z.; Eldin, S.M.; Ali, B.; Bawazeer, S.S.A.; Usman, M.; Iqbal, R.; Neupane, D.; Ullah, A.; Khan, A.; et al. Biochar–soil–plant interactions: A cross talk for sustainable agriculture under changing climate. *Front. Environ. Sci.* **2023**, *11*, 1059449. [CrossRef]
9. Głuszek, S.; Sas-Paszt, L.; Sumorok, B.; Kozera, R. Biochar–rhizosphere interactions: A review. *Pol. J. Microbiol.* **2017**, *66*, 151–161. [CrossRef] [PubMed]

10. Hussain, R.; Garg, A.; Ravi, K. Soil–biochar–plant interaction: Differences from the perspective of engineered and agricultural soils. *Bull. Eng. Geol. Environ.* **2020**, *79*, 4461–4481. [CrossRef]
11. Lyon, S.W.; Fischer, B.; Morillas, L.; Rojas-Conejo, J.; Sánchez-Murillo, R.; Suárez Serrano, A.; Frentress, J.; Cheng, C.-H.; Galicia-García, M.; Johnson, M.S. On the potential of biochar soil amendments as a sustainable water management strategy. *Sustainability* **2022**, *14*, 7026. [CrossRef]
12. Williamson, J.G.; Lyrene, P.M. The Florida blueberry industry: A decade of growth. *Proc. Fla. State Hort. Soc.* **2004**, *117*, 234–235.
13. Williamson, J.G.; Phillips, D.A. Florida's commercial blueberry industry: HS742/AC031, rev. 8/2024. *Ext. Data Inf. Source* **2024**, *2024*, 4.
14. Phillips, D.A.; Williamson, J.G. Irrigation practices for southern highbush blueberry in Florida. *Ext. Data Inf. Source* **2021**, *2021*, 6. [CrossRef]
15. Harmon, P.F.; Liburd, O.E.; Dittmar, P.; Williamson, J.G.; Phillips, D. 2022 Florida Blueberry Integrated Pest Management Guide: HS1156/HS380, rev. 11/2021. *Ext. Data Inf. Source* **2021**, *2021*. [CrossRef]
16. Phillips, D.A.; Williamson, J.G.; Lyrene, P.M.; Muñoz, P.R. Southern Highbush Blueberry Cultivars from the University of Florida: HS1245, rev. 9/2022. *Ext. Data Inf. Source* **2022**, *2022*. Available online: https://ask.ifas.ufl.edu/publication/HS1245 (accessed on 6 May 2026).
17. Kendall, L.K.; Gagic, V.; Evans, L.J.; Cutting, B.T.; Scalzo, J.; Hanusch, Y.; Jones, J.; Rocchetti, M.; Sonter, C.A.; Keir, M.; et al. Self-compatible blueberry cultivars require fewer floral visits to maximize fruit production than a partially self-incompatible cultivar. *J. Appl. Ecol.* **2020**, *57*, 2454–2462. [CrossRef]
18. Mallinger, R.E.; Chabert, S.; Naranjo, S.M.; Vo, V. Diversity and spatial arrangement of cultivars influences bee pollination and yields in southern highbush blueberry *Vaccinium corymbosum* × darrowii. *Sci. Hortic.* **2024**, *335*, 113321. [CrossRef]
19. Hirzel, J.; Pedroso Moya, V.; Balbontín, C. Characterization of fruit quality attributes and nutritional composition of ten blueberry cultivars. *Isr. J. Plant Sci.* **2023**, *70*, 91–103. [CrossRef]
20. Song, M.; Olmstead, J.W.; Rouseff, R.L.; Tomasino, E. Investigation on the profile of phenolic acids and flavonoids with antioxidant capacity in Florida highbush (*Vaccinium corymbosum* L.) and rabbiteye (*Vaccinium virgatum*) blueberries. *J. Exp. Food Chem.* **2016**, *2*, 105–113. [CrossRef]
21. Buck, B. Blueberries: A healthy, tasty snack from Florida farmers. *UF/IFAS News*, 19 March 2025.
22. Food and Resource Economics Department, University of Florida Institute of Food and Agricultural Sciences. All Florida Agriculture. 14 March 2025. Available online: https://fred.ifas.ufl.edu/extension/economic-impact-analysis-program/florida-ag-food-and-resources/all-florida-agriculture/ (accessed on 6 May 2026).
23. Milejczak, R. A Season of Highs and Lows. Florida Blueberry Growers Association. *Blueberry Blog*. 27 June 2024. Available online: https://www.floridablueberrygrowers.org/index.php?category=blueberry-blog&id=273%3Aa-season-of-highs-and-lows&option=com_dailyplanetblog&view=entry (accessed on 6 May 2026).
24. Lyrene, P.M.; Sherman, W.B. 'Star' southern highbush blueberry. *HortScience* **2000**, *35*, 956–957. [CrossRef]
25. Spiers, J.M. Establishment and early growth and yield of 'Gulfcoast' southern highbush blueberry. *HortScience* **1998**, *33*, 1138–1141. [CrossRef]
26. Dourte, D.R.; Haman, D.Z.; Williamson, J.G. Crop water requirements of mature southern highbush blueberries. *Int. J. Fruit Sci.* **2010**, *10*, 235–248. [CrossRef]
27. Williamson, J.G.; Mejia, L.; Ferguson, B.; Miller, P.; Haman, D.Z. Seasonal water use of southern highbush blueberry plants in a subtropical climate. *HortTechnology* **2015**, *25*, 185–191. [CrossRef]
28. Darnell, R.L.; Casamali, B.; Williamson, J.G. Nutrient assimilation in southern highbush blueberry and implications for the field. *HortTechnology* **2015**, *25*, 460–463. [CrossRef]
29. Imler, C.S.; Arzola, C.I.; Nunez, G.H. Ammonium uptake is the main driver of rhizosphere pH in southern highbush blueberry. *HortScience* **2019**, *54*, 955–959. [CrossRef]
30. Jiang, Y.; Zeng, Q.; Wei, J.; Jiang, J.; Li, Y.; Chen, J.; Yu, H. Growth, fruit yield, photosynthetic characteristics, and leaf microelement concentration of two blueberry cultivars under different long-term soil pH treatments. *Agronomy* **2019**, *9*, 357. [CrossRef]
31. Schreiber, M.J.; Nunez, G.H. Calcium carbonate can be used to manage soilless substrate pH for blueberry production. *Horticulturae* **2021**, *7*, 74. [CrossRef]
32. Ma, B.; Song, Y.; Feng, X.; Guo, P.; Zhou, L.; Jia, S.; Guo, Q.; Zhang, C. Integrated metabolome and transcriptome analyses reveal the mechanisms regulating flavonoid biosynthesis in blueberry leaves under salt stress. *Horticulturae* **2024**, *10*, 1084. [CrossRef]
33. Molnar, S.; Clapa, D.; Pop, V.; Hârţa, M.; Andrecan, F.A.; Bunea, C. Investigation of salinity tolerance to different cultivars of highbush blueberry (*Vaccinium corymbosum* L.) grown in vitro. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2024**, *52*, 13691. [CrossRef]
34. Song, H.; Cao, Y.; Zhao, X.; Zhang, L. Na+-preferential ion transporter HKT1;1 mediates salt tolerance in blueberry. *Plant Physiol.* **2024**, *194*, 511–529. [CrossRef]
35. Ayub, M.A.; Ahmad, H.R.; Ali, M.; Rizwan, M.; Ali, S.; ur Rehman, M.Z.; Waris, A.A. Salinity and its tolerance strategies in plants. In *Plant Life Under Changing Environment*; Academic Press: Cambridge, MA, USA, 2020; pp. 47–76.

36. Tedeschi, A.; Schillaci, M.; Balestrini, R. Mitigating the impact of soil salinity: Recent developments and future strategies. *Ital. J. Agron.* **2023**, *18*, 2173. [CrossRef]
37. Ali, A.; Biggs, A.J.W.; Marchuk, A.; Bennett, J.M. Effect of irrigation water pH on saturated hydraulic conductivity and electrokinetic properties of acidic, neutral, and alkaline soils. *Soil Sci. Soc. Am. J.* **2019**, *83*, 1672–1682. [CrossRef]
38. Gardner, W.K. Changes in soils irrigated with saline groundwater containing excess bicarbonate. *Soil Res.* **2004**, *42*, 825–831. [CrossRef]
39. Alva, A.K.; Syvertsen, J.P. Irrigation water salinity affects soil nutrient distribution, root density, and leaf nutrient levels of citrus under drip fertigation. *J. Plant Nutr.* **1991**, *14*, 715–727. [CrossRef]
40. Zaman, M.; Shahid, S.A.; Heng, L. Irrigation water quality. In *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*; Springer International Publishing: Cham, Switzerland, 2018; pp. 113–131.
41. Kramer, I.; Mau, Y. Review: Modeling the Effects of Salinity and Sodicity in Agricultural Systems. *Water Resour. Res.* **2023**, *59*, e2023WR034750. [CrossRef]
42. Malakar, A.; Snow, D.D.; Ray, C. Irrigation water quality: A contemporary perspective. *Water* **2019**, *11*, 1482. [CrossRef]
43. Florida Department of Environmental Protection. Florida's Reuse Activities. 27 January 2026. Available online: https://floridadep.gov/water/domestic-wastewater/content/floridas-reuse-activities (accessed on 6 May 2026).
44. Florida Department of Environmental Protection. Water Reuse Program. 10 September 2024. Available online: https://floridadep.gov/water/domestic-wastewater/content/water-reuse-program (accessed on 6 May 2026).
45. Florida Department of Environmental Protection. Applicable Rules for Reuse Projects. 28 October 2024. Available online: https://floridadep.gov/water/domestic-wastewater/content/applicable-rules-reuse-projects (accessed on 6 May 2026).
46. Braune, L.; Onel, G.; Borisova, T.; Useche, P. Regulations Governing the Usage of Reclaimed Water as an Alternative Water Source for Agricultural Irrigation in Florida: FE1091, 01/2021. *Ext. Data Inf. Source* **2021**, *2021*, 8.
47. Parsons, L.R.; Wheaton, T.A.; Castle, W.S. Reclaimed Water—A New Irrigation Source for Citrus Irrigation in Florida. In Proceedings of the Energy, Climate, Environment and Water: Issues and Opportunities for Irrigation and Drainage; USCID/EWRI Conference, San Luis Obispo, CA, USA, 9–12 July 2002; p. 213. Available online: https://mountainscholar.org/items/c3d190ae-8772-4367-8f7f-9375c095aa4c (accessed on 6 May 2026).
48. Parsons, L.R.; Sheikh, B.; Holden, R.B.; York, D.W. Reclaimed water as an alternative water source for crop irrigation. *HortScience* **2010**, *45*, 1626–1629. [CrossRef]
49. Parsons, L.R. Agricultural use of reclaimed water in Florida: Food for thought. *J. Contemp. Water Res. Educ.* **2018**, *165*, 20–27. [CrossRef]
50. Sheikh, B.; Nelson, K.L.; Haddad, B.; Thebo, A. Grey water: Agricultural use of reclaimed water in California. *J. Contemp. Water Res. Educ.* **2018**, *165*, 28–41. [CrossRef]
51. Toor, G.S.; Lusk, M. Reclaimed Water Use in the Landscape: Managing Salinity, Sodicity, and Specific Ions in Sites Irrigated with Reclaimed Water: SL340/SS545, 1/2011. *Ext. Data Inf. Source* **2011**, *2011*. [CrossRef]
52. Villacorta-Ranera, C.; Blanco-Gutiérrez, I.; Novo, P. Disentangling social perspectives on the use of reclaimed water in agriculture using Q methodology. *J. Environ. Manag.* **2025**, *381*, 125264. [CrossRef] [PubMed]
53. Ellis, S.F.; Ganguly, D.; Kecinski, M.; Messer, K.D. Back to the source: Consumers response to produce irrigated with different sources of recycled water. *Water Resour. Res.* **2023**, *59*, e2022WR033031. [CrossRef]
54. López-Serrano, M.J.; Velasco-Muñoz, J.F.; Aznar-Sánchez, J.A.; Román-Sánchez, I.M. Farmers' attitudes towards irrigating crops with reclaimed water in the framework of a circular economy. *Agronomy* **2022**, *12*, 435. [CrossRef]
55. Sunyer-Caldú, A.; Sepúlveda-Ruiz, P.; Salgot, M.; Folch-Sánchez, M.; Barcelo, D.; Diaz-Cruz, M.S. Reclaimed water in agriculture: A plot-scale study assessing crop uptake of emerging contaminants and pathogens. *J. Environ. Chem. Eng.* **2022**, *10*, 108831. [CrossRef]
56. Rahman, M.M.; Shahrivar, A.A.; Hagare, D.; Maheshwari, B.L. Impact of recycled water irrigation on soil salinity and its remediation. *Soil Syst.* **2022**, *6*, 13. [CrossRef]
57. Nicolás, E.; Romero Trigueros, C.; Nortes Tortosa, P.A.; Pedrero Salcedo, F.; Bayona Gambín, J.M.; Maestre Valero, J.F.; Alarcón Cabañero, J.J. Long-term physiological and agronomic responses of citrus irrigated with saline reclaimed water. In *Saline and Alkaline Water for Irrigation*; Academic Press: Cambridge, MA, USA, 2018; pp. 131–147.
58. Müller, K.; Cornel, P. Salt content of reclaimed water from sanitation facilities in informal settlements and management options for sustainable agricultural irrigation. *Water Pract. Technol.* **2015**, *10*, 99–109. [CrossRef]
59. Li, Y.; Xiao, J.; Yu, L.; Qin, D.; Cai, W.X.; Chen, X.M.; Ma, C.; Zhu, X.; Zhang, S.; Sun, Q. Impacts of reclaimed water irrigation on soil salinity, nutrient cycling, and landscape plant growth in a coastal monsoon environment. *Water* **2025**, *17*, 337. [CrossRef]
60. Ravina, I.; Gurovich, E. Exchange capacity of calcium and sodium soils as determined by different replacing cations. *Soil Sci. Soc. Am. J.* **1977**, *41*, 319–322.
61. Richter, D.D.; Johnson, D.W.; Dai, K.H. Cation exchange and Al mobilization in soils. In *Atmospheric Deposition and Forest Nutrient Cycling*; Johnson, D.W., Lindberg, S.E., Eds.; Springer: New York, NY, USA, 1992; pp. 341–377.

https://doi.org/10.3390/w18101141

62. Naylor, D.V.; Overstreet, R. Sodium-calcium exchange behavior in organic soils. *Soil Sci. Soc. Am. J.* **1969**, *33*, 848–851. [CrossRef]
63. Baruah, T.C.; Pal, R.; Poonia, S.; Siyag, R.S. Exchange equilibria of sodium versus calcium and potassium in some Aridisols. *J. Indian Soc. Soil Sci.* **1983**, *31*, 394–402.
64. Altland, J.E.; Locke, J.C.; Krause, C.R. Influence of pine bark particle size and pH on cation exchange capacity. *HortTechnology* **2014**, *24*, 554–559. [CrossRef]
65. Pietrzak, D.; Kania, J.; Kmiecik, E.; Wątor, K. Identification of transport parameters of chlorides in different soils on the basis of column studies. *Geologos* **2019**, *25*, 225–229. [CrossRef]
66. Svensson, T.; Kylin, H.; Montelius, M.; Sandén, P.; Bastviken, D. Chlorine cycling and the fate of Cl in terrestrial environments. *Environ. Sci. Pollut. Res.* **2021**, *28*, 7691–7709. [CrossRef]
67. Kauffman, S.J.; Royer, D.L.; Chang, S.; Berner, R.A. Export of chloride after clear-cutting in the Hubbard Brook sandbox experiment. *Biogeochemistry* **2003**, *63*, 23–33. [CrossRef]
68. Lovett, G.M.; Likens, G.E.; Buso, D.C.; Driscoll, C.T.; Bailey, S.W. The biogeochemistry of chlorine at Hubbard Brook, New Hampshire, USA. *Biogeochemistry* **2005**, *72*, 191–232. [CrossRef]
69. Whipker, B.E.; Bailey, D.A.; Nelson, P.V.; Fonteno, W.C.; Hammer, P.A. A novel approach to calculate acid additions for alkalinity control in greenhouse irrigation water. *Commun. Soil Sci. Plant Anal.* **1996**, *27*, 959–976. [CrossRef]
70. Haynes, R.J.; Swift, R.S. Effects of soil acidification on the chemical extractability of Fe, Mn, Zn and Cu and the growth and micronutrient uptake of highbush blueberry plants. *Plant Soil* **1985**, *84*, 201–212. [CrossRef]
71. Matkin, O.A.; Petersen, F.H. *Why and How to Acidify Irrigation Water*; Soil and Plant Laboratory Inc.: Orange, CA, USA, 1984.
72. Townsend, L.R. Effect of acidity on growth and nutrient composition of the highbush blueberry. *Can. J. Plant Sci.* **1971**, *51*, 385–390. [CrossRef]
73. Benjankar, R.; Kafle, R. Salt Concentration Measurement Using Re-usable Electric Conductivity-Based Sensors. *Water Air Soil Pollut.* **2021**, *232*, 13. [CrossRef]
74. Cañedo-Argüelles, M.; Hawkins, C.P.; Kefford, B.J.; Schäfer, R.B.; Dyack, B.; Brucet, S.; Buchwalter, D.B.; Dunlop, J.E.; Frör, O.; Lazorchak, J.M.; et al. Saving freshwater from salts. *Science* **2016**, *351*, 914–916. [CrossRef]
75. Talling, J.F. Electrical conductance: A versatile guide in freshwater science. *Freshw. Rev.* **2009**, *2*, 65–78. [CrossRef]
76. Hutton, P.; Sinha, A.; Roy, S.; Denton, R. A simplified approach for estimating ionic concentrations from specific conductance data in the San Francisco Estuary. *San Franc. Estuary Watershed Sci.* **2023**, *21*, 6. [CrossRef]
77. Hernández Bastida, J.A.; Vela de Oro, N.; Ortiz Silla, R. Electrolytic conductivity of semiarid soils (Southeastern Spain) in relation to ion composition. *Arid Land Res. Manag.* **2004**, *18*, 265–281. [CrossRef]
78. Ganesan, S.; De Zoysa, A.S.A.; Omoikhoje, I.D. Biochar for a sustainable future. In *Intelligent Technologies for Research and Engineering*; Advanced Technologies for Science and Engineering; Bentham Science Publisher: Singapore, 2024; Volume 2, pp. 213–218.
79. Mary, P.C.N.; Murugaragavan, R.; Ramachandran, J.; Karpagam, R.S.S. Biochar—A valuable soil amendment. *Biot. Res. Today* **2020**, *2*, 1058–1060.
80. Simfukwe, P.; Mwanaute, S.; Victor, B.; Chaiwa, C. Effect of Biochar on Soil Physical Properties, Growth Parameters and Yield of Soybeans on a Five-Year Fallow. *Afr. J. Agric. Res.* **2023**, *19*, 1121–1130. [CrossRef]
81. Amoriello, T.; Fiorentino, S.; Vecchiarelli, V.; Pagano, M. Evaluation of spent grain biochar impact on hop (*Humulus lupulus* L.) growth by multivariate image analysis. *Appl. Sci.* **2020**, *10*, 533. [CrossRef]
82. Rassaei, F. Biochar Enhances Rice Growth and Mitigates Total Petroleum Hydrocarbon Contamination in Soil: A Sustainable Approach for Crop Production. *Soil Sediment Contam.* **2025**, *34*, 326–351. [CrossRef]
83. Ziadi, N.; Tran, T.S. Lime requirement. In *Soil Sampling and Methods of Analysis*; Carter, M.R., Gregorich, E.G., Eds.; CRC Press: Boca Raton, FL, USA, 2007; p. 129.
84. Isimikalu, T.O. Biochar application in soil management systems. In *Biochar—Productive Technologies for a Sustainable Agriculture*; Bartoli, M., Giorcelli, M., Tagliaferro, A., Eds.; IntechOpen: London, UK, 2022; Chapter 6.
85. Amare, E.M. Biochar soil amendment: Effect on soil, crop performance, and diseases resistance. *Int. J. Food Agric. Nat. Resour.* **2023**, *4*, 82–87.
86. Kracmarova-Farren, M.; Alexova, E.; Kodatova, A.; Mercl, F.; Szakova, J.; Tlustos, P.; Stiborova, H. Biochar-induced changes in soil microbial communities: A comparison of two feedstocks and pyrolysis temperatures. *Environ. Microbiome* **2024**, *19*, 87. [CrossRef]
87. Guo, M.; Song, W. Agricultural applications of biochar. In *Interactions of Biochar and Herbicides in the Environment*; Mendes, K.F., Ed.; CRC Press: Boca Raton, FL, USA, 2022; pp. 1–22.
88. Zhang, W.; Pang, J.; Qi, J.; Lu, Y.; Liu, J.; Yu, M.; Li, H.; Wang, E.; Lambers, H. Biochar's Dual Impact on Soil Acidity Management and Crop Yield Enhancement in Acidic Soils: A Meta-Analysis. *Plant Soil* **2025**, *514*, 1849–1865. [CrossRef]
89. Medyńska-Juraszek, A. Biochar as a soil amendment. *Soil Sci. Annu.* **2016**, *67*, 151–157. [CrossRef]

https://doi.org/10.3390/w18101141

90. Sales, B.K.; Bryla, D.R.; Trippe, K.M.; Weiland, J.E.; Scagel, C.F.; Strik, B.C.; Sullivan, D.M. Amending sandy soil with biochar promotes plant growth and root colonization by mycorrhizal fungi in highbush blueberry. *HortScience* **2020**, *55*, 353–361. [CrossRef]
91. Sales, B.K.; Bryla, D.R.; Trippe, K.M.; Scagel, C.F.; Strik, B.C.; Sullivan, D.M. Biochar as an alternative soil amendment for establishment of northern highbush blueberry. *HortScience* **2022**, *57*, 277–285. [CrossRef]
92. Mukherjee, A.; Zimmerman, A.R.; Hamdan, R.; Cooper, W.T. Physicochemical changes in pyrogenic organic matter (biochar) after 15 months of field aging. *Solid Earth* **2014**, *5*, 693–704. [CrossRef]
93. Mia, S.; Dijkstra, F.A.; Singh, B. Aging induced changes in biochar's functionality and adsorption behavior for phosphate and ammonium. *Environ. Sci. Technol.* **2017**, *51*, 8359–8367. [CrossRef] [PubMed]
94. Cao, T.; Chen, W.; Yang, T.; He, T.; Liu, Z.; Meng, J. Surface characterization of aged biochar incubated in different types of soil. *BioResources* **2017**, *12*, 6366–6377. [CrossRef]
95. Huang, L.; Gu, M. Effects of biochar on container substrate properties and growth of plants—A review. *Horticulturae* **2019**, *5*, 14. [CrossRef]
96. Mancinelli, E.; Baltrėnaitė, E.; Baltrėnas, P.; Marčiulaitienė, E.; Passerini, G. Dissolved organic carbon content and leachability of biomass waste biochar for trace metal (Cd, Cu and Pb) speciation modelling. *J. Environ. Eng. Landsc. Manag.* **2017**, *25*, 354–366. [CrossRef]
97. Tang, J.; Cao, C.; Gao, F.; Wang, W. Effects of biochar amendment on the availability of trace elements and the properties of dissolved organic matter in contaminated soils. *Environ. Technol. Innov.* **2019**, *16*, 100492. [CrossRef]
98. Uchimiya, M. Influence of pH, ionic strength, and multidentate ligand on the interaction of Cd(II) with biochars. *ACS Sustain. Chem. Eng.* **2014**, *2*, 2019–2027. [CrossRef]
99. Wagner, A.; Kaupenjohann, M. Biochar addition enhanced growth of *Dactylis glomerata* L. and immobilized Zn and Cd but mobilized Cu and Pb on a former sewage field soil. *Eur. J. Soil Sci.* **2015**, *66*, 505–515.
100. Atanassova, I.; Nenova, L.; Simeonova, T.; Benkova, M.; Harizanova, M.; Ilinkin, V. Effect of biochar on heavy metal solubility and speciation in technogenic soils around Aurubis-Pirdop copper smelter in Bulgaria. *Res. Sq.* **2023**, *preprint*.
101. Hashem, M.S.; Qi, X. Treated Wastewater Irrigation—A Review. *Water* **2021**, *13*, 1527. [CrossRef]
102. Hoogendijk, K.; Myburgh, P.A.; Howell, C.L.; Hoffman, J.E. Irrigation of Agricultural Crops with Municipal Wastewater—A Review. *S. Afr. J. Enol. Vitic.* **2023**, *44*, 31–54. [CrossRef]
103. Bañón, S.; Miralles, J.; Ochoa, J.; Franco, J.A.; Sánchez-Blanco, M.J. Effects of diluted and undiluted treated wastewater on the growth, physiological aspects and visual quality of potted lantana and polygala plants. *Sci. Hortic.* **2011**, *129*, 869–876. [CrossRef]
104. Bakshi, S.; He, Z.; Harris, W.G. Biochar amendment affects leaching potential of copper and nutrient release behavior in contaminated sandy soils. *J. Environ. Qual.* **2014**, *43*, 1894–1902. [CrossRef]
105. Nepal, J.; Ahmad, W.; Munsif, F.; Khan, A.; Zou, Z. Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications. *Front. Environ. Sci.* **2023**, *11*, 1114752. [CrossRef]
106. Bolan, S.; Sharma, S.; Mukherjee, S.; Kumar, M.; Rao, C.S.; Nataraj, K.C.; Singh, G.; Vinu, A.; Bhowmik, A.; Sharma, H.; et al. Biochar Modulating Soil Biological Health: A Review. *Sci. Total Environ.* **2024**, *914*, 169585. [CrossRef]
107. Mustafa, A.; Holátko, J.; Hammerschmiedt, T.; Kučerík, J.; Kintl, A.; Baltazár, T.; Malíček, O.; Brtnický, M. The Role of Biochar Co-Pyrolyzed with Sawdust and Zeolite on Soil Microbiological and Physicochemical Attributes, Crop Agronomic, and Ecophysiological Performance. *J. Soil Sci. Plant Nutr.* **2023**, *23*, 4899–4911. [CrossRef]
108. Wang, Z.; Poudyal, S.; Kopp, K.; Zhang, Y. Response of Ornamental Plants to Salinity: Impact on Species-Specific Growth, Visual Quality, Photosynthetic Parameters, and Ion Uptake. *Front. Plant Sci.* **2025**, *16*, 1611767. [CrossRef]
109. Liang, Y.; Cao, X.; Zhao, L.; Arellano, E.C. Biochar- and phosphate-induced immobilization of heavy metals in contaminated soil and water: Implication on simultaneous remediation of contaminated soil and groundwater. *Environ. Sci. Pollut. Res.* **2014**, *21*, 4665–4674. [CrossRef]
110. Gu, Y.; Tan, X.; Cai, X.; Liu, S. Remediation of As and Cd contaminated sediment by biochars: Accompanied with the change of microbial community. *J. Environ. Chem. Eng.* **2022**, *10*, 106912. [CrossRef]
111. Schweiker, C.; Wagner, A.; Peters, A.; Bischoff, W.-A.; Kaupenjohann, M. Biochar reduces zinc and cadmium but not copper and lead leaching on a former sewage field. *J. Environ. Qual.* **2014**, *43*, 1886–1893. [CrossRef] [PubMed]
112. Barčauskaitė, K.; Anne, O.; Mockevičienė, I.; Repšienė, R.; Šiaudinis, G.; Karčauskienė, D. Determination of heavy metals immobilization by chemical fractions in contaminated soil amended with biochar. *Sustainability* **2023**, *15*, 8677. [CrossRef]
113. Ullah, S. The Effects of Zinc and Copper Stress on Plant Growth and Quality. Ph.D. Thesis, Vytautas Magnus University and Lithuanian Research Centre for Agriculture and Forestry, Kaunas, Lithuania, 2025.
114. Naruethanan, T.; Tantikul, S.; Wongsiriamnuay, T.; Khamdaeng, T.; Tippayawong, N.; Panyoyai, N. Energy efficiency and economic analysis of a biochar production system. *AIP Conf. Proc.* **2022**, *2681*, 020047. [CrossRef]

115. You, S.; Wang, X. On the Carbon Abatement Potential and Economic Viability of Biochar Production Systems: Cost-Benefit and Life Cycle Assessment. In *Biochar from Biomass and Waste: Fundamentals and Applications*; Ok, Y.S., Tsang, D.C.W., Bolan, N., Novak, J.M., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 385–408. [CrossRef]
116. González-Pernas, F.M.; Grajera-Antolín, C.; García-Cámara, O.; González-Lucas, M.; Martín, M.T.; González-Egido, S.; Aguirre, J.L. Effects of biochar on biointensive horticultural crops and its economic viability in the Mediterranean climate. *Energies* **2022**, *15*, 3407. [CrossRef]
117. Fryda, L.; Visser, R.; Schmidt, J. Biochar replaces peat in horticulture: Environmental impact assessment of combined biochar and bioenergy production. *Detritus* **2019**, *5*, 132–149. [CrossRef]
118. Tang, Y.; Li, Y.; Cockerill, T.T. Environmental and economic spatial analysis system for biochar production—Case studies in the East of England and the East Midlands. *Biomass Bioenergy* **2024**, *184*, 107187. [CrossRef]
119. Lentini, M.; Ciriello, M.; Rouphael, Y.; Campana, E.; Vaccari, F.P.; De Pascale, S. Harnessing biochar for sustainable horticulture: Strategies to cope with abiotic stress. *Horticulturae* **2025**, *11*, 73. [CrossRef]
120. Barbosa Junior, M.; Pinheiro, E.; Sokulski, C.C.; Ramos Huarachi, D.A.; de Francisco, A.C. How to identify barriers to the adoption of sustainable agriculture? A study based on a multi-criteria model. *Sustainability* **2022**, *14*, 13277. [CrossRef]
121. Canaj, K.; Mehmeti, A. Unveiling drivers and barriers in advancing agricultural wastewater reuse in Southern Italy: A SWOT analysis informed by stakeholder insights. *Clean. Water* **2024**, *1*, 100008. [CrossRef]
122. Rizzo, G.; Migliore, G.; Schifani, G.; Vecchio, R. Key factors influencing farmers' adoption of sustainable innovations: A systematic literature review and research agenda. *Org. Agric.* **2024**, *14*, 57–84. [CrossRef]
123. Ventura, D.; Consoli, S.; Barbagallo, S.; Marzo, A.; Vanella, D.; Licciardello, F.; Cirelli, G.L. How to overcome barriers for wastewater agricultural reuse in Sicily (Italy)? *Water* **2019**, *11*, 335. [CrossRef]
124. Kheiri, S. Identifying the barriers of sustainable agriculture adoption by wheat farmers in Takestan, Iran. *Int. J. Agric. Manag. Dev.* **2015**, *5*, 159–168. [CrossRef]
125. Ballesteros-Olza, M.; Blanco-Gutiérrez, I.; Esteve, P.; Gómez-Ramos, A.; Bolinches, A. Using reclaimed water to cope with water scarcity: An alternative for agricultural irrigation in Spain. *Environ. Res. Lett.* **2022**, *17*, 125002. [CrossRef]
126. Mesa-Pérez, E.; Berbel, J. Analysis of barriers and opportunities for reclaimed wastewater use for agriculture in Europe. *Water* **2020**, *12*, 2308. [CrossRef]
127. Kareska, K. Challenges and Strategic Solutions for Sustainable Agriculture. *SSRN Electron. J.* **2024**. [CrossRef]
128. Bhujel, R.R.; Joshi, H.G. Factors influencing the adoption of sustainable agricultural practices in rural regions of developing countries: A review. *Food Res.* **2024**, *8*, 81–89. [CrossRef]
129. Kalariya, B.S.; Gulkari, K.D.; Dohat, M.P.; Rathod, N.K. Factors influencing farmer adoption in problematic soil reclamation practices: A comprehensive review. *Annu. Res. Rev. Biol.* **2024**, *39*, 57–62. [CrossRef]
130. Aznar-Sánchez, J.A.; Velasco-Muñoz, J.F.; López-Felices, B.; del Moral-Torres, F. Barriers and facilitators for adopting sustainable soil management practices in Mediterranean olive groves. *Agronomy* **2020**, *10*, 506. [CrossRef]
131. Rodriguez, J.M.; Molnar, J.J.; Fazio, R.A.; Sydnor, E.; Lowe, M.J. Barriers to adoption of sustainable agriculture practices: Change agent perspectives. *Renew. Agric. Food Syst.* **2009**, *24*, 60–71. [CrossRef]