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Saline Agriculture 3.0: reframing salinity for nutritional and quality-driven food value creation

Xudong ZHANG (✉)[1], Lin WANG[2], Lidong REN[3], Christoph-Martin GEILFUS[4], Xuexian LI[5], Fusuo ZHANG[5], Christian ZÖRB[1]

1 Institute of Crop Science, Quality of Plant Products (340e), University of Hohenheim, Otto-Sander-Straße 5, 70599, Stuttgart, Germany.
2 State Key Laboratory of Efficient Utilization of Arable Land in China, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China.
3 Modern Agricultural Engineering Laboratory, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China.
4 Department of Soil Science and Plant Nutrition, Hochschule Geisenheim University, Von-Lade-Straße 1, 65366, Geisenheim, Germany.
5 State Key Laboratory of Nutrient Use and Management, National Academy of Agriculture Green Development, College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China.

KEYWORDS

Agrifood chain, functional foods, nutritional quality, Saline Agriculture 3.0, saline-derived foods, soil salinity, value-chain innovation

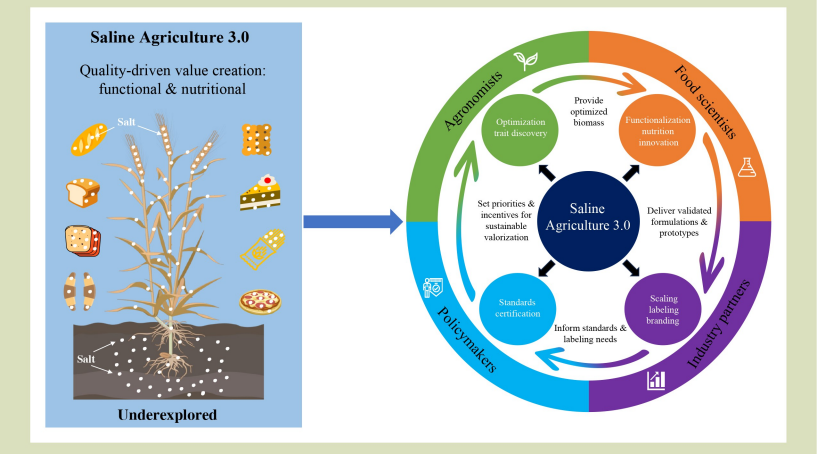
HIGHLIGHTS

- Saline Agriculture 3.0 reframes salinity from a constraint into a food value source.
- Substantial yield recovery can be achieved under moderate salinity.
- Paired yield-quality data revealed three distinct crop-salinity response configurations.
- The hypothetical model, SaltGrain, links starch-sodium interactions to saltiness perception.
- Economic outcomes of Saline Agriculture 3.0 require multistakeholder value-chain integration.

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Correspondence:
xudong.zhang@uni-hohenheim.de

GRAPHICAL ABSTRACT



ABSTRACT

Saline agriculture is increasingly important for sustaining food production on salt-affected land under climate change. This paper proposes Saline Agriculture 3.0, a three stage framework that reframes salinity from a constraint to be overcome into a potential source of nutritional, functional and product value. Building on the first two stages, soil restoration and yield resilience, Saline Agriculture 3.0 matches salinity-responsive crop traits with specific food and market applications. A quantitative yield landscape across wheat, maize, rice and barley identifies conditions where sufficient yields can be maintained under salinity. Across cereals and horticultural crops, salinity-responsive changes in mineral composition, carbohydrates, proteins and bioactive

compounds reveal opportunities for nutritional quality and nutrient-related value. These responses are further considered through food-safety and risk-assessment perspectives, including yield trade-offs, quality reproducibility, resource efficiency and potential risks associated with saline production. The hypothetical model, SaltGrain, illustrates a prospective pathway linking salinity-associated sodium accumulation with starch functionality and saltiness perception, potentially enabling reduced sodium addition in food formulations. Together, these elements establish a framework for exploring new food products and ingredients derived from salinity-responsive crops, while identifying when such quality traits can generate value and contribute to more sustainable and resource-efficient agrifood systems under environmental constraints.

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1 Saline agriculture: challenge and opportunity

Soil salinity represents a major form of land degradation driven by natural processes, including seawater intrusion in coastal regions[1], sea level rise[2], intensified evaporation in arid and semiarid areas, and limited salt leaching[3–5]. Human activities, particularly inappropriate irrigation and salt contamination from anthropogenic sources, further accelerate salinization[6,7]. Currently, soil salinization is transforming vast areas of productive agricultural land into low-yield or unproductive landscapes[8]. More importantly, this trend is expected to intensify under climate change, creating an increasing challenge for global food production[9].

Beyond reducing yield, salinity disrupts plant growth through osmotic stress, ion toxicity and nutrient imbalance at cellular and whole-plant scales[10,11]. These constraints threaten food security not only through harvest losses but also through compromised crop nutritional quality, potentially exacerbating hidden hunger in vulnerable populations[12,13]. The impacts extend beyond agriculture, affecting livelihoods, freshwater availability and socioeconomic stability[1]. The global extent of this challenge is substantial. Recent assessments (as of 2021) covering 118 countries (85% of global land area) indicate that more than 424 Mha of topsoil (0–30 cm) and 833 Mha of subsoil (30–100 cm) are salt-affected, with annual economic losses estimated to exceed 27 billion USD[8,14]. However, current strategies remain largely focused on either soil reclamation or improving salt tolerance, leaving an underexplored opportunity: transforming saline environments from a constraint into a platform for sustainable and value-oriented food production.

Here, we propose a three-stage framework for the evolution of saline agriculture (Fig. 1). Saline Agriculture 1.0 focuses on restoring soil functionality via physicochemical and biological amelioration, creating a viable root environment. Saline Agriculture 2.0 shifts from modifying soils to improving crop performance by integrating genetic modifications with precise agronomic management to stabilize and increase yield under saline conditions[16–18]. Saline Agriculture 3.0 moves beyond yield optimization toward quality-oriented production, leveraging stress-responsive physiological and metabolic traits, including altered ion homeostasis and nutrient distribution. The aim is to generate nutritionally enhanced and higher value-added products while ensuring that quality benefits outweigh potential yield, resource and safety trade-offs. These three stages represent complementary objectives, with the third stage building on the soil management and yield resilience established in the first two stages.

As global agriculture has the challenge of feeding more than 9 billion people, the goal of saline agriculture should extend beyond maintaining crop survival or maximizing yield alone. Instead, it should optimize the balance among productivity, nutritional quality, environmental sustainability, and socioeconomic value[19]. This review repositions saline agriculture from a remediation-oriented approach into a future food system capable of contributing to both food and nutrition security.

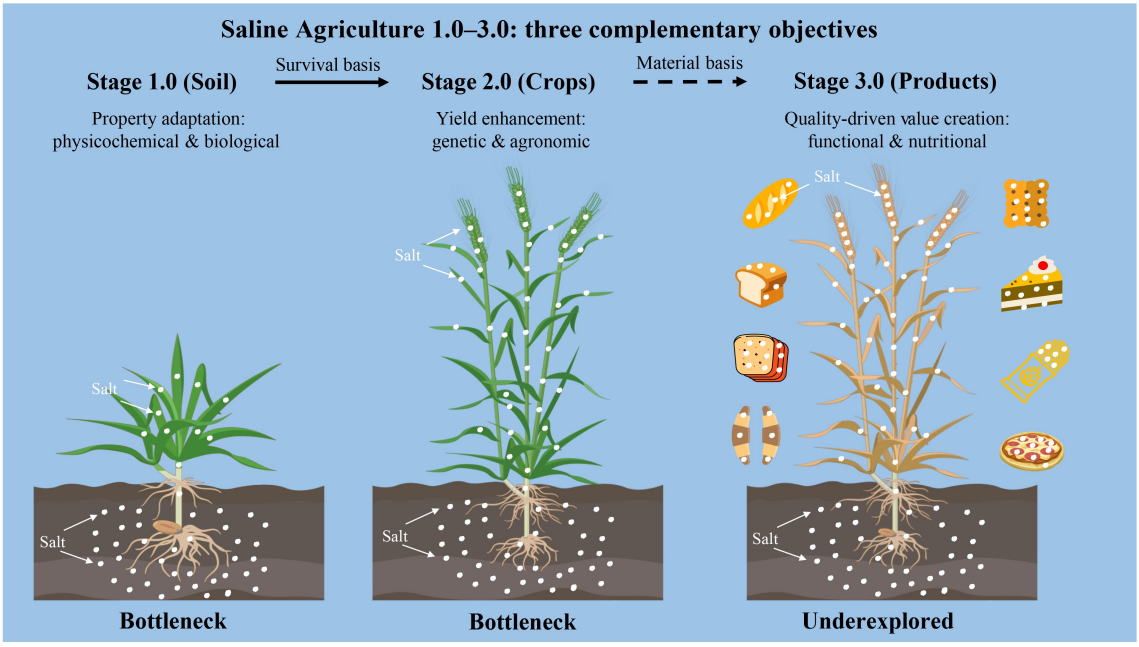


Fig. 1 A three-stage framework transforming saline agriculture from yield-centric resilience to quality-driven value creation. Saline agriculture is re-envisioned through a progressive framework encompassing three interconnected and complementary stages. Saline Agriculture 1.0 (soil adaptation): establishes the foundation by alleviating soil ion imbalance and osmotic constraints through physicochemical and biological approaches, enabling crop establishment. Saline Agriculture 2.0 (crop yield enhancement): integrates genetic and agronomic strategies to improve productivity under saline conditions, while facing inherent yield limitations. Saline Agriculture 3.0 (quality-driven value creation): shifts the focus from survival and yield optimization toward the production of functionally and nutritionally enhanced crops, leveraging salinity-induced traits to create value-added food systems. The icons of soils and plants were created using Generic Diagramming Platform (GDP)[15].

2 Saline Agriculture 1.0: soil amelioration to engineer the foundation

Saline Agriculture 1.0 concentrates on restoring degraded soils by directly modifying the physicochemical and biological properties that restrict crop survival (Fig. 1). Physical measures reduce soil salinity through hydraulic interventions, including leaching, surface drainage and subsurface engineering, such as drainage pipes and vertical wells, which collectively lower the water table and facilitate salt removal[20]. Chemical approaches primarily target sodicity and nutrient imbalance. Calcium-based amendments, such as gypsum, promote cation exchange by replacing exchangeable Na^+ with Ca^{2+}, facilitating soil aggregation, improving soil structure and further enhancing water infiltration and aeration[21]. Organic amendments, including compost and biochar, act through both physical and chemical pathways. They improve soil structure and water retention while simultaneously increasing cation exchange capacity, organic carbon content and microbial activity[22,23]. Together, these solutions rebuild the physical structure and fertility of salt-affected soils, creating a more favorable environment for root establishment.

Biological approaches complement physicochemical restoration by harnessing ecosystem processes to gradually mitigate salinity. Deep-rooted plants can function as biological pumps that access deeper water sources, lower local water tables and reduce upward salt transport through capillary movement[24]. Their root systems also generate biopores[25], enhance carbon inputs[26] and stimulate microbial processes that support soil aggregation and nutrient cycling[27]. In addition, cover crops and microbial inoculation can increase microbial diversity, strengthen ecological networks and

improve soil resilience under saline stress[28]. Together, these approaches enhance soil biological fertility and microbiome functioning, increasing the capacity of soils to buffer and mitigate the negative impacts of salinity.

Despite these advances, Saline Agriculture 1.0 has inherent scalability constraints. Physicochemical remediation requires substantial material inputs, energy investment, and infrastructure, limiting its application across large and heterogeneous saline landscapes. Biological restoration, although more sustainable, generally operates on ecological timescales that may not match the urgent demand for food production. More essentially, improving soil conditions alone cannot fully overcome the physiological limitations of crops exposed to persistent salinity. Therefore, the next transition requires shifting from engineering soils to accommodate crops toward tolerating saline environments, marking the emergence of Saline Agriculture 2.0.

3 Saline Agriculture 2.0: crop yield enhancement by genetic and agronomic strategies

Once soil environments are stabilized to support crop survival, the next challenge is to enhance grain production under saline conditions. Two complementary approaches have been widely explored (Fig. 1). Genetic approaches improve intrinsic salt tolerance through crossbreeding, mutation breeding, transgenic modification and targeted genome editing[29], including CRISPR/Cas9-mediated regulation of salt-responsive genes such as bZIP49[30] and ZmHAK4[31], overexpression of transport-related genes such as SOS1[32,33] and engineering of protective metabolic pathways such as dimethyl sulfoniopropionate[34]. A field-based example illustrates the potential of this strategy, where introgression of the ancestral HKT1:5 sodium transporter into durum wheat enhanced Na^+ exclusion from shoots and increased grain yield by about 25% under moderate salinity[13,17]. Agronomic approaches enhance crop performance by optimizing crop-soil-environment interfaces[35] through improved irrigation and nutrient use[18,36], application of biostimulants or nanocarriers[37], soil amendments[38] and diversified crop rotations[39].

To provide a quantitative overview of yield outcomes under saline field conditions, we extracted reported grain yields of the four main cereal crops (wheat, maize, rice and barley) from 35 studies (Table S1). For this analysis, saline conditions were defined as electrical conductivity of the saturated soil paste extract (ECe) of $\geqslant$ 4 dS·m^{-1}, with 4 $\leqslant$ ECe < 8 dS·m^{-1} representing moderate and 8 $\leqslant$ ECe $\leqslant$ 16 dS·m^{-1} representing high salinity. The surveyed studies included both genetic and agronomic approaches, and we summarized yield ranges and arithmetic means by crop and strategy and compared them descriptively with global average yield references[40] (Table 1). Given the descriptive nature of these data, the following conditional breakdowns by salinity level are presented to identify crop-specific response patterns rather than to compare strategies directly. Under moderate salinity, the mean paired relative difference for agronomic management was 22.6% in wheat, 46.8% in maize, 41.7% in rice and 17.2% in barley. Under high salinity, the corresponding values were 23.5%, 57.5%, 73.7% and 9.9%, respectively, although the available evidence was uneven among crops and strategies. Genetic approaches showed variable responses under moderate salinity, with mean paired relative differences of 10.0% in wheat, 55.5% in rice and 572.3% in barley. The extreme barley value (572%) arose from an unusually low wild-type control (0.19 t·ha^{-1}) against transgenic lines overexpressing the *Arabidopsis* vacuolar H^+-pyrophosphatase gene, which yielded 0.89–1.47 t·ha^{-1} (Table 1 and Table S1)[41], illustrating the sensitivity of relative percentages to low control values. No genetic data were available for maize at this salinity level. Under high salinity, genetic approaches had mean paired relative differences of 21.9% in wheat, 24.2% in maize and 27.1% in rice, whereas no genetic data were available for barley.

Under moderate salinity, mean agronomic yields approached or exceeded the global average yield references for wheat (4.24 vs 3.64 t·ha^{-1}), maize (6.06 vs 5.80 t·ha^{-1}), rice (4.77 vs 4.76 t·ha^{-1}) and barley (3.92 vs 3.22 t·ha^{-1}). Under high salinity, agronomic yields remained above the corresponding references for wheat (3.76 t·ha^{-1}), rice (6.38 t·ha^{-1}) and barley (4.18 t·ha^{-1}), whereas maize yield declined to 2.11 t·ha^{-1}. Overall, these descriptive patterns indicate that agronomic management showed positive mean paired relative differences across the four crops under both moderate and high salinity, while genetic approaches showed more variable responses. This quantitative yield landscape provides a basis for asking where yield resilience can be coupled with quality-oriented value creation. Given that the underlying studies differ in genotypes, environments, salinity levels and management practices, these values are descriptive summaries rather than statistically comparable treatment effects.

Table 1 Descriptive summary of absolute grain yields under saline field conditions for four dominant cereal crops, with global average yield references

Crop	References (t·ha^{-1})	ECe (dS·m^{-1})	Strategy	*n*	*k*	Range (t·ha^{-1})	Mean (t·ha^{-1})	Increase (%)
Wheat	3.64	4–8	Genetic	3	11	1.24–6.65	4.15	10.0
		4–8	Agronomic	10	58	1.50–8.12	4.24	22.6
		8–16	Genetic	3	12	1.02–4.43	2.82	21.9
		8–16	Agronomic	5	24	1.95–5.86	3.76	23.5
Maize	5.80	4–8	Agronomic	6	41	4.27–9.58	6.06	46.8
		8–16	Genetic	1	4	2.86–3.03	2.93	24.2
		8–16	Agronomic	1	1	2.11–2.11	2.11	57.5
Rice	4.76	4–8	Genetic	1	11	0.62–2.68	1.75	55.5
		4–8	Agronomic	5	21	3.22–6.80	4.77	41.7
		8–16	Genetic	1	8	7.60–7.90	7.75	27.1
		8–16	Agronomic	2	20	2.75–8.16	6.38	73.7
Barley	3.22	4–8	Genetic	1	4	0.89–1.47	1.26	572.3
		4–8	Agronomic	2	20	2.35–5.54	3.92	17.2
		8–16	Agronomic	1	12	3.69–4.61	4.18	9.9

Note: Genetic strategies include genetic engineering approaches, including transgenic modification and targeted gene editing, mutation breeding and crossbreeding for the development of salt-tolerant varieties. Agronomic strategies include biochar application, fertilization, chemical and organic amendments, microbial inoculation, biostimulants, water and irrigation management, and practices such as mulching and tillage. Values represent arithmetic means and observed ranges extracted from a literature survey of published saline field studies conducted using the Web of Science database and updated to 23 June 2026. Study identification and selection followed a systematic search and screening process (Fig. S1), with two parallel search strategies used to identify field studies addressing genetic and agronomic interventions. The dataset comprised 35 studies with soil salinity (ECe) of 4–16 dS·m^{-1}, with $4 \leqslant ECe < 8$ dS·m^{-1} representing moderate and $8 \leqslant ECe \leqslant 16$ dS·m^{-1} representing high salinity. The source studies listed in Table S1. The values are presented solely as a descriptive summary of reported grain yields. The studies encompassed diverse crop genotypes, salinity levels, field environments and management practices, and therefore should not be interpreted as statistically comparable estimates or causal effects between strategies. No statistical comparisons or inferential analyses were performed. The number of studies is given as *n* and the number of matched treatment-control pairs as *k*. Range represents the minimum to maximum reported treatment yield. Increase (%) represents the mean relative difference across matched treatment-control pairs, calculated for each pair as (treatment yield – corresponding control yield) / corresponding control yield × 100 and then averaged across all matched pairs. Global average yield references are from FAOSTAT (2024)[40].

Importantly, yield resilience is an important but not the final milestone for saline agriculture. The quantitative evidence above identifies a measurable production space in which sufficient grain yields can be maintained under salinity, particularly through agronomic management. Across all four cereals under moderate salinity and for wheat, rice and barley under high salinity, mean yields remained at or above global average yield references. Genetic and agronomic strategies therefore represent complementary routes to establishing this production baseline, although their deployment constraints may differ. Within genetic strategies, crossbreeding and selection of salt-tolerant genotypes can be broadly integrated into crop improvement, whereas transgenic and genome-editing approaches may be subject to additional regulatory, environmental, political and consumer-acceptance considerations that vary across countries and markets. Thus, yield performance alone does not determine the scalability or broader system value of a strategy. Nevertheless, this production baseline creates the material basis for Saline Agriculture 3.0, which moves beyond yield preservation toward quality-oriented value creation. The next challenge is therefore to determine where quality enhancement can be integrated with yield resilience to generate nutritional, functional or economic value under saline conditions.

4 Saline Agriculture 3.0: product valorization for a quality-driven market framework

The yield landscape established above defines the production baseline for Saline Agriculture 3.0, where sufficient grain production can be maintained under salinity. Thus, the

objective can extend beyond yield preservation toward product quality and value creation. Saline Agriculture 3.0 focuses on the valorization of crops produced on already salt-affected land or with constrained-quality water, rather than deliberately introducing salinity into productive agricultural systems. Rather than treating salinity solely as a constraint to be overcome, Saline Agriculture 3.0 considers how saline environments can be managed to generate differentiated nutritional, functional, and market attributes while maintaining adequate production. This shift reframes salinity from a stress condition requiring compensation into a potential source of product differentiation, provided that quality gains are achieved without disproportionate yield, resource, food-safety or environmental costs.

4.1 Salinity-responsive quality traits for product valorization

Yield resilience provides the production basis for valorization but the value proposition of Saline Agriculture 3.0 depends on whether salinity can generate reproducible quality traits that enable differentiated food applications. A salinity-induced change should not be judged simply as an increase or decrease in quality parameters, since quality depends on the desired product and end use. For example, variation in wheat grain protein can support different applications from bread to biscuits and cakes, while changes in starch properties can determine suitability for specific processing applications. In horticultural crops, variation in chili pepper pungency or in soluble solids, acidity and pigments in fruits and vegetables can differentiate fresh-market, processing or functional food applications. Thus, Saline Agriculture 3.0 seeks to match salinity-responsive traits with specific product requirements rather than maximize a universal quality index.

Evidence across cereals and horticultural crops indicates that saline environments can alter multiple quality dimensions, including carbohydrate composition, protein functionality, nutritional metabolites, bioactive compounds and sensory-related attributes[42–48]. In cereals, salinity can modify starch accumulation, amylose content, granule structure and processing properties, including pasting and gelatinization behavior, while changes in starch molecular structure may also influence resistant starch formation and enzymatic digestibility[44–46]. This evidence is consistent with the concept of stressed starch, referring to starch with altered physicochemical and functional properties resulting from environmental stress during crop cultivation[49]. Related concepts of nutrient starch and stressed nutrient starch further recognize the influence of nutrient management and environmental conditions, including salt stress, on starch properties[42]. These concepts describe specific stress- or nutrition-responsive starch traits, whereas Saline Agriculture 3.0 extends this perspective from trait response to product valorization. It connects salinity-responsive traits with yield conditions and specific end-use requirements to identify potential food and market value. Salinity can likewise alter protein accumulation and composition. For example, rice grown under elevated salinity (soil ECe $\geqslant$4 dS·m^{-1}) was found to have increased total protein content, reaching about 11% at 6 dS·m^{-1}, associated with enhanced accumulation of prolamin and glutelin storage proteins[50–52]. In wheat, salinity systematically alters protein composition by increasing the gliadin-to-glutenin ratio and modifying high-molecular-weight glutenin subunits[53]. Such changes may create distinct opportunities for product optimization. A higher gliadin-to-glutenin ratio and weaker glutenin strength can favor more extensible doughs suited to cookies and biscuits[54], whereas preserved HMW-GS and stronger glutenin networks support bread-making properties, such as dough strength and loaf volume[55].

This principle extends beyond cereal grains to vegetables and fruits[47,48]. In tomato, moderate salinity has been reported to increase lycopene, sugars, vitamin C, total soluble solids, titratable acidity and organic acid accumulation[56]. In chili pepper, salinity can enhance capsaicinoid biosynthesis and flavor-related capsaicin and dihydrocapsaicin accumulation in roots, leaves and fruits[57]. In eggplant, salinity elevates anthocyanin content through activation of phenylpropanoid pathways[58]. Comparable salinity-driven enrichment of polyphenols, flavonoids and antioxidant activity has been reported in leafy vegetables[59], while legumes can have an increase in isoflavones[60]. Given that these quality responses depend on salinity intensity and genotype, they may enable the development of contrasting quality profiles intended for specific end uses. Since quality traits are often reported as concentrations, an increase in concentration does not necessarily indicate greater production of the constituent per unit land when edible yield declines. The reporting basis (e.g., fresh or dry weight) should also be considered when interpreting nutritional value.

These responses illustrate a broader principle. Saline

agriculture need not be to eliminate every physiological consequence of salinity, but to identify crop-genotype-salinity combinations in which specific responses translate into desirable and market-relevant product attributes. The opportunity therefore lies not in a universal beneficial effect of salt, but in targeted quality diversification, where a manageable yield baseline is combined with a reproducible trait that creates nutritional, functional, processing, sensory or economic value. The magnitude and desirability of these responses remain context dependent, making trait-specific characterization and product-oriented evaluation essential for determining which saline production systems can generate genuine added value. Such evaluation is equally important for identifying cases where quality gains are insufficient to justify the associated yield, resource or safety trade-offs.

4.2 SaltGrain as a hypothesized case: starch-salt interactions and salt perception

Among these quality opportunities, starch provides an illustrative case for how salinity-responsive grain traits could be translated into a differentiated food function. In this sense, the plant Na^+/K^+ balance connects mechanisms of salinity adaptation with downstream food quality and human health considerations[43,61]. Standard starch-salt systems typically introduce sodium externally after starch formation, whereas saline-grown grains develop starch under elevated ionic conditions. Salinity can substantially increase sodium accumulation in cereal grains. For example, Na^+ concentrations in wheat grains have been reported to increase by about thirtyfold relative to non-saline controls[62]. Independent imaging evidence from shoot bases of common reed[63] and leaf chloroplasts of *Vigna riukiuensis*[64] further reveals spatial co-localization of starch and Na^+ under salt stress, detected by confocal laser scanning microscopy and energy dispersive X-ray spectroscopy, respectively, and accompanied by simultaneous increases in starch and ion accumulation. These observations suggest that starch-associated functional groups, potentially including inherent phosphate groups, may contribute to Na^+ association within plant tissues[63]. Whether comparable ion-starch interactions develop in saline-grown grains, and whether they subsequently influence sodium retention or release during food consumption, remains unknown. The *in vivo* evidence given above therefore provides the basis for the SaltGrain (namely grains cultivated under salt stress)[43] hypothesis, with salinity-induced increases in amylose content and a proposed endogenous ion-starch association during grain development (Fig. 2(a)). Preliminary evidence from cereal crops, including triticale[65] and maize[66], further indicates that salinity may increase grain amylose content, providing initial support for this proposed starch response. This proposed pathway remains to be tested at the grain and food-product levels.

Independent *in vitro* evidence provides a complementary experimental basis for considering this possibility (Fig. 2(b)). In starch-salt model systems, high amylose starch exhibits greater initial and in-mouth saltiness perception than normal and waxy starches[67], providing experimental evidence that starch amylose content is associated with differences in saltiness perception[68]. These *in vitro* starch-salt mixing experiments represent a system in which sodium is externally introduced to starch, providing a model for examining starch-salt effects on saltiness perception. However, these model systems do not reproduce the ionic environment or structural development of saline-grown grain. Thus, the available evidence supports the plausibility of a starch-sodium-sensory pathway but does not yet establish that salinity-induced starch remodeling enhances salt perception in food products. Direct characterization of ion-starch interactions, sodium release during digestion and oral processing, and sensory responses in saline-grown grain products will be required to test this hypothesis. If validated, this mechanism could establish a basis for developing saline-derived grain products in which altered starch-salt interactions contribute to salt perception. Such a mechanism could potentially deliver the saltiness that consumers expect with less added salt.

Importantly, reduced added-salt requirements do not necessarily translate into reduced total sodium in the finished product, because saline-grown grain may already contain elevated endogenous sodium. The relevant question is therefore whether a product made from saline-grown grain can achieve acceptable saltiness at a lower total sodium content than a comparable product made from non-saline grain. Testing this would require at least two comparisons: sensory responses at equal total sodium and total sodium at equal perceived saltiness. Comparisons with non-saline grain, starch composition-matched materials, and externally sodium-matched formulations would help distinguish a starch-mediated mechanism from an ordinary formulation effect.

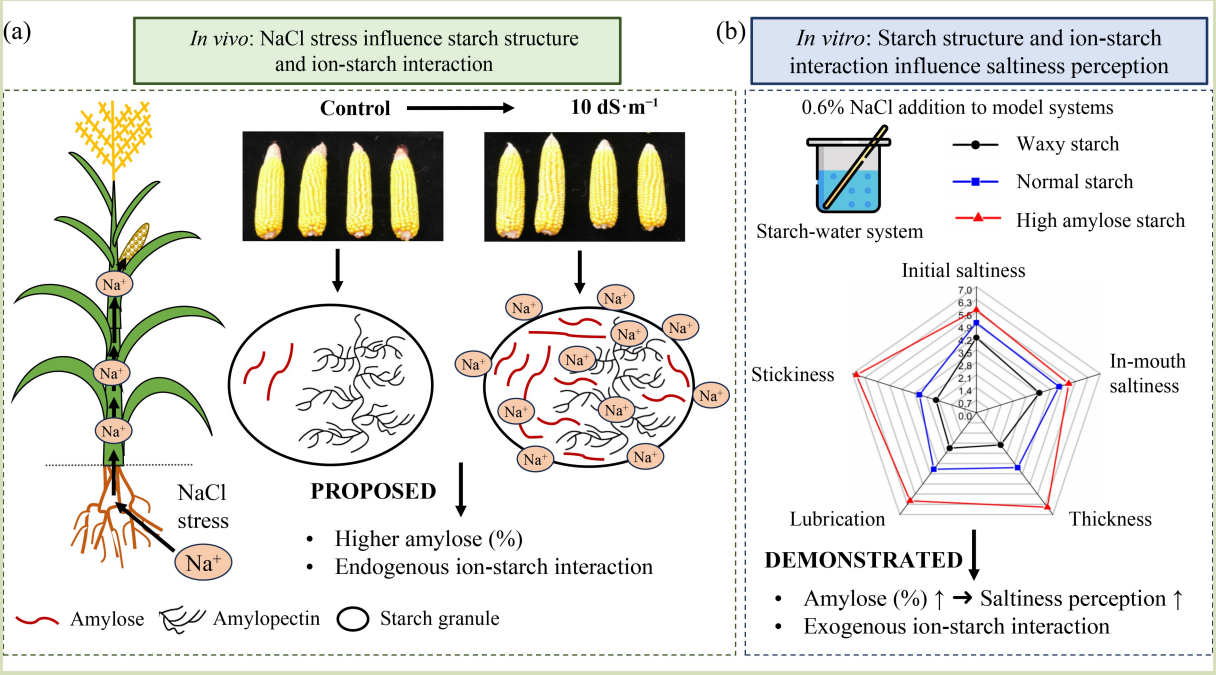


Fig. 2 Proposed and experimentally demonstrated components of the SaltGrain hypothesis. (a) Proposed: salinity-induced increases in amylose content and endogenous ion-starch interaction represent a proposed mechanism-oriented pathway during grain development. (b) Demonstrated: *in vitro* starch-salt mixing provides experimental evidence that high amylose starch exhibits greater saltiness perception than normal and waxy starches, within a starch-based system involving exogenous sodium and starch. The two panels distinguish the proposed *in vivo* mechanism from the experimentally demonstrated *in vitro* saltiness response.

5 Defining the Saline Agriculture 3.0 opportunity space

5.1 Yield-quality configurations

Three yield-quality configurations define the Saline Agriculture 3.0 opportunity space: (1) yield declines under salinity, but quality valorization may justify the production penalty; (2) yield remains comparable with non-saline production, allowing quality differences to provide additional value; and (3) yield increases under salinity while quality changes create additional valorization potential, representing a potentially rare double benefit. Saline Agriculture 3.0 therefore requires crop- and context-specific evaluation of whether quality value is sufficient to offset production, resource, safety and market trade-offs rather than assuming a universal benefit of salinity.

The following examples span paired yield-quality responses under soil salinity (based on ECe) in cereals, illustrating contrasting configurations across different experimental and production contexts. The available evidence across cereal-salinity combinations is summarized in Fig. 3 and Table S2. Paired yield and quality responses varied among crops and salinity levels. In wheat, average grain yield decreased by 25.6% at 7.5 dS·m^{-1} and by 50.7% at 15 dS·m^{-1}, while grain protein increased by 6.2% and 17.2%, respectively[69], potentially shifting end-use suitability from biscuit or cake toward bread applications[70]. In rice, grain yield decreased by 40.5% under moderate salinity and by 72.1% under high salinity, while amylose content decreased by 14.5% and 1.5%, respectively[71]. The larger decrease at moderate salinity is consistent with softer, stickier cooked rice, whereas the smaller decrease at high salinity is consistent with firmer, less-sticky cooked rice[72]. In barley, grain yield decreased by 24.5% at 7 dS·m^{-1} and by 41.0% at 14 dS·m^{-1}, while grain protein increased by 28.7% and 30.9%, respectively, based on the average response across six tested genotypes[73], potentially shifting end-use suitability from malting toward food or feed applications[74]. However, genotype-specific responses can differ substantially: in the

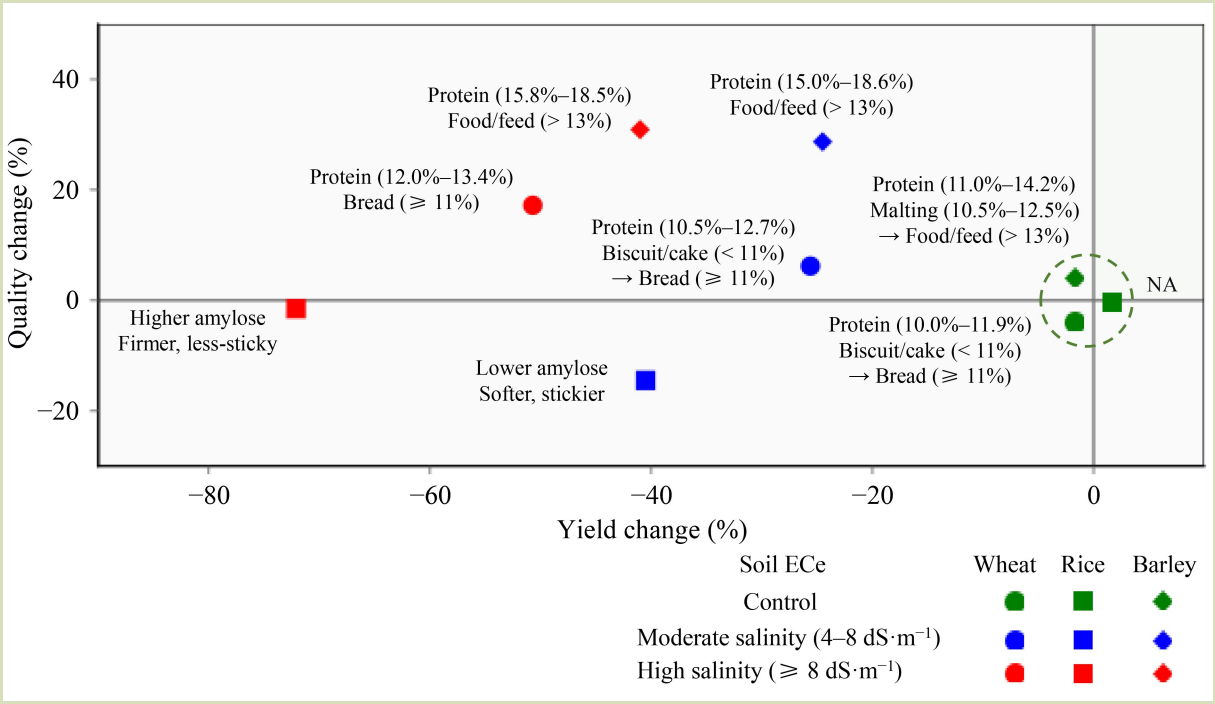


Fig. 3 Representative paired yield-quality response space for cereal crops under salinity. Each point represents a crop by salinity combination (non-saline control at [0,0]; moderate, 4 ⩽ ECe < 8 dS·m^{-1}; high, ECe ⩾ 8 dS·m^{-1}) positioned by mean paired change in grain yield (*x*-axis) and mean paired change in a selected grain-quality trait (*y*-axis) relative to the non-saline control. Quality traits are grain protein for wheat and barley and amylose content for rice. Labels indicate the absolute quality range across genotypes (where available) and the corresponding end-use direction. For rice, absolute amylose values were not available (NA) and directions are presumptive. The green dotted circle indicates the region encompassing the non-saline controls for all crops. Crop icons are offset for visual clarity but all correspond to [0,0]. Yield and quality changes were calculated as 100 × (treatment − control) / control using paired control-treatment data; for wheat and barley, values are means across reported genotypes from paired experiments, and for rice, values are from a published meta-analysis and represent mean relative changes.

genotype Furat1, the increase in grain protein relative to the non-saline control was smaller at 14 dS·m^{-1} (42.5%) than at 7 dS·m^{-1} (64.6%), although both responses represented increases relative to the corresponding control[73]. Together, these examples illustrate the potential for cereal systems such as wheat, rice, and barley to occupy different positions within the yield-quality opportunity space, including cases in which yield declines while quality traits change in directions that may provide additional valorization potential. In this sense, the cereal examples primarily illustrate the first configuration (yield decline with quality change), while also demonstrating the quality change component that could support the third configuration if yields were maintained or increased through management, provided that the target quality trait is preserved. Future studies should therefore evaluate yield and target quality traits within the same genotype by salinity by management combinations to determine whether these benefits can be achieved simultaneously.

Maize provides an illustration of an evidence gap in which the yield penalty is documented but evidence for accompanying grain-quality changes remains limited. Under high salinity (10.0–12.0 dS·m^{-1}), grain yield decreased by 33.6% relative to the control across five maize genotypes[75]. However, direct evidence linking salinity to maize grain-quality traits such as amylose content is currently lacking. A mechanistic hypothesis has proposed that interactions between the chloride-channel-related protein ZmSIP/anoctamin and starch branching enzyme may influence amylose metabolism in amyloplast under salt stress, potentially contributing to increased grain

amylose content under salinity[66]. Given that paired yield-quality data were not available, maize was not included in Fig. 3. Although a substantial yield penalty has been demonstrated, whether salinity-induced changes in grain amylose content could provide compensatory valorization through improved saltiness perception, as proposed in the SaltGrain hypothesis model (Fig. 2), remains to be experimentally established.

The plausibility of these potential end-use interpretations is further supported by examining the absolute values of the corresponding quality traits under salinity, with the non-saline control providing the reference baseline. Protein content is a long-established quality index for differentiating end uses in both wheat[70] and barley[74]. For wheat, grain protein content under moderate salinity (7.5 $dS{\cdot}m^{-1}$) ranged from 10.5% to 12.7% across the four investigated genotypes, spanning the biscuit/cake (< 11%) and bread (⩾ 11%) ranges[76], whereas under high salinity (15 $dS{\cdot}m^{-1}$) it ranged from 12.0% to 13.4%, falling entirely within the bread range. The non-saline control ranged from 10.0% to 11.9%, also spanning both categories[69]. This indicates that salinity can shift wheat genotypes from a mixed biscuit/cake-bread profile toward a clearer bread-oriented profile. For barley, grain protein content under moderate salinity (7 $dS{\cdot}m^{-1}$) ranged from 15.0% to 18.6% and under high salinity (14 $dS{\cdot}m^{-1}$) from 15.8% to 18.5%[73], both falling entirely within the food/feed range (> 13%)[77], whereas the non-saline control ranged from 11.0% to 14.2%[73], spanning the malting (10.5–12.5%) and food/feed (> 13%) ranges[77]. This indicates that salinity shifted barley away from the malting range toward food/feed applications across all tested genotypes. These absolute values support the plausibility of the potential quality valorization indicated in Fig. 3, while recognizing that other processing properties also influence final end-use performance.

The opportunity space also extends beyond cereals. Representative horticultural studies show that salinity itself can simultaneously alter yield and quality, providing additional examples of the configurations described above. In each case, the comparison is between salinity treatments and the corresponding non-saline control. In tomato, marketable yield was unaffected up to an irrigation-water salinity (ECi) of 2.5 $dS{\cdot}m^{-1}$ but declined by 7%–8% per unit increase in ECi above this threshold, while total soluble solids increased by up to 49% at 10 $dS{\cdot}m^{-1}$ and titratable acidity by 61%. This example corresponds to the first configuration, in which a yield penalty may be offset by quality valorization such as fresh-market or processing applications[78]. In sweet bell pepper, fruit number and size did not differ significantly between NaCl treatments (50 and 75 $mmol{\cdot}L^{-1}$) and the control, indicating no detected penalty in these yield components. However, total yield was not reported. At 50 $mmol{\cdot}L^{-1}$ NaCl, the strongest enrichment of targeted bioactive traits was observed, including about tenfold increases in kaempferol and procyanidin, with potential value for antioxidant- or phytochemical-rich fresh products. At 75 $mmol{\cdot}L^{-1}$ NaCl, total protein, carbohydrates, lycopene, total carotenoids, and total phenols increased by 50%, 18%, 68%, 13% and 18%, respectively, although several targeted bioactive compounds declined relative to the lower salinity level, potentially favoring products emphasizing broader nutritional attributes[79]. This example corresponds to the second configuration, in which quality differentiation can provide additional value without a detected yield trade-off in the measured yield components. In onion, low salinity produced a genotype-dependent yield response. Bulb yield was 1.3%–1.8% higher in cvs Bhima Red and Bhima Shakti at soil ECe of 0.5 $dS{\cdot}m^{-1}$ than in the non-saline control, although the statistical significance of this small increase was not reported. Antioxidant activity and total phenols increased progressively with salinity. This low-salinity response illustrates the third configuration in cvs Bhima Red and Bhima Shakti, in which a slight yield gain combined with quality changes could support fresh-market production. At high soil salinity (3.55 $dS{\cdot}m^{-1}$), antioxidant activity and total phenols increased by up to 87.9% and 105%, respectively, in cv Bhima Red, although bulb yield declined substantially. The stronger quality enrichment at high salinity could potentially support value-added or antioxidant-rich products despite substantial yield penalties. These contrasting responses were strongly genotype- and salinity-dependent[80].

In combination, these examples show that the three yield-quality configurations provide an initial screening framework for the Saline Agriculture 3.0 opportunity space. The first configuration includes cases where quality differentiation may compensate for a yield penalty, the second where quality value may be gained without a detectable yield penalty, and the third where concurrent yield and quality gains may offer a rare double benefit. However, these configurations indicate potential rather than establish a viable opportunity. Whether a given yield-quality combination warrants pursuit of Saline Agriculture 3.0 depends on its end-use relevance and the economic, resource, safety and market conditions.

5.2 Conditions for pursuing Saline Agriculture 3.0

A yield-quality opportunity is not automatically a Saline Agriculture 3.0 opportunity. Its value depends on whether the quality value can justify associated production costs and risks within a suitable saline production context (Table 2). Evidence from saline-irrigated tomato provides a useful illustration. In a 3-year field study, increasing irrigation-water salinity improved soluble solids, total acidity, vitamin C and other quality attributes, but higher salinity also reduced yield, with the strongest salinity treatment decreasing yield by 22.4%–31.1%[81]. Complementing this agronomic evidence, a field-level economic analysis of processing tomatoes in California provides directly relevant economic data[82]. Fresh yield decreased from 104 to 96.9 t·ha^{-1}·yr^{-1}, but total soluble solids rose from 5.36% to 6.03% and price from 51.20 to 52.67 USD·t^{-1}, so that net benefit increased from 655 to 741 USD·ha^{-1}·yr^{-1} despite an additional 435 USD·ha^{-1}·yr^{-1} in drainage-disposal costs. This net gain was realized only under site-specific drainage-reuse conditions. Thus, a quality response becomes relevant to Saline Agriculture 3.0 only when it can generate sufficient value to compensate for the associated yield or resource trade-off.

The production context is therefore critical. Salinity should primarily be considered where it provides an alternative use for salt-affected land or saline water resources rather than creating an incentive to replace productive non-saline land. Likewise, the quality response must be sufficiently reproducible and connected to an identifiable product attribute. For example, a recent field study found that tomato marketable yield was maintained up to an irrigation-water salinity of 2.5 dS·m^{-1}, whereas higher salinity progressively reduced yield while increasing soluble solids and acidity[78], illustrating how a defined salinity range may provide a realistic window for balancing production and quality.

Food safety represents a boundary condition rather than a requirement to eliminate salinity-induced ion accumulation, including sodium. In plants, excessive sodium accumulation can disrupt nutrient balance and induce oxidative damage[83], although sodium can also have beneficial physiological roles, including contributing to osmotic adjustment and, in some species, partially substitute for potassium in functions such as cell expansion[84]. Sodium is likewise an essential contributor to human extracellular fluid balance and osmoregulation[85]. This distinction is particularly important for the SaltGrain hypothesis, in which controlled sodium accumulation is proposed as part of a potential starch-sodium-sensory pathway. The relevant question is therefore whether sodium accumulation remains appropriate for the intended product and dietary exposure, and whether the resulting change provides a demonstrated or testable food function. In contrast, potentially harmful heavy metals such as cadmium, lead and arsenic should remain within applicable safety limits, because salinity can alter their uptake and promote accumulation in edible tissues[86]. Thus, sodium accumulation should not be treated as inherently disqualifying, but rather evaluated in

Table 2 Go / No-Go conditions for Saline Agriculture 3.0

Criterion	Go	No-go
Land status	Land is already salt-affected or at risk of salinization	Requires converting non-saline productive land
Yield penalty	Yield loss is moderate and can be compensated by quality premium or value capture	Yield loss is too large to be economically or nutritionally offset
Quality trait	Quality trait is reproducible across sites and seasons and relevant to a market application	Quality trait is inconsistent or has no clear market demand
Food safety	Sodium and other contaminants remain within acceptable limits for the intended product	Sodium or other contaminants exceed acceptable limits or create unacceptable health risks
Resource use	Water, energy, and input use are lower than or comparable to standard or remediation production	Irrigation or management worsens long-term salinization or increases freshwater demand
Producer value capture	Certification, traceability or premium markets allow producers to capture added value	Processing costs or market structure absorb the premium; producers do not benefit
System-level benefit	Net nutritional, environmental, and economic gains exceed those of yield-focused or remediation alternatives	No clear system-level advantage over standard or remediation-based strategies

Note: Go, the criterion is satisfied and supports further evaluation of the crop-salinity-quality combination; and No-go, the criterion is not satisfied and the associated risks or trade-offs are likely to outweigh the potential benefits. This table is a screening tool, not a quantitative model. Each criterion should be evaluated for specific crop-salinity-quality combinations.

relation to its concentration, dietary exposure, food function, and the overall contaminant profile of the product.

Resource efficiency provides a further filter. The use of saline water or salt-affected land should offer a resource advantage relative to available alternatives rather than simply transferring the salinity problem elsewhere. For example, saline water irrigation has been investigated specifically as an alternative to freshwater use, but its benefits depend on salinity level, irrigation management, soil conditions, and the resulting yield and water use responses. Meta-analysis of tomato production found that saline irrigation reduced yield and overall irrigated water use efficiency, while lower salinity water provided more favorable yield-quality trade-offs[87]. Thus, the use of saline resources should be justified by a demonstrable system-level advantage rather than by quality improvement alone.

Finally, value capture determines whether a biological quality response can become an agricultural opportunity. A quality trait may have nutritional, functional or sensory value without generating additional returns to producers if processing, certification, distribution or market constraints absorb the potential premium. The relevant question is therefore whether a plausible pathway exists for the added product value to reach producers.

6 Enabling Saline Agriculture 3.0: From opportunity to implementation through value-chain integration

Once a yield-quality opportunity passes the go/no-go conditions (Table 2), the central challenge shifts from identifying a biological response to demonstrating that it can function as a product attribute (Fig. 4). This requires sequential validation across the value chain. Agronomists and breeders establish reproducible genotype-salinity combinations and production practices. Food scientists determine whether quality traits are retained through processing and produce measurable nutritional, functional, or sensory effects. Industry partners assess whether these effects support product differentiation and consumer acceptance, while policymakers provide standards for food safety, traceability, labeling and certification. Thus, value-chain integration is not an additional criterion for identifying an opportunity, but the pathway through which a validated quality trait can be translated into a differentiated product.

Existing saline food systems demonstrate that environmental adaptation can become part of product differentiation when it generates recognizable product attributes. For instance, saline halophytes, such as *Sarcocornia* and *Salicornia,* are marketed as distinctive salty vegetables with nutritional and organoleptic characteristics and recognized commercial potential[88]. Geographical indication systems provide a broader precedent for converting distinctive product characteristics into market value. Vadehavslam protected geographical indication provides a complementary example in which grazing on sodium- and potassium-rich salt meadows contributes to a distinctive salty taste that forms part of the protected regional identity of the product[89]. Across European Geographical Indication/ Traditional Speciality Guaranteed (GI/TSG) products, the average sales-value premium was estimated at 2.07 times relative to comparable standard products, although the premium varied substantially among product categories and individual products[90]. This provides a general example of how product differentiation can generate higher unit value, rather than an expected premium or profit estimate for saline-grown crops. Such evidence illustrates that product differentiation becomes relevant to Saline Agriculture 3.0 only when a recognizable quality attribute can support higher unit value and provide a pathway for value capture.

SaltGrain provides one prospective example of this pathway rather than the definition of Saline Agriculture 3.0. Its proposed starch-sodium-sensory relationship would require validation across genotypes, salinity conditions, processing steps and consumer responses before supporting a differentiated product. More broadly, Saline Agriculture 3.0 becomes implementable when a reproducible salinity-responsive trait can be connected to a defined product attribute, a credible production and processing pathway, and mechanisms for product recognition and value capture. The framework therefore moves beyond identifying quality responses toward establishing when and how those responses can be translated into differentiated foods and viable saline production systems.

7 Conclusions and future outlooks

Saline Agriculture 3.0 extends saline agriculture from restoring soil and maintaining yield toward creating differentiated food value. The quantitative yield landscape demonstrates that substantial production can be maintained under saline

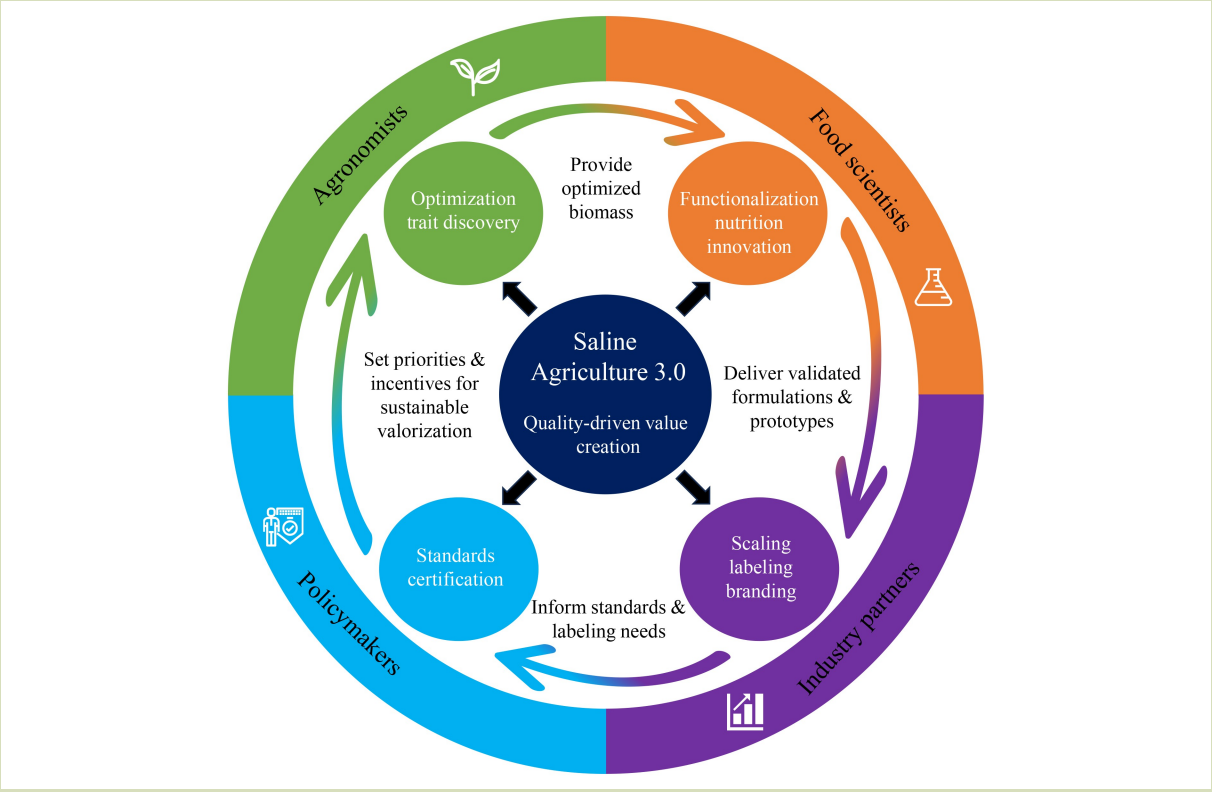


Fig. 4 Multistakeholder framework for enabling Saline Agriculture 3.0. Quality-driven saline agriculture requires coordinated contributions from agronomists and breeders, food scientists, industry partners and policymakers. Together, these stakeholders connect saline production with quality assessment, food applications, market development, food safety and value capture, enabling salinity-responsive traits to be translated into food and economic value.

conditions, particularly through agronomic management, providing a measurable baseline for exploring quality-oriented production. Across cereals and horticultural crops, the evidence further shows that salinity can generate distinct yield-quality configurations, from quality gains accompanying yield penalties to cases where quality differentiation occurs without yield loss or alongside modest yield increases. These responses define an opportunity space rather than a universal benefit of salinity.

The central challenge is therefore to identify crop-genotype-salinity combinations in which a reproducible quality trait has sufficient nutritional, functional, processing, sensory or market value to justify its production costs and risks. The proposed go/no-go conditions provide a basis for screening these opportunities against production context, yield trade-offs, food safety, resource efficiency and value capture. Once an opportunity passes these conditions, value-chain integration can determine whether the trait can be validated, translated into a recognizable product attribute, and captured as additional product value. The SaltGrain hypothesis illustrates this broader pathway, but it remains a plausible mechanism rather than an established product function, and testing it under real production and market conditions is a necessary next step. Saline Agriculture 3.0 therefore represents a shift from managing salinity solely as a constraint toward selectively using saline environments to generate measurable and potentially valuable food attributes.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2026729 contains supplementary materials (Fig. S1; Tables S1–S2).

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Compliance with ethics guidelines

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