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An Ethical Inquiry into Translation in the International Communication of Ginseng and Deer Antler Culture: From Cultural Representation to Value Negotiation

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Abstract This study conducts a systematic investigation into the ethical issues of translation in the international dissemination of ginseng and deer antler (shenrong) culture, focusing on how these traditional medicinal and dietary resources are culturally represented, reinterpreted, and ethically challenged in cross-cultural contexts. The article first outlines the core connotations of shenrong culture, emphasizing its roots in the holistic life philosophy and Yin-Yang balance theory of Traditional Chinese Medicine (TCM), while highlighting how differences in functional consumption preferences, regulatory systems, and ethical orientations in global markets significantly influence translation practices. It then constructs an analytical framework from three perspectives-cultural representation ethics, cross-cultural adaptation ethics, and value-negotiation ethics-to reveal the structural dilemmas faced by translators when striving to faithfully convey traditional knowledge, comply with target-language regulations, and address animal-ethics debates and cultural differences. Through case analyses of brand translations, packaging and promotional language, efficacy claims, and typical mistranslations, the study illustrates the mechanisms by which shenrong culture is functionalized, commodified, and deculturalized in global discourse. Building on the tension between responsibility ethics and communicative ethics, the article proposes balanced approaches such as a "stratified cultural visibility strategy," emphasizing that explanatory translation, contextual supplementation, and cross-stakeholder collaboration are essential for protecting the cultural knowledge system of shenrong while ensuring effective intercultural communication. Ultimately, the study calls for establishing an ethics-oriented translation system for TCM culture to promote the precise, sustainable, and responsible international dissemination of shenrong culture.
Keywords Shenrong culture; Translation ethics; Cross-cultural communication; Cultural representation; Value negotiation

1 Introduction

As global interest in health and wellness continues to rise, the value of traditional medicinal and dietary resources is being re-evaluated within cross-cultural contexts. As a composite resource that embodies medicinal efficacy, nutritional functions, and cultural symbolism, shenrong-primarily referring to ginseng, deer antler, and related products-has gradually moved beyond its East Asian epistemological roots into the international marketplace of health products and cultural discourse. Existing studies show that ginseng is valued not only for its traditional therapeutic functions but also for its wide-ranging applications in modern agriculture, nutrition, and animal sciences. For example, residues from American ginseng extract have been used as feed additives for sika deer, significantly improving livestock immunity and production performance (Wu et al., 2024). Deer antler, renowned for its remarkable regenerative capacity, has become a prominent model in global mammalian regeneration research, with evidence spanning stem cell discovery (Qin et al., 2023), organ regeneration mechanisms (Wang et al., 2019), and cartilage protection (Yao et al., 2020; Guan et al., 2021). As global consumption patterns shift toward "wellness-health maintenance-functional foods", the demand for cross-cultural communication of shenrong culture continues to expand. This trend reflects not only international consumers' growing preference for natural health products but also increasing global curiosity about Eastern philosophies of life, holistic medical frameworks, and traditional knowledge systems. Consequently, how to accurately represent shenrong culture, effectively convey its cultural meanings, and reasonably reconstruct its value systems in international communication has become a pressing issue for both academia and industry.

Within this cross-cultural exchange, translation is no longer limited to linguistic conversion; it functions as a key mechanism for cultural understanding, meaning construction, and value negotiation. On one hand, translation carries the dual tasks of knowledge transformation and cultural interpretation, requiring the creation of meaningful bridges across different symbolic systems, medical discourses, and historical narratives. For instance, translating the regenerative features of deer antler or the health benefits of ginseng involves multi-layered filtering through traditional medical theory, biomedical evidence, and health-related norms in the target language. Translators must not only convey scientific facts-such as the rapid tissue regeneration capability of deer antler (Wang et al., 2019; Qin et al., 2023) or ginseng's positive effects on animal health (Wu et al., 2024), but also grapple with fundamental differences in medical epistemology across cultural systems. On the other hand, translation operates within power structures, regulatory frameworks, and cultural capital dynamics. Translation strategies, discursive choices, and cultural compromises can directly shape international audiences' perceptions and acceptance of shenrong culture. The rapid growth of research and global trade surrounding shenrong products has further underscored the critical role of translation in constructing cultural narratives, mediating cultural differences, and establishing knowledge legitimacy (Yao et al., 2020; Guan et al., 2021).

Nevertheless, the international dissemination of shenrong culture reveals a series of deep ethical challenges, including the authenticity of cultural representation, the semantic migration of traditional knowledge, the reconstruction of cultural meanings under commercialized narratives, the cross-contextual interpretation of medical attributes, and the negotiation of value systems across cultures. In international contexts, shenrong is often framed through the lens of health products, functional supplements, or alternative medicine. While such re-narration caters to market demand, it may inadvertently simplify or distort the original cultural knowledge system. As ginseng and deer antler increasingly enter the focus of scientific research (Qin et al., 2023; Wu et al., 2024), translators face mounting ethical pressure regarding cultural choices: their decisions involve not only professional competence but also ethical judgment regarding cultural representation, scientific accuracy, and market compliance. For example, when translating traditional functions of shenrong, translators must balance the need to faithfully convey cultural complexity with the need to align with the cognitive frameworks of target readers. When addressing scientific findings, they must avoid overstating efficacy or misrepresenting empirical evidence (Wang et al., 2019; Yao et al., 2020). Therefore, systematically examining the ethical issues in translating shenrong culture within international communication is essential not only for improving the quality of cultural expression but also for fostering fairness and sustainability in cross-cultural exchanges of health-related knowledge.

2 Core Connotations of Shenrong Culture and the Context of Its International Communication

2.1 Shenrong culture embodies core TCM concepts such as the holistic life paradigm and Yin-Yang balance

The knowledge system of shenrong culture is rooted in the holistic life paradigm of Traditional Chinese Medicine (TCM), whose underlying logic is built upon the philosophical principles of "correspondence between heaven and humanity" and "overall harmony". As tonic medicinal materials, ginseng and deer antler carry cultural meanings far beyond mere physiological enhancement; they are closely associated with abstract life concepts such as the generation of qi, the preservation of essence, and the harmonization of Yin and Yang (Jia et al., 2009; Zhang et al., 2024). For instance, ginseng has traditionally been regarded as the "King of Qi-supplementing herbs", with core functions including tonifying qi, strengthening the spleen, nourishing the blood, and balancing Yin and Yang-used to help the body resist fatigue, illness, and aging (Jia et al., 2009; Potenza et al., 2022). Modern pharmacological research further reveals its adaptogenic properties as well as its immunomodulatory and neuroprotective effects, yet these findings do not replace its foundational role within the TCM life paradigm centered on the notion of qi (Shi et al., 2019; Zhang et al., 2024). Deer antler has traditionally been associated with kidney nourishment, bone strengthening, and vitality enhancement, and is often used to support weak constitutions. Its annual regenerative capacity is regarded as a symbol of vitality, renewal, and the power of rebirth (Wang et al., 2019; Qin et al., 2023; Zhao et al., 2025). As such, shenrong culture represents not merely a compilation of medicinal knowledge but a composite knowledge structure that integrates medical theory, symbolic meaning, and ritual/liturgical practices (Guan et al., 2021; Xia et al., 2022).

However, this cultural framework-grounded in Yin-Yang, Five Elements theory, and the interrelatedness of the organ systems-faces semantic gaps and cognitive translation challenges in cross-cultural communication. Western biomedical discourse, oriented around anatomy, physiology, molecular mechanisms, and evidence-based medicine, lacks direct equivalents for concepts such as qi, jing (essence), or Yin-Yang (Potenza et al., 2022; Zhang et al., 2024). Expressions in shenrong culture such as "tonifying deficiency", "strengthening the righteous to dispel pathogenic factors", or "unity of essence, qi, and spirit" involve not only linguistic conversion but also the adjustment of cognitive frameworks and the restructuring of cultural logic. Without adequate explanation of TCM's holistic worldview and long clinical tradition, the cultural and medical connotations of shenrong may easily be reduced to perceptions of "non-science", "mysticism", or reinterpreted through consumer-oriented labels such as "anti-fatigue" or "anti-aging" (Ichim and De Boer, 2021). Thus, communicating shenrong culture internationally requires balancing the depth of its original meaning with cross-cultural intelligibility, making translation a key mechanism for semantic bridging and conceptual reframing.

2.2 Rising global market demand amid regulatory and cognitive disparities

Driven by the expanding global demand for functional foods and natural health products, shenrong-related goods have witnessed notable growth in international markets. Ginseng has become one of the best-selling herbal medicines worldwide, with a global market size exceeding USD 2.1 billion and products distributed across six continents (Ichim and De Boer, 2021; Potenza et al., 2022). Deer antler, due to its regenerative properties and potential health benefits, has also gained increasing attention, with global annual production reaching approximately 1 300 tons and continuing to rise alongside medicinal and wellness demand (Zhao et al., 2025). Consumers in Europe, North America, Southeast Asia, and Australia show growing interest in health concepts such as "natural", "traditional", and "holistic nourishment", creating new opportunities for the commercial dissemination of shenrong products. However, international acceptance of shenrong is often shaped by frameworks of "functional consumption" or "natural supplements", rather than a systematic understanding of TCM's life philosophy and the deeper cultural connotations of shenrong (Suh et al., 2019). As a result, shenrong culture is easily recoded into Western consumer categories such as "immune booster" or "anti-fatigue product," diluting its philosophical foundations and cultural depth.

At the same time, shenrong products entering global markets must navigate widely divergent regulatory systems. Countries differ significantly in the categorization of herbal medicines and animal-derived supplements, safety standards, labeling rules, and advertising claims (Suh et al., 2019; Ichim and De Boer, 2021). For ginseng, quality authentication and the identification of genuine vs. adulterated products are major challenges; mislabeling and adulteration not only undermine consumer trust but also pose safety risks (Ichim and De Boer, 2021). Many regions impose strict restrictions on medical claims such as "treat" or "cure", requiring instead functional expressions like "supports" or "helps maintain", which shape the permissible boundaries of shenrong-related discourse in target-language texts (Potenza et al., 2022). For deer antler, regulations on the importation, quarantine, and labeling of animal-derived materials are often stricter, and concerns about animal welfare and sustainability are increasingly incorporated into regulatory oversight (Zhao et al., 2025). These institutional differences and epistemological mismatches jointly form challenges for the international communication of shenrong culture.

2.3 Animal ethics and cultural differences as sensitive points in communication

Within globalized communication, shenrong culture inevitably becomes subject to cross-cultural ethical scrutiny, with animal ethics being particularly sensitive. As an animal-derived material, deer antler's harvesting practices and related welfare concerns are evaluated through strict ethical frameworks in some cultural contexts. Although deer antler harvesting in northeastern China has a long history and is guided by experiential norms such as "taking appropriately and nurturing sustainably", modern animal welfare discourses place greater emphasis on "minimizing pain, optimizing management, and ensuring sustainable use" (Wu et al., 2024; Zhao et al., 2025). Research shows that improving husbandry practices, controlling appropriate harvesting timing, and implementing stress-reducing procedures can partially mitigate deer stress responses (Wu et al., 2024). Nevertheless, cultural attitudes toward the medicinal use of animal products vary widely, and in some countries the public or media associate animal-based medicines with "cruelty" or "unnecessariness" (Suh et al., 2019). As a result, deer antler becomes not only a medical and cultural topic but also an ethical flashpoint in international communication.

Beyond animal ethics, cultural differences also constitute major sensitive zones in the dissemination of shenrong culture. Western audiences, lacking experiential grounding for concepts such as "tonifying", "deficiency", or Yin–Yang, may misinterpret them as mystical, unscientific, or superstitious; by contrast, TCM views these concepts as "functional diagnostic language" derived from long-term clinical experience and systematic theorization (Jia et al., 2009; Zhang et al., 2024). Moreover, in the Chinese context, shenrong often holds symbolic and socio-cultural significance-appearing in practices such as festive gifting, longevity blessings, and postpartum nourishment-yet these dimensions are frequently weakened or omitted in international communication, resulting in fragmented and decontextualized cultural representation (Potenza et al., 2022). For compound formulas combining ginseng, deer antler, and other medicinal materials (e.g., KGC-HJ3), cross-cultural communication introduces additional layers of complexity, including safety perceptions, synergistic mechanisms, and the interpretive challenge of multi-herb formulations (Lee et al., 2018; Suh et al., 2019). Translators must navigate these cultural differences and ethical sensitivities with precision, maintaining cultural depth, ensuring ethical coherence, and facilitating cross-cultural intelligibility. Any inappropriate narrative strategy may amplify cultural misunderstandings or trigger public controversy.

3 A Translation Ethics Framework for International Communication

3.1 Ethics of cultural representation: preserving cultural meaning and traditional values without distortion

In the international dissemination of shenrong culture, the core concern of cultural representation ethics is to ensure that translation faithfully conveys the meaning structures of the source culture and the traditional knowledge systems embedded within them. As an important symbol rooted in East Asian medical culture, shenrong embodies not only medicinal efficacy but also a broader worldview concerning life cultivation, health preservation, classical bencao narratives, and philosophical understandings of the human–nature relationship (Chen, 2023; Kadier et al., 2025). TCM is fundamentally built upon unique epistemological categories-such as Yin-Yang, qi, and the Five Elements-which serve both as medical concepts and as carriers of cultural identity and symbolic meaning (Min et al., 2024; Kadier et al., 2025). If translation of shenrong is guided solely by the consumption logic of the target market or the dominant biomedical discourse, without regard for the historical and philosophical contexts behind these concepts, it risks producing a "flattened" cultural representation. In such cases, the tri-layered structure of culture-medical theory-symbolism may be reduced to a single product-oriented narrative or commercial sign (Ding and Zheng, 2024). Thus, cultural representation ethics stresses that translation should not become a process of cultural dilution but rather a practice of protecting cross-cultural knowledge and extending cultural meaning.

At the same time, cultural representation ethics requires translators to maintain high precision and interpretive responsibility when dealing with terminology, classical cultural references, and traditional medical expressions. Concepts such as "tonifying qi", "warming and strengthening", and "harmonizing Yin and Yang" have clearly defined theoretical positions within the TCM framework, yet they lack direct equivalents in Western biomedical discourse. Literal rendering or replacing them with single functional terms often diminishes their historical and philosophical depth (Zhang and Dong, 2020; Chen, 2023). Studies show that unannotated literal translations of TCM terminology (e.g., formula names, symbolic metaphors) can lead to misunderstanding and cultural identity loss, whereas the appropriate use of annotations and strategies of foreignization/domestication helps construct a dynamic balance between intelligibility and cultural fidelity (Ding and Zheng, 2024; Min et al., 2024). Therefore, cultural representation ethics can be summarized as requiring both intelligibility and non-attenuation: on one hand, necessary explanation and structural elaboration should help target readers grasp essential meanings; on the other, excessive "cultural simplification" must be avoided so that symbolic and theoretical dimensions of the original epistemology are not hollowed out, reducing shenrong to a functionally oriented yet culturally shallow commodity.

3.2 Ethics of cross-cultural adaptation: aligning with target-culture expectations and regulatory requirements

The ethics of cross-cultural adaptation concerns the acceptability and legitimacy of translations within the target culture. As global health product regulations continue to tighten, shenrong-related information must comply with various norms governing food safety, health claims, advertising, and cross-border e-commerce (Ichim and De Boer, 2021; Kadier et al., 2025). Experience from the global spread of TCM shows that societies differ significantly in health beliefs, medical systems, and the regulation of animal-derived products. Practices or terminology considered routine in the Chinese context may provoke skepticism, controversy, or even legal concerns elsewhere (Chen, 2023; Chen et al., 2025). For instance, directly translating "tonifying the kidney and enhancing yang" or "prolonging life" into claims such as "treats erectile dysfunction" or "extends lifespan" may violate health-claim regulations in many countries and constitute misleading advertising (Ichim and De Boer, 2021). Thus, cross-cultural adaptation ethics requires translators to faithfully convey source-culture meaning while systematically identifying the legal, cultural, and epistemological structures of the target environment to prevent misinterpretation or legal disputes (Figure 1).

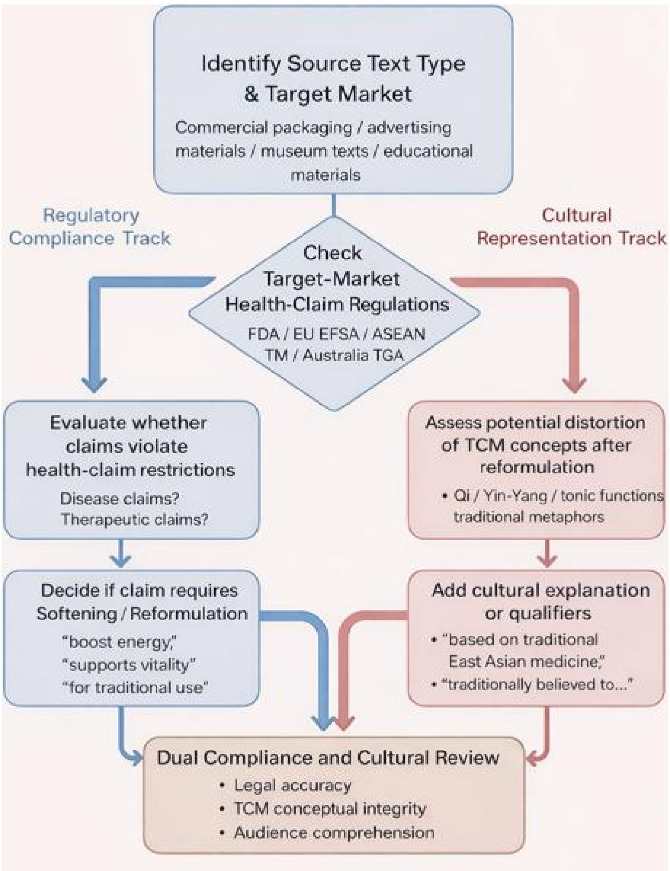

Figure 1 Dual compliance-culture check process for the translation of ginseng and deer antler claims in global markets

Cross-cultural adaptation ethics also involves understanding the cognitive patterns and cultural expectations of target audiences. For readers unfamiliar with TCM, traditional medical concepts require contextualization and structured explanation to avoid semantic misinterpretation (Min et al., 2024). For example, translating "qi and blood deficiency" simply as "lack of energy" risks being read as ordinary fatigue, rather than a diagnostic concept anchored in a full system of pattern differentiation. Studies indicate that moderate use of "rewriting" strategies-such as contextualizing terms, adjusting metaphors, or adding functional clarifications to formula names-can help bridge knowledge and cultural gaps (Zhang and Dong, 2020). However, such rewriting must be conducted cautiously: neither erasing source-culture logic for the sake of audience accommodation nor rigidly preserving original forms that hinder comprehension. Cross-cultural adaptation ethics therefore represents a form of careful adjustment, aiming to construct a dynamic balance between communicability and authenticity rather than one-sided cultural export or one-sided accommodation.

3.3 Ethics of value negotiation: seeking balanced expression amid cultural conflict

In international communication, shenrong culture inevitably enters a field of value contestation involving scientific knowledge, traditional medical beliefs, market logic, cultural identity, and consumer ethics (Chen, 2023; Kadier et al., 2025). Conflicts may arise from divergent views on animal welfare, differing health beliefs, or contrasting interpretations of medicinal symbolism. For instance, while deer antler is regarded in its original context as a highly valuable tonic with deep symbolic meaning, in societies with strong animal-protection consciousness, the very notion of using animal-derived medicinal materials may provoke doubt or resistance (Zhang and Dong, 2020; Kadier et al., 2025). In such complex contexts, translators are not merely linguistic mediators but also coordinators of value. The ethics of value negotiation therefore emphasizes that translators must avoid allowing any single discourse to dominate, nor should they absolutize traditional culture. Instead, they should seek translatable, mutually accessible expressive spaces among differing discursive systems (Ding and Zheng, 2024).

This negotiation process often requires multiple mediation strategies, such as combining foreignization and domestication, adding supplementary explanations, and transparently presenting product origins and cultural background, with the goal of fostering understanding without erasing differences (Zhang and Dong, 2020; Ding and Zheng, 2024). Studies indicate that for culturally dense TCM concepts, retaining key terms in transliteration and providing detailed annotation helps prevent “cultural erasure” while creating opportunities for learning and engagement in the target culture (Chen, 2023; Min et al., 2024). In international marketing of shenrong products, clearly presenting harvesting methods, sustainability practices, and benefit-sharing mechanisms not only addresses ethical concerns in target societies but also prevents cultural appropriation and one-directional commodification (Ichim and De Boer, 2021; Liu et al., 2021). From the perspective of value negotiation ethics, the goal of translation is not to create a superficially harmonious, unified narrative but to provide a dialogic space where multiple values may coexist-allowing different cultures to reach “mutually intelligible” understandings amid reasonable divergence.

4 Directions for Case Analysis

4.1 Comparative analysis of Chinese–English translations in international Shenrong brands

In the global dissemination of shenrong products, comparative analysis of Chinese and English translations provides an effective entry point for revealing translation-ethics issues. Many brands, when targeting overseas markets, adopt strategies such as “medicalization”, “maximizing functional claims”, or “cultural de-emphasis” to align with the cognitive habits and regulatory environments of target consumers. For instance, while Chinese packaging for ginseng or deer antler products often highlights traditional notions such as “strengthening the body and supporting essential qi”, English translations are frequently reduced to vague expressions like “boost energy” or “support vitality”. Such simplification weakens the depth of knowledge and philosophical nuance rooted in TCM theory within shenrong culture. Research on international ginseng products shows that brands often use labels such as “wild”, “forest-farmed”, or “semi-wild” when translating variety, origin, or cultivation methods. However, these terms lack standardized definitions across brands, creating consumer misunderstandings regarding product authenticity and value (Ichim and De Boer, 2021; Liu et al., 2021). This type of “technically sophisticated but semantically ambiguous” translation exemplifies the tension between cultural-representation ethics and market-driven discourse.

Furthermore, many international brand translations exhibit what may be called “structural cultural omission”, in which the cultural roles and narrative functions of the original text are ignored. For example, symbolic references, historical narratives, or ritual contexts associated with shenrong culture are often deleted entirely from English packaging or websites, replaced by standardized marketing language such as “quality”, “purity”, or “science-backed”. This stands in stark contrast to certain American forest-farmed ginseng brands that emphasize “sustainability”, “CITES certification”, and “environmental stewardship” in English markets while rarely referencing the TCM cultural background (Liu et al., 2021). A comparison of the Chinese and English versions reveals that Chinese texts tend to follow a “traditional efficacy–cultural symbolism” logic, while English texts follow a “functional supplement-ethical consumption” logic. This structural shift reflects the trade-offs made by translators and brand owners among cultural-representation ethics, market communication goals, and sustainability narratives, providing important material for further analysis of translation ethics.

4.2 Translation issues in packaging and promotional claims: efficacy and cultural expression

Packaging and promotional language are the most direct and commercially oriented textual forms in international shenrong communication. Their translation is constrained not only by target-country regulations but also by consumer expectations within those markets. In terms of efficacy expression, many brands-seeking to match market appeal-translate traditional claims such as “tonify qi and strengthen the exterior” or “prolong life” into medically oriented assertions such as “improve immunity”, “anti-aging effects”, or “treat fatigue”. Although these translations increase clarity and marketing appeal, they may violate strict health-claim regulations in certain markets (Ichim and De Boer, 2021). Studies show that in North American and EU markets, translating traditional dietary or tonic language into explicit “disease-prevention” or “treatment” claims can be regarded as misleading, potentially leading to administrative penalties, product removal, or even lawsuits (Ichim and De Boer, 2021; Liu et al., 2021). More importantly, such translations obscure the long-term, balance-focused logic of shenrong culture rooted in TCM, causing international audiences to misinterpret shenrong as offering immediate, quantifiable biomedical effects-thus generating ethical distortions in cross-cultural meaning transfer.

Simultaneously, cultural expressions on packaging and promotional materials often display tendencies toward “cultural softening” or “cultural stylization”. Some products, aiming to attract consumers interested in Eastern culture, adopt generalized phrases such as “Eastern wisdom”, “ancient remedy”, or “secret tonic”, reducing complex medical theories and cultural experience into exoticized symbols. Others, attempting to avoid associations with “superstition” or cultural distance, adopt highly neutralized, de-culturalized translations, retaining only vague labels like “herbal supplement” or “traditional formula” (Liu et al., 2021). For core TCM concepts such as “qi” or “Yin-Yang”, translations often adopt semi-explanatory phrases like “energy balance” or “holistic harmony”. Without proper contextual and theoretical supplementation, however, such phrases risk becoming aesthetically pleasing but conceptually empty marketing rhetoric. Critical analysis of these translation strategies reveals how shenrong culture is recoded into a “functional commodity discourse” in cross-cultural settings, along with the ethical consequences of this transformation.

4.3 Cultural and market impacts of typical mistranslations

Typical mistranslations in the international communication of shenrong not only create semantic deviations but may also have deeper impacts on cultural representation, brand image, and consumer trust. One common issue involves mistranslation-or strategically misleading translation-of terms associated with product authenticity and quality markers. For example, mistranslating “cultivated” as “wild”, exaggerating “forest-farmed” as “wild-like”, or incorrectly labeling plant parts (e.g., confusing “root” with “leaf” or “fruit”) misleads consumers in evaluating product value and efficacy, and damages both brand credibility and regional reputations (Ichim and De Boer, 2021). Research shows that in markets with strict herbal supplement regulations, such mistranslations can trigger regulatory investigations, product recalls, or accusations of “deceptive marketing” (Ichim and De Boer, 2021; Liu et al., 2021). Thus, translation errors in shenrong-related products extend beyond linguistic inaccuracies to issues of supply-chain transparency, certification integrity, and consumer rights.

On the cultural level, imprecise or culturally insensitive translations may reinforce misunderstandings or prejudice toward TCM and shenrong culture. For instance, mistranslating “zī bǔ qiáng shēn” (tonifying and strengthening the body) as "medical treatment" or "cure" implies therapeutic effects that could trigger regulatory scrutiny and deepen consumer disappointment or skepticism when expected effects are not achieved. Translating "qì xuè bù zú" (qi and blood deficiency) as "lack of blood" may lead to biomedical ridicule or confusion, reinforcing stereotypes of TCM as "unscientific". Additionally, if promotional materials emphasize the "potency" of deer antler while ignoring animal-welfare considerations-especially in societies with strong animal-rights values-they may provoke media criticism or moral backlash (Liu et al., 2021). These cases demonstrate that responsible cross-cultural translation requires both cultural competence and anticipatory risk awareness. Only by balancing linguistic accuracy, cultural representation, ethical transparency, and regulatory compliance can translation effectively support the responsible international communication of shenrong culture.

5 Ethical Challenges in Translating Shenrong Culture Texts

5.1 The tension between cultural authenticity and communicative effectiveness

The foremost ethical challenge in the international dissemination of shenrong cultural texts lies in the structural tension between cultural authenticity and communicative effectiveness. On one hand, shenrong culture is deeply rooted in the TCM knowledge system, whose semantic framework is grounded in holistic perspectives, qi–blood theory, and the dynamic balance of Yin and Yang. Understanding ginseng and deer antler thus requires attention to philosophical, medical, and ritual dimensions simultaneously (Ding and Zheng, 2024; Hasan, 2024). Cultural authenticity demands that translators preserve these conceptual structures, metaphors, and cultural references as much as possible, allowing readers to access the complex worldview embedded in TCM and its symbolic understandings of health, longevity, and mind–body balance (Hasan, 2024; Ramadilla et al., 2024). However, for international audiences lacking TCM literacy, such faithful representation may result in perceptions of "information overload" or "conceptual opacity", thereby reducing readability and persuasive power in real communicative contexts.

On the other hand, a communicative-effectiveness approach emphasizes adapting shenrong texts to the linguistic habits and cultural expectations of target audiences-simplifying terminology, replacing culturally specific metaphors, or reframing meanings through analogies familiar to the target culture (Ding and Zheng, 2024; Zeynalova, 2025). For example, rendering "bǔ qì yǎng xuè" as "boost immunity" or "enhance vitality" may increase immediate intelligibility, yet it detaches shenrong from its TCM framework of holistic regulation and re-encodes it within the categories of modern nutrition or functional foods (Hasan, 2024). Such "communication-friendly" transformations broaden audience accessibility but risk diluting or misrepresenting core cultural logic. The translator's constant negotiation between fidelity to cultural authenticity and accessibility for target readers therefore constitutes an ongoing ethical decision-making process (Ramadilla et al., 2024).

5.2 Ethical variation across text types: advertisements, exhibitions, museum materials, and beyond

The textual forms involved in the cross-cultural dissemination of shenrong culture are highly diverse, including commercial advertisements, packaging copy, e-commerce descriptions, museum labels, exhibition narratives, popular-science writing, and even policy documents. These texts differ significantly in purpose, functionality, legal constraints, and audience structure, resulting in distinct ethical requirements for translation. Commercial advertisements and packaging texts are market-oriented and persuasive by design. They often employ simplified, amplified, or emotionally charged language to highlight product value and consumer benefits, making them prone to exaggeration or cultural symbolization (Ichim and De Boer, 2021; Hasan, 2024). Given the existing issues of ginseng adulteration and mislabeling, translation that further inflates functional claims or downplays compositional differences may directly damage consumer trust and even compromise public health. For such texts, ethical standards center on compliance, accuracy, and avoidance of misleading claims (Table 1).

In contrast, exhibition texts and museum materials prioritize educational functions, cultural transmission, and knowledge preservation. Shenrong-related content is often embedded within narratives of bencao history, medical culture, and local traditions, requiring translations that maintain high precision in terminology, accurately present historical contexts, and reconstruct cultural meaning with sensitivity (Ramadilla et al., 2024). The ethical focus of these texts therefore shifts from persuasion to cultural stewardship. Translators are expected to preserve key terms, provide annotation when necessary, and explain the multifaceted roles of shenrong in rituals, customs, and social relationships with cross-cultural sensitivity (Hasan, 2024; Ramadilla et al., 2024). Ethical discussions about shenrong translation that disregard these differences among text types and apply uniform standards risk impracticality and may create new misunderstandings.

Table 1 Comparison of ethical priorities across different text types in the translation of ginseng and deer antler-related content

Text type	Primary communicative purpose	Key audience	Major legal/regulatory constraints	Ethical priorities	Recommended translation strategies
Commercial advertising	Persuasion; brand positioning	Global consumers; health-product buyers	Health-claim regulations (FDA, EFSA); truth-in-advertising rules	Avoid misleading claims; ensure transparency	Moderate simplification + clear hedging terms; avoid medicalized claims
Product packaging	Product identification; mandatory information disclosure	Consumers; regulatory authorities	Labeling standards; ingredient disclosure; origin rules	Accuracy; prevent cultural misinterpretation	Standardized terminology; weakened claims; dual-track wording (function + cultural note)
E-commerce product pages	Dense information display; trust-building	Cross-border consumers; platform regulators	Platform-specific ad rules; prohibition of disease claims	Avoid misleading visuals/text; prevent over-symbolization	Segmented “function vs. culture” structure; include disclaimers; provide origin/traceability notes
Exhibition Interpretation	Cultural education; contextual explanation	Museum visitors; cultural audiences	Clarity standards; institutional language norms	Maintain cultural depth; avoid stereotyping	Retain key terms + explanatory notes; provide historical/cultural background
Museum/historical documentation	Cultural preservation; knowledge systematization	Scholars; cultural institutions	Documentation standards; heritage-preservation norms	Protect terminology system; high precision	Preserve terms (transliteration + notes); maintain theoretical framework
Science Communication / Policy texts	Public education; policy clarity; normative communication	General public; regulators; policymakers	Scientific evidence requirements; policy language standards	Prevent pseudo-scientization; emphasize clarity	Scientific language dominant; culturally sensitive explanations of TCM concepts

5.3 Conflicts between chesterman’s ethics of commitment and Pym’s ethics of cooperation

Ethical challenges in translating shenrong culture can also be interpreted through tensions within translation ethics theory itself, most notably the conflict between Chesterman’s ethics of commitment (or representation) and Pym’s ethics of cooperation. Chesterman’s framework stresses the translator’s responsibility to faithfully represent the source text and culture, maintaining the integrity of meaning, style, and cultural values while avoiding distortive rewritings that dilute structural or cultural depth (Hasan, 2024; Hu, 2024). For culturally dense shenrong texts, this approach helps preserve TCM philosophy and traditional knowledge, preventing shenrong from being reduced to a shallow functional commodity image. However, excessive insistence on “strong representation” may result in translations that are too culturally dense and cognitively inaccessible for general health consumers or non-specialist audiences, thereby limiting communicative reach and effectiveness (Ramadilla et al., 2024).

By contrast, Pym’s ethics of cooperation emphasizes the translator’s role as a facilitator of intercultural communication, prioritizing target audience comprehension and interaction. This approach encourages flexible adaptation and rewriting when needed to reduce misunderstanding and communicative barriers (Hasan, 2024;

Ramadilla et al., 2024). In the context of shenrong culture, this could involve providing explanatory translations for complex terms, adding functional descriptions to formula names, or reframing narratives using conceptual frameworks more familiar to the target culture (Ding and Zheng, 2024). While such strategies enhance communicative accessibility, they risk being co-opted by market logic: in advertising or packaging contexts, an overemphasis on audience accommodation may lead to cultural oversimplification or strategic vagueness, undermining the theoretical integrity and value density of shenrong culture (Hu, 2024).

6 Translation Strategies from the Perspective of Value Negotiation

6.1 Responsibility-oriented ethics: reinforcing culturally authentic representation

Within a value-negotiation framework, a responsibility-oriented ethical approach emphasizes that translators bear the duty to preserve the authentic cultural representation of shenrong in cross-cultural communication. This responsibility extends beyond textual "fidelity" to the complete transmission of the traditional knowledge system, value orientations, and medical philosophy embedded in shenrong culture (Zhang and Dong, 2020). Traditional expressions such as "tonifying qi and nourishing blood", "benefiting essence", "harmonizing Yin and Yang", and "strengthening the righteous to consolidate the root" are not mere functional descriptions but conceptual crystallizations grounded in centuries of TCM theory and practice, carrying specific diagnostic logics and life philosophies (Wu et al., 2013). Thus, responsibility-oriented ethics requires translators to avoid reducing these terms to single biomedical descriptors of modern functional effects. Instead, translators should employ explanatory translation, framework-based interpretation, or annotations to bridge semantic gaps and preserve the knowledge structure of the source culture (Zhang and Dong, 2020). For example, adding clarifying phrases such as "rooted in traditional East Asian medical cosmology" or "a concept derived from holistic regulatory principles" can enhance intelligibility without sacrificing cultural depth.

However, strengthening cultural authenticity does not mean ignoring potential misunderstandings or cultural conflicts. In practice, certain culturally rich terms or formula names rendered through direct translation without contextual explanation often confuse or alienate international audiences unfamiliar with TCM or animal-derived medicinal traditions-especially when deer antler is involved, as it may trigger ethical and emotional sensitivities (Wu et al., 2013). Responsibility-oriented ethics is therefore not a call for rigid preservation but for "interpreted fidelity": providing appropriate background information and conceptual clarification without diluting cultural meaning, enabling target audiences to understand why these terms matter and how they maintain coherence within the source culture. In doing so, translators not only safeguard the identity of shenrong culture but also promote respect for-and understanding of-diverse medical traditions within global health discourse (Zhang and Dong, 2020; Kadier et al., 2025).

6.2 Communication-oriented ethics: enhancing communicative effectiveness and audience understanding

A communication-oriented ethical approach emphasizes that translation, as an act of intercultural communication, should optimize expression according to context and audience characteristics, while maintaining the integrity of core cultural structures. Shenrong culture is disseminated internationally through diverse channels-including advertisements, packaging, e-commerce listings, exhibition texts, museum materials, popular-science writing, and policy documents-each with distinct audience expectations, cultural literacy levels, and informational needs (Han, 2025). Consequently, translation strategies must be highly adaptive and context-specific.

For advertising texts, translators may structure the content around "functional positioning-safety-traditional background", using regulation-compliant neutral phrasing such as "helps support vitality/energy" instead of unverified therapeutic claims, thereby balancing compliance with cultural signaling (Ichim and De Boer, 2021; Han, 2025). For museum or educational materials, translators should employ annotations and concise theoretical explanations to help audiences understand the systemic logic behind terms like "tonifying qi" or "harmonizing Yin and Yang". For academic or museum-style texts, maintaining terminological precision and narrative coherence is essential, allowing for greater informational density and theoretical depth (Ramadilla et al., 2024).

From the perspective of communication ethics, translators must actively manage cultural distance, ensuring smooth transmission of shenrong-related knowledge across cultural systems rather than relying on superficial label-matching. For audiences entirely unfamiliar with TCM, a "layered explanatory model" is particularly effective: Layer 1: Provide intuitive, relatable meanings (e.g., energy regulation, joint support). Layer 2: Add theoretical context (e.g., based on the Yin-Yang balance doctrine). Layer 3: Incorporate scientific evidence when appropriate (e.g., deer antler extract's regulatory effects on cartilage cells). This creates an organic bridge across cultural, scientific, and market discourses (Yao et al., 2020; Han, 2025). The goal of communication ethics is not "accommodation for its own sake", but rather the creation of a space in which culturally authentic concepts can be understood without triggering unnecessary resistance or misinterpretation.

6.3 Mechanisms for balancing cultural authenticity and communicative effectiveness

Responsibility ethics and communication ethics often exist in tension: the former prioritizes cultural depth and authenticity, while the latter emphasizes communicative clarity and accessibility. To achieve a dynamic balance in translating shenrong culture, a "text-type stratified translation strategy" can serve as a practical mechanism. This approach assigns different degrees of cultural visibility and conceptual explanation according to the text type: High visibility: Dense cultural and theoretical presentation in museum materials and academic texts. Moderate visibility: Interpretive adaptation in exhibitions and popular-science writing. Low visibility: Accessible functional expressions in advertisements and packaging (Zhang and Dong, 2020; Kadier et al., 2025). This "gradient of cultural visibility" acknowledges differences in audience capacity and informational needs, treating cultural content as a resource that can be contextually allocated rather than as an all-or-nothing choice.

In practice, maintaining this balance requires institutionalized, interdisciplinary, and multi-stakeholder collaboration. Translators, brand owners, museum institutions, industry associations, researchers, and regulatory bodies can jointly develop standards for terminology, translation style guides, and boundaries for efficacy claims in the international dissemination of shenrong culture, thus reducing cultural fragmentation and mitigating ethical risks stemming from inconsistent individual decisions (Han, 2025; Kadier et al., 2025). For instance, "traditional terminology explanation templates" could be developed to specify how terms like "tonify qi" or "benefit essence" should combine transliteration, interpretation, and annotation across text types. Scientific findings-such as the potential cartilage-regenerative functions of deer antler extracts (Yao et al., 2020)-may be introduced in consumer-facing texts with clear evidence-level indicators to prevent misinterpretation as confirmed medical efficacy (Ichim and De Boer, 2021). Through such balancing mechanisms, translation becomes not a passive struggle between authenticity and effectiveness but an active value-negotiation practice at the center of responsible cross-cultural communication.

7 Conclusion

7.1 Balancing cultural representation and cross-cultural adaptation in shenrong translation

The international dissemination of shenrong culture reflects the deep extension of the TCM knowledge system into global contexts. Its translation requires establishing a demonstrable dynamic balance between cultural representation and cross-cultural adaptation. On one hand, core TCM concepts carried by ginseng and deer antler-such as qi, Yin-Yang, essence and blood (jing-xue), and holistic regulation-lack direct equivalents in dominant Western epistemological frameworks. Overemphasizing biomedical reinterpretation from the target culture's perspective risks compressing complex cultural–medical structures into a one-dimensional narrative of "functionalized, commodified" products. On the other hand, international communication requires translations to be intelligible, compliant with local regulations, and compatible with the target culture's value orientations; otherwise, they cannot be integrated into existing health discourses or gain institutional and market-level legitimacy.

Thus, the core task of shenrong translation is not to choose rigidly between "fidelity" and "adaptation", but to construct a reasoned equilibrium between cultural authenticity and communicative effectiveness. Practically, this balance relies on integrating explanatory expressions, contextual supplementation, and narrative restructuring. For example, while retaining terms such as "tonifying qi", "benefiting essence", and "harmonizing Yin and Yang", translators may use intra-textual or inter-textual annotations to situate them within TCM's holistic worldview. Meanwhile, adjusting health-oriented phrasing to meet regulatory and cognitive expectations of the target culture helps lower comprehension barriers. This translational practice requires translators to act simultaneously as cultural interpreters and cross-cultural strategists-preserving cultural authenticity while creating viable entry points for shenrong culture in global settings.

7.2 How translation ethics helps address cultural differences and value conflicts

Given the reality that shenrong culture spans multiple boundaries-cultural, medical, commercial, and ethical-translation ethics offers a structured analytical framework for managing cultural differences and value conflicts. Ethics of cultural representation reminds translators to maintain the integrity of traditional knowledge and semantic ecology, guarding against the excessive dilution, symbolization, or decontextualization of TCM-related knowledge under global trade and health-consumption logics. Cross-cultural adaptation ethics guides translators to adopt compliant, culturally sensitive strategies when confronting diverse regulatory environments concerning medical claims, animal-derived ingredients, and resource sustainability, thereby avoiding mistranslation, exaggerated claims, or expressions that conflict with target-cultural ethical norms.

Most importantly, value-negotiation ethics emphasizes that translators function not merely as linguistic transmitters but as mediators among competing discourses. Shenrong-related translation frequently intersects with issues such as animal welfare, ecological sustainability, traditional knowledge rights, and global biodiversity governance. Under such conditions, the translator's work involves not only delivering information but also ensuring-through transparent, accurate, and responsibility-aware choices-that different knowledge systems and value claims are represented fairly within the text. Translation ethics, therefore, is not merely a set of professional norms but a foundational mechanism for building cross-cultural trust, reducing misunderstanding, and preventing the inappropriate use of traditional medical knowledge.

7.3 Constructing an ethical translation system for the international dissemination of TCMculture

Based on the above analysis, constructing an ethical translation system for TCM culture-including shenrong traditions-is both an academic necessity and a practical requirement for the sustainable development of TCM-related trade under initiatives such as "TCM Going Global" and the Belt and Road framework. Such a system should include at least three interconnected dimensions: Translation practice and education: Developing culturally sensitive translation guidelines that define translatability boundaries, explanatory paths, and contextual requirements for core concepts such as qi, Yin-Yang, and essence-blood, thus avoiding arbitrary and inconsistent handling in practice.Interdisciplinary and intersectoral collaboration: Situating translation within intersecting domains of medicine, ecology, trade regulation, and cultural studies-particularly ensuring that translation does not obscure unsustainable practices when wildlife-derived resources are involved. Ethical review and compliance assessment: Establishing mechanisms aligned with industry standards to conduct "content-ethics-regulation" evaluations for shenrong texts intended for global markets, thereby reducing long-term risks at the source.

Building such an ethical translation system would enable shenrong culture to achieve more precise, stable, and ethically sound pathways of global dissemination. On one hand, it would enhance the epistemic status of TCM culture and reduce the likelihood of marginalization or misinterpretation in global health discourse. On the other hand, under principles of sustainable use and strict regulation, it would promote synergy between traditional medicine and global biodiversity conservation-laying the foundation for the responsible international communication of China's rich medical and ecological heritage.

Authors' contributions

An Yuanyuan was the principal investigator of this study, responsible for the literature review and data analysis, as well as the writing and revision of the initial manuscript. The author has read and approved the final manuscript.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Review Article Open Access

Photobiology in Hydroponics: Effects of Artificial Light Quality on Crop Growth, Metabolism and Resilience

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Abstract Hydroponic cultivation has emerged as a highly efficient method for producing high-quality crops in controlled environments, where artificial lighting plays a central role in determining plant performance. This study synthesizes current knowledge on how artificial light spectra (particularly blue, red, green, far-red and UV-A/B) affect plant growth, metabolism and stress resilience in soilless cultivation systems. The review highlights an integrated framework of light quality-metabolism-stress resistance and discusses how spectral composition influences both productivity and functional quality. Red and blue wavelengths, widely used due to their photosynthetic roles, are shown to increase yields by approximately 15%-25% compared with monochromatic or broad-spectrum light. Emerging evidence further emphasizes the functional relevance of green, far-red and ultraviolet light in modulating biomass accumulation, secondary metabolite production and abiotic stress responses. The study underscores the importance of tailoring light quality according to species, growth stage and desired agronomic outcomes, integrating dynamic lighting strategies, crop-specific "light recipes" and AI-assisted control. Understanding and leveraging photobiological responses in hydroponics are essential to achieving sustainable, high-performance food production.

Keywords Hydroponics; Artificial light spectra; Photobiology; LED-based lighting strategies; Dynamic lighting control

1 Introduction

Hydroponic cultivation has gained prominence as a viable and sustainable alternative to traditional soil-based agriculture, offering advantages such as optimized resource use, spatial efficiency and the potential for year-round production under controlled environments (Pomoni et al., 2023; Singh et al., 2024). In such systems, light is not only a vital energy source for photosynthesis but also serves as a primary environmental signal regulating plant growth, morphogenesis, metabolism and stress adaptation (Paradiso and Proietti, 2022).

Unlike field-grown crops that experience fluctuating and often suboptimal light conditions, hydroponic systems provide a unique opportunity to manipulate light quality (spectral composition), intensity and photoperiod with high precision. This capacity for control allows researchers and growers to tailor lighting strategies to the specific physiological needs of crops, potentially enhancing productivity and nutritional value (Olle and Viršile, 2013; Mitchell et al., 2015).

The advent of light-emitting diode (LED) technology has revolutionized artificial lighting in controlled environment agriculture (CEA). LEDs offer the ability to emit narrow wavelength bands with low heat output and high energy efficiency, enabling fine-tuned photobiological responses in plants (Bourget, 2008). Numerous studies have investigated the effects of different light spectra, particularly red and blue light, on plant morphology and photosynthesis, but a comprehensive synthesis focusing on photobiological responses in hydroponically grown crops remains limited.

Furthermore, recent evidence suggests that light quality can modulate the biosynthesis of secondary metabolites such as flavonoids, terpenes and antioxidants (Dou et al., 2017), as well as influence tolerance to abiotic stresses including salinity, drought and thermal fluctuations (Dou et al., 2017; Hasan et al., 2017). These responses are particularly relevant in hydroponic systems, where environmental parameters can be fine-tuned to optimize both plant health and functional quality. This study aims to provide an integrative overview of how artificial light quality affects plant photomorphogenesis, secondary metabolism and abiotic stress responses in hydroponic systems. We also discuss emerging technologies that enable dynamic and spectrum-adaptive lighting strategies and explore their potential in precision agriculture applications.

2 Fundamentals of Photobiology in Plants

Light is a fundamental environmental signal that regulates not only photosynthesis but also a wide array of developmental and metabolic processes in plants. Through the perception of specific wavelengths, plants adjust their growth patterns, morphology, resource allocation and stress responses in a process known as photomorphogenesis (Wang et al., 2022). Understanding the photobiological basis of these responses is essential for optimizing artificial lighting strategies in hydroponic systems.

2.1 Photoreceptors and their spectral sensitivity

Plants possess specialized photoreceptors that absorb specific portions of the light spectrum and initiate signaling cascades:

Phytochromes are chromoproteins that perceive red (R: 620-700 nm) and far-red (FR: 700-750 nm) light (Wang et al., 2022). They control seed germination, stem elongation, shade avoidance and flowering. Phytochrome-mediated responses depend on the red:far-red light ratio, a critical indicator of canopy density and competition (Legris et al., 2019).

Cryptochromes and phototropins absorb blue (B: 400-500 nm) and UV-A (320-400 nm) radiation. Cryptochromes are involved in photoperiodic flowering, hypocotyl inhibition, and circadian clock regulation, while phototropins (control phototropism, chloroplast relocation and stomatal opening (Li and Yang, 2007).

UVR8 is a unique UV-B photoreceptor that perceives short-wavelength radiation (280-315 nm) and triggers protective responses including the induction of flavonoid biosynthesis, ROS scavenging enzymes and DNA repair mechanisms (Yin and Ulm, 2017).

These photoreceptors not only regulate specific processes individually but also work in concert to coordinate growth, resource allocation and adaptation to environmental stimuli. Their activity underlies many of the photobiological responses observed in hydroponic crops, as will be discussed in subsequent sections.

2.2 Photosynthesis and the action spectrum

Photosynthetically active radiation (PAR: 400-700 nm) encompasses the range of wavelengths used by photosystems I and II to drive electron transport and CO_2 fixation. Among these, red and blue wavelengths are the most effective for stimulating photosynthesis due to their strong absorption by chlorophyll a and b (Wimalasekera, 2019).

However, green light (500-570 nm), traditionally considered less important due to lower chlorophyll absorption, has gained renewed attention. While not as efficient on a per photon basis, green wavelengths can penetrate deeper into leaf tissues and inner canopy layers, thus supporting photosynthetic activity in shaded leaves, especially in dense or multilayered hydroponic systems. This spatial complementarity enhances whole-plant photosynthetic performance when green light is used in combination with red and blue (Smith et al., 2017).

Understanding the action spectrum, the relative quantum efficiency of different wavelengths for photosynthesis, enables precise tailoring of light spectra in artificial lighting systems. In hydroponic setups, this is particularly valuable to maximize light-use efficiency (LUE), optimize biomass accumulation and reduce energy costs, especially when combined with spectral tuning technologies.

2.3 Photobiological responses in hydroponic contexts

In hydroponic systems, the absence of soil and the use of controlled environments allow the isolation and manipulation of light as a single variable, making it an ideal platform to investigate photobiological responses. Under these conditions, plants often display heightened sensitivity to spectral changes due to the stability of other growth factors (Dou et al., 2017).

These responses are mediated by specialized photoreceptors, including phytochromes, cryptochromes, phototropins and UVR8, which together orchestrate a wide range of physiological processes such as seedling de-etiolation, stomatal regulation, and flowering (Folta and Carvalho, 2015).

Recent research in indoor hydroponic systems has examined how varying light intensities, particularly under controlled red and blue LED spectra, influence plant growth and quality. In a study involving basil (*Ocimum basilicum* L.) and lettuce (*Lactuca sativa* L.), increasing the photosynthetic photon flux density (PPFD) from 100 to 300 μmol/m^2/s LED to a progressive rise in biomass accumulation, with optimal yield observed at 250 μmol/m^2/s. Beyond this level, no additional yield gains were reported. Importantly, at 250 μmol/m^2/s, lettuce exhibited significantly higher antioxidant activity, as well as increased levels of total phenolics and flavonoids. These findings suggest that moderate enhancements in light intensity not only maximize biomass production but also improve the nutritional quality of leafy vegetables grown in controlled indoor environments (Pennisi et al., 2020).

Moreover, manipulating the red:far-red ratio in vertical farming setups can regulate shade-avoidance responses, affecting plant height, leaf expansion and resource partitioning, which has direct implications for optimizing space and uniformity in multilayer production systems (Park and Runkle, 2017).

In summary, a deeper understanding of photoreceptor-mediated signaling and its modulation by artificial spectra is essential for tailoring light recipes that enhance growth, nutritional quality, and stress resilience in soilless crops. Hydroponic cultivation thus provides a unique opportunity to refine photobiological strategies for sustainable and efficient crop production.

2.4 Light quality and secondary metabolism in hydroponic crops

Light quality, particularly spectral composition, plays a critical role in modulating secondary metabolism in plants (Hasan et al., 2017), a set of biochemical pathways that generate compounds such as phenolics, flavonoids, alkaloids and terpenes, many of which are associated with stress tolerance, antioxidant activity and nutritional value (Böttger et al., 2018). In hydroponic systems, the high degree of environmental control offers an ideal context to fine-tune spectral inputs and thereby modulate these metabolic pathways with precision.

Blue light has been shown to influence the biosynthesis of phenolic compounds and flavonoids through the activation of key transcription factors in the phenylpropanoid pathway. This regulation is particularly relevant in leafy greens and culinary herbs, where antioxidant capacity is a core attribute of functional quality. For instance, in hydroponically cultivated japanese mint (*Mentha canadensis* L.), blue light significantly increased the production of monoterpenes such as menthol and menthone, indicating an upregulation of specialized metabolite pathways (Ueda et al., 2021). Similarly, kale (*Brassica oleracea* L. var. *acephala*) microgreens exposed to blue LEDs showed higher levels of phenolic compounds like quercetin and sinapic acid, accompanied by enhanced antioxidant activity (Lee et al., 2023). In basil, studies on microgreens and in vitro cultures confirmed that blue light elevates levels of rosmarinic acid and total phenolics, thus enhancing its nutritional profile (Nazir et al., 2020).

Red light, while primarily promoting photosynthesis and biomass accumulation, generally has a limited effect on secondary metabolism compared to blue or UV-A radiation (Hasan et al., 2017). However, combining red with blue light often produces synergistic effects, enhancing both vegetative growth and bioactive compound production. This has been demonstrated in crops such as sweet wormwood (*Artemisia annua* L.), where red-blue

LEDs significantly increased flavonoid, phenolic and artemisinin content (Rai et al., 2024) and in lettuce, basil and kale, where red-blue combinations improved antioxidant properties and pigment accumulation (Trivellini et al., 2023).

Far-red light, although less efficient at directly driving photosynthesis, plays a key regulatory role in plant development through phytochrome-mediated signaling pathways, influencing growth, secondary metabolism and phenological responses (Demotes-Mainard et al., 2016). In mint (*Mentha haplocalyx* Briq.), supplementation with far-red light enhanced biomass accumulation and photosynthetic performance while significantly promoting the biosynthesis of phenolic compounds and flavonoids such as luteolin and methylchavicol, suggesting its utility in improving both growth and medicinal value (Yu et al., 2024). Likewise, in basil, night interruption with far-red light increased flavonoid content by over 40% and improved biomass partitioning toward leaves, contributing to enhanced quality and postharvest durability (Fallah et al., 2024). These findings are consistent with meta-analytical evidence showing that moderate far-red supplementation significantly increases plant height, leaf area and dry biomass in vegetable crops, while also modulating nutritional traits like soluble sugars (Zhang et al., 2024).

Although not part of the photosynthetically active radiation (PAR), UV-A radiation plays a pivotal role as an environmental signal, particularly as an elicitor of secondary metabolism. In lettuce, exposure to UV-A-enriched light environments has been shown to significantly enhance the accumulation of phenolic compounds and anthocyanins, along with improved antioxidant capacity, especially when applied during the pre-harvest phase (Tsormpatsidis et al., 2008).

In conclusion, spectral management in hydroponic systems offers a powerful tool to modulate the synthesis of secondary metabolites, enabling the production of high-value crops with enhanced functional properties. Understanding the specific roles of different wavebands is key to designing light recipes that balance productivity with nutritional and sensory quality.

2.5 Light as a tool for abiotic stress management in hydroponic systems

In hydroponic systems, where environmental parameters can be tightly controlled, light becomes not only a driver of photosynthesis but also a powerful modulator of stress responses. Specific light spectra can mitigate the adverse effects of abiotic stresses such as salinity, heat, drought-like conditions and nutrient imbalances (Islam et al., 2021; Soufi et al., 2023), all of which may arise even under soilless cultivation due to recirculating nutrient solutions, equipment malfunction or high evaporative demand.

Blue light has been widely associated with enhanced antioxidant defenses, primarily through the activation of genes encoding antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD) (Soufi et al., 2023; Trivellini et al., 2023).

UV-A radiation can act as a priming agent, inducing mild oxidative stress that triggers acclimation responses. In controlled studies with hydroponic kale pre-harvest exposure to combined UV-A radiation and chilling stress enhanced abiotic stress tolerance by increasing phenolic compound accumulation and antioxidant enzyme activity, without compromising growth or photosynthetic capacity (Lee et al., 2019).

Red and far-red light influence phytochrome signaling pathways that regulate stomatal conductance and water-use efficiency (Legris et al., 2019). In aeroponics systems, manipulating the red:far-red ratio has been proposed as a method to reduce transpiration and improve tolerance to short-term water deficit without compromising biomass production (Carotti et al., 2023).

Furthermore, light-nutrient interactions are increasingly recognized as key to optimizing stress resilience. Under nitrogen-limited conditions, combined red and blue light improves nitrogen-use efficiency by enhancing enzymes involved in carbon-nitrogen metabolism. In tomato (*Solanum lycopersicum* L.) seedlings, a 3:1 red:blue ratio upregulated nitrate reductase and glutamine synthetase activity (Wang et al., 2017), while in spinach (*Spinacia* *oleracea* L.), blue-green-red light combinations boosted biomass and key nitrogen-assimilating enzymes under low nitrogen supply (Ramezani et al., 2023). In summary, beyond growth promotion, targeted light treatments serve as a non-chemical strategy to improve abiotic stress tolerance in hydroponic crops, contributing to the sustainability and resilience of soilless food production systems.

2.6 Design of lighting strategies in hydroponic systems

Designing effective lighting strategies in hydroponic systems requires an integrative approach that considers spectral quality, light intensity, photoperiod and spatial distribution (Figure 1). Unlike field or greenhouse cultivation, hydroponic systems, especially in fully controlled environments, allow for precise modulation of light parameters, offering a unique opportunity to optimize photosynthetic efficiency and plant quality.

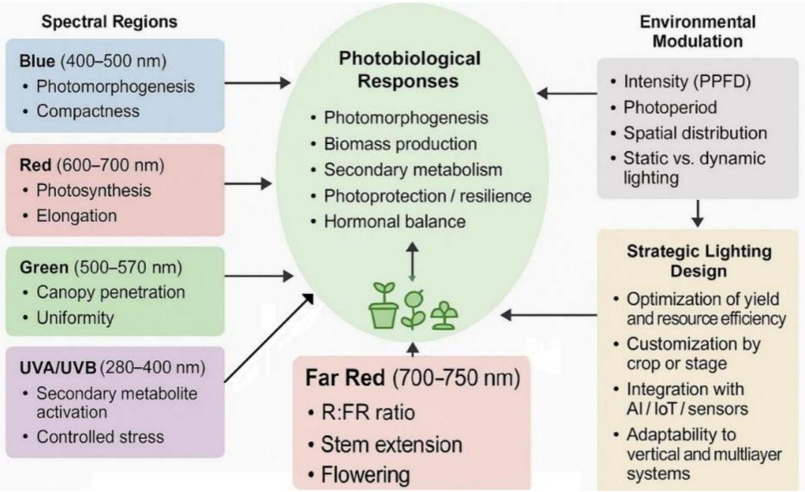

Figure 1 Conceptual diagram summarizing plant photobiological responses to different spectral regions in hydroponic systems and their integration into lighting design strategies for optimizing growth, efficiency and stress resilience

2.6.1 Photoperiod and light intensity

Photoperiod plays a key role in plant development by interacting with circadian rhythms and flowering regulation. Most leafy vegetables and herbs respond positively to long-day photoperiods (e.g., 16 h light / 8 h dark), which promote vegetative growth and delay flowering (Adams and Langton, 2005). This response has been demonstrated in several species, including lettuce, basil and arugula (*Eruca sativa* L.), where a 16-hour photoperiod significantly enhanced foliar biomass and overall yield compared to shorter photoperiods.

Optimal light intensity must be defined according to crop-specific requirements and phenological stage, while ensuring energy efficiency. In general, moderate to high PPFD values (e.g., 200-300 μmol/m^2/s) are often used in indoor cultivation (Pennisi et al., 2020; Gavhane et al., 2023), although the ideal range may vary. Importantly, increasing light intensity beyond a certain threshold does not always improve yield and may reduce resource-use efficiency (Engler and Krarti, 2021).

2.6.2 Directional lighting

The orientation and positioning of lighting, such as top-down, side-lighting or intercanopy lighting, can significantly impact light interception and canopy uniformity (Stamford et al., 2023). Side-lighting, for example, has been shown to enhance leaf expansion and uniformity in multilayer systems, particularly when green light is included to penetrate deeper into the canopy (Schipper et al., 2023).

2.6.3 Spectral customization

Tailoring the light spectrum according to crop species or development stage is becoming increasingly viable with programmable LED systems. For example, seedling stages may benefit from blue enriched light to promote compact growth (Treder et al., 2016), while reproductive stages may require red and far-red components to stimulate flowering (Bojka, 2020). The ability to shift spectral profiles over time allows for fine-tuned control of morphogenesis, metabolism and yield.

In summary, lighting strategy design in hydroponics should go beyond simple illumination and incorporate principles of photobiology, precision agriculture and crop-specific requirements. Thoughtfully designed lighting schemes can enhance both productivity and sustainability in soilless cultivation systems.

3 Agronomic Applications and Case Studies

The application of photobiological principles in hydroponic systems has led to significant advancements in crop performance, particularly for leafy vegetables and herbs. Controlled lighting environments offer the opportunity to optimize plant morphology, nutrient composition and productivity through spectral tuning and light management strategies.

3.1 Light source technologies and their agronomic implications

In hydroponic systems, artificial light sources determine both the quantity and quality of photosynthetically active radiation (PAR), influencing plant morphology, metabolism, and resource-use efficiency. Among the commonly used technologies-light-emitting diodes (LEDs), high-pressure sodium (HPS) lamps, and fluorescent lamps-each differs in spectral characteristics, energy performance, and suitability for various growth stages (Table 1).

Table 1 Comparative overview of artificial light sources used in hydroponic crop production

Technology	Advantages	Limitations
LED	Efficient, tunable spectrum, low heat, long life	High upfront cost
HPS	High light intensity, low initial cost	Inefficient spectrum, high heat; shorter lifespan
Fluorescent	Inexpensive, low heat, effective for propagation	Limited spectrum, lumen decay, not ideal for full cycle

LEDs have become the preferred option for hydroponic cultivation owing to their precise spectral tunability, high photon efficacy and long operational lifespan (50,000-100,000 h). Their ability to finely adjust red and blue light ratios optimizes photosynthesis and enhances the biosynthesis of bioactive compounds, such as phenolics and flavonoids, thereby improving both yield and nutritional quality. In addition, the reduced infrared emissions of LEDs lower canopy temperatures and water demand compared with high-pressure sodium (HPS) systems, contributing to higher overall resource-use efficiency (Dannehl et al., 2021; Knyazeva et al., 2024).

By contrast, HPS lamps emit primarily within the yellow–green spectral region, which is suboptimal for photosynthetic performance. Their high thermal output increases transpiration and water stress in plants, while their relatively short lifespan (10,000-20,000 h) and declining efficiency over time limit their long-term viability for intensive hydroponic production (Dannehl et al., 2021).

Fluorescent lamps, although affordable and characterized by low heat emission, provide limited spectral flexibility and insufficient intensity for full-cycle crop cultivation. Consequently, their use is generally restricted to propagation and early growth stages rather than large-scale or commercial applications (Seiler et al., 2017; Stamford et al., 2023).

In a word, LEDs are emerging as the standard in hydroponic lighting due to resource efficiency and crop-quality enhancements. HPS and fluorescents retain niche uses in propagation or legacy systems but are increasingly being phased out.

3.2 Crop specific responses

Multiple hydroponic studies demonstrate that lighting quality and strategy significantly influence both plant productivity and nutritional composition. In lettuce, comparative experiments under LED versus HPS lighting revealed 15% reduced water consumption under LEDs without compromising yield. Notably, LED treatments increased key phenolic compounds and overall phenolic content compared to HPS (Dannehl et al., 2021). Further, dynamic red and blue LED regimens in lettuce boosted xanthophyll accumulation and enhanced photosynthetic indices and transpiration efficiency (Samuolienė et al., 2021).

In basil, the use of LED lighting has shown superior performance compared to fluorescent tubes. In a study testing four LED spectral profiles, including combinations of red, far-red, blue, green and UV, both cultivars displayed significantly greater total biomass and phenolic content under LED treatments, compared to fluorescent control (Bantis et al., 2016). A more recent study found that combinational red, blue and far-red LEDs further elevated biomass and phenolic production relative to white LEDs (Rahman et al., 2021).

Tomato research indicates that even short LED light supplementation during night periods of red/blue/far-red spectrum can enhance yield nutritional quality (Arif et al., 2024). In cucumber (*Cucumis sativus* L.), nutrient film technique (NFT) trials comparing LED-only lighting with combined HPS+LED and HPS-only treatments found the highest yields and chlorophyll content under LED-only conditions. Enhanced gas exchange and PSII efficiency in LED-only compartments further supported fruit yield improvements (Gajc-Wolska et al., 2021) Additionally, cucumber seedlings grown under red/blue LEDs developed stronger root systems and higher biomass accumulation than controls.

Microgreens, due to their short growth cycle and high nutritional density, are particularly sensitive to light conditions. Both the spectral composition and intensity of artificial lighting significantly influence their morphological development, pigment accumulation and nutrient content. Optimizing parameters such as the blue:red light ratio and total photon flux density can modulate key traits including shoot elongation, biomass production and the synthesis of bioactive compounds (Zhang et al., 2020; Partap et al., 2023). In a hydroponic study, increasing the proportion of blue light from 0% to 100% consistently reduced shoot elongation in mustard (*Brassica juncea* L.) and kale microgreens, while simultaneously enhancing the accumulation of macro and micronutrients (Brazaitytė et al., 2021).

Collectively, these studies illustrate a consistent trend: LED lighting enhances both productivity and functional quality across a range of hydroponic crops. Crop-specific ‘lighting recipes’, including tailored red:blue ratios, supplemental periods and dynamic light profiles, enable optimization of distinct outcomes such as yield, antioxidant capacity, and nutrient accumulation. This supports the concept of precision lighting in hydroponic horticulture to meet both agronomic and nutritional goals.

3.3 Practical implications of artificial light strategies in hydroponics

The evidence reviewed across multiple hydroponic crops highlights the central role of light spectrum and intensity as modulators of both productivity and nutritional quality. LEDs (owing to their customizable spectra, energy efficiency, and minimal heat output) consistently outperform traditional lighting systems such as HPS and fluorescent lamps in both yield optimization and enhancement of phytochemical profiles. These advantages are particularly evident in leafy greens and microgreens, where short cycles allow rapid phenotypic responses to spectral adjustments.

Species-specific outcomes underline the necessity of tailored “light recipes.” For instance, lettuce benefits from moderate red:blue ratios (e.g., 3:1) for biomass and phenolic accumulation (Dannehl et al., 2021), while basil and tomato exhibit improved functional traits under red and far-red enriched environments (Bantis et al., 2016; Arif et al., 2024) . Microgreens, by contrast, respond to blue-dominant spectra with reduced elongation and elevated nutrient density, although responses vary significantly between cultivars (Zhang et al., 2020).

From an agronomic perspective, these findings support a paradigm shift toward dynamic lighting strategies in commercial hydroponic systems. Implementing crop and stage specific light profiles (potentially using programmable LED arrays and sensor-integrated control) could enhance both resource use efficiency and final product quality. This precision lighting approach aligns with broader goals of sustainable intensification in controlled-environment agriculture (Stanghellini and Katzin, 2024).

4 Challenges and Future Perspectives

4.1 Technical and scientific bottlenecks

Despite rapid advances in artificial lighting, several technical and scientific constraints continue to limit the large-scale implementation of optimized spectral control in hydroponic systems. LED lighting, though markedly more efficient than conventional HPS or fluorescent systems, still entails substantial energy demands and high initial costs. The installation of LED arrays typically represents 40%-60% of the total setup cost, but payback can be achieved within 3-5 years due to reduced electricity consumption and extended lifespan (Patel, 2024).

In terms of energy performance, LEDs exhibit efficiencies of approximately 3.2-3.5 μmol/J, roughly double that of HPS systems, which range between 1.4-1.7 μmol/J (Dannehl et al., 2021). Nonetheless, lighting remains one of the most energy-intensive components in commercial hydroponic systems, accounting for 25%-35% of total operational energy use. Although integrating AI-assisted dimming strategies can reduce this demand by 15%-20%, challenges persist in balancing spectral optimization with cost-effective implementation.

Another critical limitation lies in the complexity of spectral interactions. Light quality, intensity and photoperiod interact dynamically with temperature, humidity and nutrient status, making standardization across systems difficult. Discrepancies in experimental setups and reporting metrics also hinder the establishment of universal lighting "recipes" for specific crops, thereby restricting reproducibility and scalability.

4.2 Knowledge and research gaps

At the scientific level, our understanding of how specific wavelengths regulate plant metabolism and morphogenesis remains incomplete. While red and blue spectra are well studied, the physiological mechanisms triggered by green, far-red and ultraviolet radiation require further exploration. These spectral regions often display species-dependent and context-specific effects, complicating model development for precise spectral recommendations.

Integrating omics-based research can help fill these gaps. Transcriptomic and metabolomic studies, for instance, have revealed how light quality influences the expression of transcription factors such as HY5 and MYB, which control the biosynthesis of secondary metabolites and antioxidant pathways (Wu et al., 2023; Zeng et al., 2023). However, comprehensive multi-omics models linking light perception to metabolic regulation are still scarce (Zhang et al., 2022). Developing such integrative frameworks would enable predictive spectral modeling, advancing from empirical experimentation toward mechanism-driven control.

Artificial intelligence offers a promising avenue to accelerate the development of adaptive horticultural lighting systems. Machine learning and deep learning models have been successfully applied to predict light-response patterns and optimize spectral compositions, such as red-to-blue light ratios, in order to balance plant productivity with energy efficiency (Durmus, 2020). Recent developments integrate AI with real-time sensor inputs (including chlorophyll fluorescence, canopy temperature and CO_2 exchange) to create self-regulating lighting systems that adjust spectral outputs based on plant feedback (Srinivasan et al., 2024). Despite this progress, the lack of large, standardized datasets and benchmarks remains a critical limitation to fully validate and generalize these AI-driven systems across diverse crops and cultivation environments.

4.3 Future directions and integrated solutions

The next generation of hydroponic photobiology will depend on bridging molecular knowledge, intelligent technology and sustainable management. Integrating AI-powered lighting systems with sensor networks and cloud-based analytics can enable precision control, dynamic energy savings and data-driven decision-making. The convergence of omics research, machine learning and environmental monitoring represents a new paradigm for achieving both efficiency and resilience in crop production.

At the same time, economic and policy frameworks will be crucial to ensure accessibility and scalability. Initial investments in LED infrastructure remain a key barrier, particularly for small enterprises. However, global sustainability programs are increasingly providing financial and regulatory support. The European Green Deal (European Commission, 2020) includes incentive mechanisms for energy-efficient technologies and smart agriculture, while the FAO (2022) underscores the importance of digital agriculture and artificial intelligence in enabling "green transitions" within agri-food systems. Establishing standardized certification systems for energy performance, alongside public–private partnerships, will accelerate adoption and promote long-term economic viability.

Ultimately, the sustainable evolution of hydroponic lighting requires simultaneous progress in technological innovation, fundamental research and institutional collaboration. The integration of omics-driven understanding with intelligent control and supportive policy environments will define the next frontier in achieving productive, resilient, and environmentally responsible hydroponic systems.

5 Conclusion

In hydroponic agriculture, where environmental variables can be tightly controlled, artificial lighting emerges as a central factor not only for biomass accumulation but also for shaping plant morphology, metabolism and functional quality. This review demonstrates that light quality, intensity and photoperiod interact in complex ways with plant photoreceptors and metabolic networks, influencing growth performance, nutrient composition, and stress resilience.

Red and blue light remain the fundamental drivers of photosynthesis and photomorphogenesis, yet expanding the spectrum to include green, far-red and UV-A/B wavelengths provides new opportunities for fine-tuning physiological responses. Such spectral diversification enables both yield optimization and the enhancement of bioactive compounds, essential for the development of high-quality, functional crops.

Beyond physiological optimization, the integration of omics-based research and artificial intelligence offers a path toward precision photobiology. Multi-omics studies can clarify the regulatory mechanisms underlying spectral responses, while AI-driven control systems enable adaptive and energy-efficient lighting management. Together, these advances promise to transform hydroponic systems into intelligent, self-optimizing production environments capable of real-time response to plant needs.

However, technological innovation alone will not ensure sustainability. Future progress depends on coupling scientific and digital advances with supportive economic and policy frameworks. Coordinated global efforts that integrate research, industry and governance will be essential to accelerate the adoption of energy-efficient technologies, foster equitable access and enhance the resilience of agri-food systems.

In summary, overcoming the current technological and economic barriers in hydroponic photobiology will require bridging molecular-level understanding of light signaling with intelligent control and policy frameworks. The convergence of omics-driven research, AI-based spectral management and renewable energy integration represents the next frontier in achieving efficient, resilient and sustainable hydroponic production.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Research Article Open Access

Growth, Yield, and Quality Performance of Swamp Cabbage (*Ipomoea aquatica*) Cultivars under NFT Hydroponic System

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Abstract The experiment was conducted to study the growth, yield and quality of swamp cabbage (*Ipomoea aquatica*) varieties grown with Nutrient Film Technique (NFT) hydroponic system in the net house of the Department of Horticulture, Hajee Mohammad Danesh Science and Technology University' Dinajpur during the period of May-July 2023. The single-factor experiment was run with three swamp cabbage cultivars, BARI swamp cabbage-1 (V1), La procesa swamp cabbage-1 (V2), and Nice green swamp cabbage (V3) under Complete Randomized Design (CRD) with three replications. The average temperature and humidity (daytime) for the study period were 33.86 °C and 91.5%. The results showed that BARI swamp cabbage-1(V1) was better than other cultivars. BARI swamp cabbage-1 (V1) exhibited the highest plant height, leaf area, fresh weight per plant, yield and dry matter percentage, which was found to be 30.33 cm, 664.80 mm^2, 235.03 g, 34.83 ton/ha and 12.33%, respectively. The study examined the performance of two swamp cabbage flowers growing in the same hydroponic system. Nice green (V3) showed the highest number of leaf (31 leaf/plant) and good adaptation increase. It also excelled in SPAD readings and vitamin C content. Nonetheless, results from V2 (LP-1) were only moderate compared to the other two. BARI swamp cabbage-1 (V1) is resulted superior in chlorophyll-a and β-carotene concentration compared to others. So, it was the highest yield and quality performer. The study's findings show the NFT hydroponic system is a suitable system to grow swamp cabbage sustainably especially in the area with limited water and land. The NFT growing aytem that is V1 (BARI swamp cabbage-1) demonstrated best performance for high yield and quality among the tested cultivars.
Keywords Swamp cabbage (*Ipomoea aquatica*); NFT; Hydroponic; Growth and yield performance

1 Introduction

In addition to being a source of food, the swamp cabbage (*Ipomoea aquatica*) was traditionally used for medicinal purposes. Swamp cabbage or Kangkong, a member of the Convolvulaceae family, generally grows in wet soils and is an aquatic plant. In particular, the evidence suggests that the extracts of leaves and stem showed antidiabetic, anti-inflammatory and antioxidant activities. Swamp cabbage (*Ipomoea aquatica*), known as Water Spinach or Kang Kong, is a rapidly growing semi-aquatic vegetable in Asia and tropical climates. Swamp cabbage is used as food due to the various nutritional properties it has, including the presence of iron, food fibers, vitamins A, B and C. helps to maintain intestinal health, as well as preventing anemia and increasing immunity (Shah et al., 2023). Swamp cabbage helps to protect ecosystems of wetlands by absorbing excess nutrients from water, which improves its quality. Therefore, the cabbage of the swamp is a potential functional food (Ahmed et al., 2022). Due to climate change and population growth, the swamp cabbage has been taken as a solution for sustainable agricultural growth.

The nutrient circulation of the system's system minimizes water waste and environmental influences and supports sustainable goals of food production (Jensen, 1997; Resh, 2020). Global challenges such as food shortages, land deterioration and water shortages have accelerated the introduction of sustainable cultivation methods such as hydroponics, which enables plants without a soil with optimized nutrient levy (Sousa et al., 2024). Under the hydroponic techniques, nutrient film technology (NFT) for its efficient nutrient and water consumption, a higher root oxygen supply and the compact design for urban and small agriculture (Puerta et al., 2007; Baiyin et al., 2021). NFT systems facilitate continuous nutrient supply and enable the adjustment of nutrient concentrations in real time, which are tailored to specific growth stages, which improves growth, the yield and quality of leaf vegetables such as swamp cabbage (Ahmed et al., 2022; Shah et al., 2023).

The versatility of NFT systems, including temperature regulation and scalability, deals with seasonal stress and improves production efficiency, decisively for the variable climate Bangladesh (Payumi et al., 2022; Das et al., 2022). In addition, the NFT cultivation reduces work in connection with soil preparation and weeds and offers an inexpensive and sustainable alternative to the traditional floor base (Kumar et al., 2023).

In Bangladesh, swamp cabbage is promising due to its adaptability in agrocological zones and fast growth cycle for improving nutritional security and nutrition. Traditional swamp coal cultivation is based on swampy countries, but hydroponic NFT systems can change production by enabling year-round growth in rural and urban environments in the middle of the challenges of land deterioration and climate variaability (Reddy et al., 2022; Ahmed et al., 2023).

This study evaluated three swamp cabbage (*Ipomoea aquatica*) cultivars—BARI Swamp Cabbage-1, La Procesa Swamp Cabbage-1, and Nice Green—under a Nutrient Film Technique (NFT) hydroponic system during the pre-monsoon and summer seasons in a net-house environment. Growth characteristics, yield components, and key quality traits were systematically assessed to compare cultivar performance under NFT conditions. The primary objective was to identify high-yielding and high-quality swamp cabbage cultivars suitable for NFT hydroponic production, thereby providing a scientific basis for cultivar selection and promoting sustainable and efficient hydroponic cultivation in Bangladesh and similar agro-ecological regions..

2 Materials and Methods

The experiment was took place at the Hajee Mohammad Danesh Science and Technology University's net house in Dinajpur, in the department of horticulture. The experiment aims to give the required information under a number of subheadings pertaining to the instruments and supplies utilized in the current study as well as the procedures employed.

2.1 Experimental site and conditions

The experiment was conducted in the net house and laboratory of the Department of Horticulture, Hajee Mohammad Danesh Science and Technology University (HSTU), Dinajpur, Bangladesh. The study was carried out during the pre-monsoon and summer seasons, with plant growth and yield evaluation conducted from May to July 2023, while biochemical analyses were performed from August to October 2023. The experimental site is geographically located at 25°39′ N latitude and 88°04′ E longitude, at an elevation of 37.5 m above sea level.

During the experimental period, the average maximum air temperature ranged from 32.24 °C to 34.86 °C, while the average minimum temperature varied between 26.61 °C and 28.28 °C, accompanied by high relative humidity (91.43%-92.05%). These climatic conditions are considered suitable for swamp cabbage (*Ipomoea aquatica*) growth. Monthly average temperature and relative humidity data were obtained from the Climate and Weather Department of the Bangladesh Wheat and Maize Research Institute, Noshipur, Dinajpur, to ensure accurate environmental characterization of the study period.

2.2 Experimental materials

Three swamp cabbage (*Ipomoea aquatica*) cultivars were used as experimental materials: BARI Swamp Cabbage-1 (V1), La Procesa Swamp Cabbage-1 (V2), and Nice Green (V3) (Figure 1). These cultivars were selected based on their commercial importance, yield potential, and adaptability to soilless cultivation. Seeds were procured from the local market of Dinajpur and were sown after ensuring uniformity and viability.

This experiment analyzed the morphological and biochemical characteristics of three swamp cabbage cultivars in a nutrient-film technique (NFT) system in a net house: (1) BARI Swamp Cabbage-1 (V1) is a high-yielding cultivar with rapid growth and long, thin-leaf green leaves; (2) LP-1 (V2) is a vigorous cultivar, known to have uniform, deep-green foliage and excellent adaptability to a wide range of environmental conditions; and (3) Nice Green Swamp cabbage (V3).

Figure 1 Three swamp cabbage cultivars used in this experiment

These cultivars are largely known to be very productive and capable of adapting to soilless cultivation, making them applicable in the year-round production. The aim of the current research was to evaluate the possibility of these cultivars in terms of maximizing yield and quality in controlled environmental conditions. The local market in Dinajpur procured the seeds of the three varieties in the local market.

2.3 NFT hydroponic system and experimental layout

The experimental set up was achieved through the use of the nutrient film technique (NFT) hydroponic system in a net house (Figure 2). It included cultivation channels, nutrient reservoir, and a circulation unit provided with submersible pumps that were turned on at the same time. The channels were constantly fed with nutrient solution to ensure that sufficient amounts of nutrients and aeration to the plant roots were provided and thus maintained a productive photo-synthetic activity. The trial design was based on a triple replication, perfectly randomized design (CRD). Each replication was to be carried out by growing all three cultivars under the same environmental conditions and management procedure.

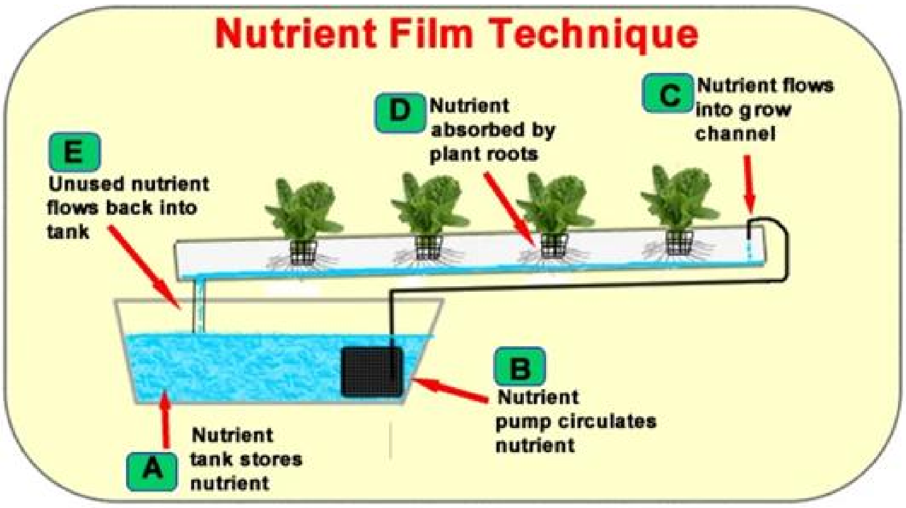

Figure 2 Diagram of hydroponic cultivation system

The type of design used was a totally randomized design (CRD) which was a formal experimental set-up. But actually the experiment was carried out on three replications of every cultivar and they all were grown under the same environmental and management conditions and no extreme variations were added.

2.4 Nutrient solution preparation and management

The nutritional needs of the plants were satisfied using the modified Murashige and Skoog (MS) nutrient formulation (Murashige and Skoog, 1962). The nutrient solution was first centred down into two separate stock solutions (Solution 2 and Solution 3) to prevent precipitation of calcium and phosphate salts. Table 1 gives the detailed composition of these stock solutions.

To prepare the working solution, Solution A (500,300 mL) and Solution B (125,300 mL) were mixed in 25,000 mL of water in a 30,000 mL reservoir. The resulting nutrient solution was pumped continuously in the Nutrient Film Technique (NFT) system until the cultivation period ended.

Table 1 Nutrient solution composition

Concentration of Nutrient Solution-A	
Component	Concentration (g/L)
KNO_3	45.30
Ca $(NO_3)_2$	26.70
NH4NO_3	1.33
Fe-chelate (6%)	3.00
Concentration of Nutrient Solution-B	
KH_2PO_4	20.00
$MgSO_4$	20.00
K_2SO_4	15.30
KNO_3	14.70
$MnSO_4$	0.16
$ZnSO_4$	0.23
B	0.23
$CuSO_4$	0.03
Na_2MoO_4	0.01

Note: Adopted from Murashige and Skoog (1962)

Solution A was made with the dissolution of 114.12 g of nutrients in 2,500 mL of distilled water and Solution B was made by dissolving 0.605 g of nutrients in 500 mL of distilled water. Table 1 shows the chemical composition of each constituent and its concentrations in both stock solutions in details. Solution A contained mainly nitrogen, calcium, potassium and iron, and Solution B contained phosphorus, magnesium, potassium and essential micronutrients needed to grow the plant.

To prepare the final working nutrient solution, 500 mL of Solution A and 125 mL of Solution B were mixed with 25,000 mL of water in a 30,000 mL nutrient reservoir. Throughout the cultivation period, the nutrient solution was in circulation inside the nutrient film technique (NFT) system. The nutrient solution was observed and corrected periodically to maintain its status in terms of electrical conductivity (EC) and pH to provide the best environment to grow swamp cabbage.

2.5 Monitoring of pH, EC, and TDS

Digital meters were used to measure the ph, electrical conductivity (EC) and total dissolved solids (TDS) of the nutrient solution periodically. The pH level was kept at 6.0-7.0 and is the ideal range of swamp cabbage growth; slight pH increments were corrected with the addition of vinegar. The EC was maintained at 0.8-1.0 MS/cm in the early stage of growth and at 1.2-1.8 MS/cm in the later stages, as recommended in the standard hydroponics. Whenever EC was much higher than the desired level, water was diluted and when EC was much lower than desired, nutrient solution was added.

TS is a metric that is used to identify the quality of solutions by determining the quantity of mineral dissolved in water. A TDS meter (model D272, Henan Wanbang EP TECH Co., Ltd., Liangyuan, China) is normally employed to identify the total dissolved solids of a solution, which is usually water.

TDS may be estimated based on EC observations as dissolved ionic solids like salts and minerals increase the conductivity of a solution. In Swamp-Kohl, the highest EC range was held at 0.8-1.0 MS/cm in the initial 10-15 days and 1.2-1.8 MS/cm in the rest of the growth period (Teodor et al., 2021). In case EC values were high, water was added to reduce EC values, and in situations where EC values were low, more nutrient solution was added to increase the conductivity. Swamp cabbage has seasonal changes in PH and electrical conductivity..

2.6 Seed germination, Seedling emergence, transplanting, and crop management

The germination of seeds was done in blocks of sponges soaked in water and placed in plastic trays and then covered overnight to maintain moisture (Figure 3). The seedlings emerged in a window of two days, and the germination rate was approximately 97 per cent (Figure 4) for all cultivars. The germination was followed by the addition of a dilute nutrient solution that would help to promote early plant growth.

On 26 May 2023 the healthy and evenly grown ten-day-old seedlings were relocated to the Nutrient Film Technique (NFT) system. Regular intercultural intervention was done to maintain uniformity in growth by routine gap filling, system sanitation and plant monitoring.

Figure 3 Seed placement for germination

Figure 4 Seedling emergence

2.7 Algae, pest, and nutrient management

The proliferation of algae was curbed by preventing the light penetration of nutrient reservoirs and pipelines by covering with black polyethylene sheeting, and systematic sanitisation in tandem with the nutrient replacement process. Small amounts of hydrogen peroxide were put in place to retard the growth of algae. There were no cases of pest or pathogenic infestation that were reported during the trial and this could be credited to the introduction of a soilless hydroponic system of cultivation. Initially, a replacement of nutrient solutions was done on a ten day basis but this was later changed to a five day basis to ensure that it was more adjusted to physiological rates of uptake of nutrients by plants (Figure 5).

Figure 5 Plant harvesting

2.8 Harvesting and data collection

Data were collected at various Days After Transplanting (DAT) on the following morphological, yield contributing, and quality criteria.

2.8.1 Morphological parameters

Plant height, measured using a scale from each plant at 7-day intervals starting at 10 DAT and continuing until 56 DAT, was defined as the distance between the tips of the tallest leaves from the ground. The units were stated in centimeters.

The swamp cabbage plant's overall height was measured at two growth intervals in order to determine the absolute growth rate, or AGR. The daily growth rate was calculated by dividing the difference in plant height by the number of days between the two measurements. The following formula was used to determine the absolute growth rate:

$$\text{Absolute growth rate (AGR)}=\frac{H_2\text{-}H_1}{t_2\text{-}t_1}\text{cm/day}$$

Where, H_1 means height for D1, H_2 means height for D2

Starting at 10 days after transplanting (DAT) and continuing at seven-day intervals, the number of leaves on each plant was recorded until 56 DAT. At the last stage of harvest, the number of branches on each plant was noted. Every primary branch that emerged from the main stem was manually counted, and the average number of plants in the sample was calculated.

The leaf surface was estimated using an index counter in a portable digital leaf zone (YMJ-B, China). The process is to activate the digital lai counter by feeding it and preparing for use. The Zone Index Compt (LAI) is a specialized tool to quantify the surface of the leaves per unit of surface on the ground. A fresh sheet is chosen for the measurement and transmitted through the device sensor. The sensor, specially designed for this purpose, measures the foliar surface (MM2). Leaf length (length of the leaf between the apex and the base of the leaf-stalk) of each plant was recorded at 14-day time intervals starting at 14 days after transplanting (DAT) with a Leaf Area Index Meter, until 42 DAT.

Using the same Leaf area Index Meter, the leaf length to breadth ratio was measured from each plant at 7-day intervals beginning 14 days after transplanting (DAT) and continuing until 42 DAT. At the last stage of harvest, the swamp cabbage plants were carefully uprooted in order to measure the length of their roots. A measuring scale was used to determine the distance between the root collar and the tip of the longest root. Next, the sampled plants' average root length was determined.

2.8.2 Yield and yield contributing parameter

At each harvest, the plant yield per plant was expressed in grams. The final yield per plant was calculated by adding these figures from each harvest. The final yield per plant was multiplied by the planting density to obtain the total marketable plant yield per hectare. The leaves were then sun-dried for three weeks, followed by another drying in an electric oven at 70 °C for three days. The percentage of the dry mass was calculated using the following formula:

$$\text{Dry Weight}=\frac{\text{Dry weight of plant}}{\text{Fresh weight of plant}}\times 100$$

In order to determine the percentage of the dry matter, the fresh weight of the swamp cabbage system was first recorded. As soon as a constant weight was reached, the dry weight was measured using an electronic balance (G G T100, Germany).

2.8.3 Quality parameters

The space was recorded at 14 that 28 and 42. A spad-502 plus (Horiba, Japan) model of a renowned manufacturer was used to measure the chlorophyll content in plant leaves. In the method, clean leaves were picked, the spad-502 plus calibrated, the sensor (2 × 3 mm) were placed on the leaves and spades.

The mix was made by the filter paper from Whatman no. Chlorophyll "A" in leaves was determined using the method of Nagata and Yamashita (1992). 1 filtered and the absorption at 445 Nm and 663 Nm measured. Chlorophyll "A" stop was calculated using the formula. A gram macerated sheet was mixed with 10 mL acetone hexan mixture (4: 6) and swirled for 5 minutes:

$$\text{Chlorophyll-a (mg/100 g fw)} = 0.999A663-0.0989A645$$

Where, A663 and A645 are the absorbances at 663 nm and 645 nm, respectively.

The same procedure used to measure chlorophyll "a" was used to measure chlorophyll "b" in leaves. The following formula was used to determine the amount of chlorophyll "b":

$$\text{Chlorophyll-b (mg/100 g fw)} = -0.328A663+1.77A645$$

The amount of beta-carotene in leaves was measured using the technique outlined by Tsiakaras et al. (2014). Ten milliliters of an acetone-hexane (4:6) combination were combined with one gram of macerated leaf, and the mixture was vortexed for five minutes. After passing the combination through Whatman No. 1 filter paper, absorbance measurements were made at 445, 663, 505, and 453 nm. The following formula was used to determine the beta-carotene content:

$$\beta\text{-carotene (mg/100 g fw)} = 0.216A663-1.22A645-0.304A505+0.452A453$$

Five grams of leaf tissue were homogenized in 100 mL of oxalic-eda acid solution. The homogenerate was centrifuged at 1,500 rpm for 15 minutes and the Sirnaant was filtered through Whatman n. 1. The ecorbic acid content was determined using the spectrophotometric procedure described by Farajzadeh and Nagizadeh (2003). Absorbance was measured at 760 nm and the concentration of ascorbic acid was quantified using a standard curve of l-ascorbic acid. A 5 mL rate has been mixed with metaphosphoric acid, sulfuric acid and ammonium molybdaded reagents.

2.9 Statistical analysis

The Statistix 10 statistical tool was used to statistically examine the data gathered for various parameters, and analysis of variance was carried out for each recorded parameter. At the 5% level of probability, the Least Significant Difference (LSD) value was used to quantify the importance of the variation in means.

3 Results and Analysis

The results obtained from the experiment are presented and analyzed in this section based on data collected at different days after transplanting (DAT). Growth, yield, and quality parameters of three swamp cabbage (*Ipomoea aquatica*) cultivars grown under the NFT hydroponic system were statistically analyzed, and significant differences among cultivars were identified. The results are organized into thematic subsections to highlight growth dynamics, morphological traits, yield components, dry matter accumulation, and quality attributes, with tables and figures used to summarize the key findings..

3.1 Morphological parameters

According to these results, V1 has a genetic advantage in the growth of height, which qualifies it as a cultivar for the production of ideal biomass of the NFT system. Significant variations have been observed in the height of the plants between the Cape Cape Cultivars to various DAT, with the exception of 35 and 42 DAT (Table 2). Over time, the height of all cultivars has gradually increased with V1 (Bari Swamp Cabbage-1) which continually produces the highest plants compared to V2 (LP-1) and V3 (Bel Green). The heights of the system varied from 30.33 cm to 27.43 cm per 56 DAT, with V1 that continues to be the highest, followed by V3 and V2 in that order.

Table 2 Plant height of swamp cabbage cultivars at different days after transplanting (DAT)

Cultivar	Plant height (cm)							
	7 DAT	14 DAT	21DAT	28 DAT	35 DAT	42 DAT	49 DAT	56 DAT
V1	15.63 a	18.20 a	22.13 a	25.03 a	26.13NS	27.40NS	29.07 a	30.33 a
V2	13.80 c	16.10 b	19.23 b	22.63 ab	24.36	25.83	26.73 b	27.43 b
V3	14.73 b	16.56 b	19.20 b	21.86 b	24.63	26.76	28.17 ab	28.70 ab
LSD (0.05)	0.88	1.05	1.52	2.89	2.76	1.92	1.52	1.72
CV (%)	2.98	3.09	3.77	6.23	5.51	3.62	2.73	2.99

Note: V1 = BARI swamp cabbage-1; V2 = La procesa swamp cabbage-1; V3 = Nice green swamp cabbage; NS = Non-significant. Means in the same column with different letter(s) are significant at the 0.05 level of probability

The differences observed in the height of the plants between the cultivars can be attributed to their genetic variations. A significant trait that affects the surrender is the height of the plant. In any case, V1 (Bari Swamp Cabbage-1) produced the highest plant, followed by V3 (Bel Green) and V2 (LP-1). Due to the innate cultivation model of the plant, it has been observed that the height of the plant has increased over time. Even environmental factors such as the availability of nutrients, the efficiency of the absorption of water and the adaptability to growth conditions can play a role, but the intrinsic varietal characteristics remain a primary determining factor. The higher performance of V1 suggest greater genetic potential for the extension of the stem and vegetative growth, probably due to the highest cell division rates and internal lengthening (2020), this shows that V1 has a higher development potential. It could be due to the varietal traits of the plant. In line with the previous results of Rahman et al. (2020).

3.2 Absolute growth rate (AGR) per plant

V1 had the highest AGR at 56 DAT (0.62 cm/day), which was much higher than V3S (0.43 cm/day), but not much of V2 (0.59 cm/day). In general, V1 (Bari Swamp Cabbage-1) had a larger AGR than V2 (LP-1) and V3 (beautiful green swamp cabbage). The higher AGR in V1 in early growth stages indicates strong vegetative growth, which could lead to better accumulation of biomass. The absolute growth rate varied significantly throughout the DAT, which indicates the different growth habits of the varieties (Table 3).

Table 3 Absolute growth rate per plant of swamp cabbage cultivars at different days after transplanting (DAT)

Cultivar	Absolute growth rate (cm/day)						
	14 DAT	21 DAT	28 DAT	35 DAT	42 DAT	49 DAT	56 DAT
V1	0.44 a	0.54 a	0.56 a	0.58 a	0.58 a	0.58 a	0.62 a
V2	0.24 c	0.27 c	0.33 c	0.36 c	0.43 b	0.42 b	0.59 b
V3	0.36 b	0.38 b	0.47 b	0.49 b	0.54 a	0.58 a	0.43 c
LSD (0.05)	0.05	0.02	0.05	0.05	0.04	0.03	0.03
CV (%)	7.30	2.38	5.38	5.66	4.62	2.75	2.43

Note: V1 = BARI swamp cabbage-1; V2 = La procesa swamp cabbage-1; V3 = Nice green swamp cabbage; NS = Non-significant. Means in the same column with different letter(s) are significant at the 0.05 level of probability

The AGR results show that V1 has a notable early growth advantage that might be utilized to maximize production plans by using staggered planting methods or early harvests (Tsiakaras et al., 2014).

3.3 Number of leaves per plant

The number of leaves per plant varied significantly among swamp cabbage cultivars at various DATs (Table 4). All cultivars showed a rise in leaf yield over time, however V1 (BARI swamp cabbage-1) produced the most leaves over all DAT compared to V2 (LP-1) and V3 (Nice Green). Compared to V2 (6.67) and V3 (8.33), V1 exhibited the highest leaf number (8.66) at 7 DAT. At 56 DAT, V1 had 32.33 leaves, V2 had 25.33, and V3 (31.00) was right behind V1. Its genetic potential for high photosynthetic efficiency which is necessary for ideal development and yield is highlighted by V1's enhanced leaf output.

Table 4 Number of leaves per plant of swamp cabbage cultivars at different days after transplanting (DAT)

Cultivar	Number of leaves per plant							
	7 DAT	14 DAT	21 DAT	28 DAT	35 DAT	42 DAT	49 DAT	56 DAT
V1	8.66 a	11.33 a	14.67 a	18.00 a	22.00 a	25.00 a	27.67 a	32.33 a
V2	6.67 b	9.33 b	11.33 b	13.67 b	16.00 b	18.67 b	22.33 b	25.33 b
V3	8.33 a	10.67 ab	14.33 a	17.67 a	21.33 a	24.33 a	27.33 a	31.00 a
LSD (0.05)	1.15	1.63	1.53	1.49	1.76	1.48	1.15	1.48
CV (%)	7.32	7.82	4.29	4.53	4.46	3.29	2.24	2.52

Note: V1 = BARI swamp cabbage-1; V2 = La procesa swamp cabbage-1; V3 = Nice green swamp cabbage; NS = Non-significant. Means in the same column with different letter(s) are significant at the 0.05 level of probability

The amount of leaves per plant varied significantly as a result of variability at different DAT. V1 consistently produced more leaves than other cultivars, which may have been due to its genetic potential. According to Haque et al. (2022), this implies that V1 is an excellent choice for maximizing foliage, which is essential for overall production.

3.4 Number of branch per plant

At 14, 28, 35 and 42 days after the transplant (DAT), a significant difference in the number of branches per plant was observed in the swamps (Table 5). With 8.33 branches up to 42 DAT, V1 was again in the lead, followed by V3 (7.33) and V2, which very few (5.33) had. V1 developed most branches (3.00) at 14 DAT and exceeded V2 (2.00), while V3 (2.33) entered the middle. Over time, the industry production with V1 (Bari Swamp Cabbage-1) continuously rose, which produce V2 (LP-1) and V3 (beautiful green). V1's ability to produce more branches reflects its strong growth habits and the potential for higher biomass and earnings. At 21 DAT, however, no such difference was found.

Branching ability is a significant factor in determining the overall yield potential. V1's higher branching contributed to its superior performance. Because of its improved branching, which facilitates better light interception and nutrient usage, V1 is a good choice for high-yielding systems (Karim et al., 2018).

Table 5 Number of branch per plant of swamp cabbage cultivars at different days after transplanting (DAT)

Cultivar	Number of branch per plant				
	14 DAT	21 DAT	28 DAT	35 DAT	42 DAT
V1	3.00 a	4.33NS	5.67 a	7.00 a	8.33 a
V2	2.00 b	3.33	4.33 b	4.67 b	5.33 b
V3	2.33 b	4.33	5.33 ab	6.33 a	7.33 a
LSD (0.05)	0.67	1.15	1.15	1.48	1.15
CV (%)	13.64	14.43	11.30	12.42	8.25

Note: V1 = BARI swamp cabbage-1; V2 = La procesa swamp cabbage-1; V3 = Nice green swamp cabbage; NS = Non-significant. Means in the same column with different letter(s) are significant at the 0.05 level of probability

3.5 Leaf area

With every DAT, remarkable variations in the leaf area were found in the case of swamp cabbage. V1 exceeded V2 (222.33 mm^2) and V3 (263.95 mm^2) by recording the largest leaf area (647.81 mm^2) at 14 DAT (Table 6). The largest leaf area was regularly observed by V1 (Bari Swamp Cabbage-1) compared to V3 (beautiful green) and V2 (LP-1). This pattern was still available at 42 DAT, whereby V1 is still better (664.80 mm^2), while V2 and V3 had noticeably reduced the leaf surfaces. The consistently larger leaf surface in V1 reflects its genetic advantage for efficient photosynthesis and contributes to higher growth and earnings potential.

Table 6 Leaf area of swamp cabbage cultivars at different days after transplanting (DAT)

Cultivar	Leaf area (mm^2)		
	14 DAT	28 DAT	42 DAT
V1	647.81 a	682.43 a	664.80 a
V2	222.33 b	329.74 b	283.93 b
V3	263.95 b	303.90 b	273.84 b
LSD (0.05)	54.00	92.65	39.63
CV (%)	6.94	10.86	4.87

Note: V1 = BARI swamp cabbage-1; V2 = La procesa swamp cabbage-1; V3 = Nice green swamp cabbage; NS = Non-significant. Means in the same column with different letter(s) are significant at the 0.05 level of probability

Leaf area is one of the most crucial variables affecting photosynthetic capability and output potential. The larger leaf area of V1 demonstrates its suitability for intensive cropping systems (Ahmed et al., 2022).

The leaf breadth of the various swamp cabbage cultivars varied noticeably at each DAT (Table 7). V1 (BARI swamp cabbage-1), V2 (LP-1), and V3 (Nice Green swamp cabbage) consistently produced the widest leaves. At 14 DAT (33.26 mm), V1's leaves were the broadest and notably larger than those of V2 (23.88 mm) and V3 (23.79 mm). This pattern continued at 42 DAT, with V1 still holding a dominant position (33.89 mm). Wider leaves in V1 suggest the possibility of improved photosynthetic efficiency and light interception, both of which are essential for plant development and yield.

Larger leaves on V1 may increase its ability to absorb sunlight, resulting in improved yield and growth (Khan et al., 2020).

Table 7 Leaf breadth of swamp cabbage cultivars at different days after transplanting (DAT)

Cultivar	Leaf breadth (mm)		
	14 DAT	28 DAT	42 DAT
V1	33.26 a	34.53 a	33.89 a
V2	23.88 b	25.68 b	24.78 b
V3	23.79 b	24.44 b	24.12 b
LSD (0.05)	3.06	5.23	2.22
CV (%)	5.59	9.42	4.03

Note: V1 = BARI swamp cabbage-1; V2 = La procesa swamp cabbage-1; V3 = Nice green swamp cabbage; NS = Non-significant. Means in the same column with different letter(s) are significant at the 0.05 level of probability

3.6 Leaf length

Significant differences in leaf length were observed between the swamp cabbage cultivars at each day after transplantation (DAT) (Appendix VIII) (Table 8). Compared to V2 (LP-1) and V3 (Nice green swamp cabbage), the leaves of V1 (BARI swamp cabbage-1) were consistently longer. At 14 DAT, V1's leaves were the longest (19.48 mm), significantly longer than those of V2 (9.30 mm) and V3 (11.12 mm). This pattern persisted at 42 DAT, with V2 consistently having the shortest leaves and V1 maintaining its advantage (19.61 mm). V1's longer leaves demonstrate its genetic superiority in creating larger foliage, which promotes improved photosynthetic efficiency and increased yield potential.

Table 8 Leaf length of swamp cabbage cultivars at different days after transplanting (DAT)

Cultivar	Leaf length (mm)		
	14 DAT	28 DAT	42 DAT
V1	19.48 a	19.75 a	19.62 a
V2	9.30 b	12.79 b	11.05 b
V3	11.12 b	12.42 b	11.77 b
LSD (0.05)	1.38	1.51	1.29
CV (%)	5.15	5.06	4.46

Note: V1 = BARI swamp cabbage-1; V2 = La procesa swamp cabbage-1; V3 = Nice green swamp cabbage; NS = Non-significant. Means in the same column with different letter(s) are significant at the 0.05 level of probability

Its vigor and productivity may be supported by the longer leaves in V1, which could suggest a genetic advantage in environmental adaptation (Haque et al., 2021).

3.7 Length-to-breadth (L/W) ratio

The length-to-breadth (L/W) ratios of swamp cabbage cultivars showed considerable variation from 14 to 42 DAT, but not at 28 DAT (Appendix IX). In contrast to V2 (LP-1) and V3 (0.47), V1 (BARI swamp cabbage-1) consistently exhibited the highest L/W ratio at 14 DAT (Table 9). V1 kept its advantage (0.58) at 42 DAT, indicating that it could be able to more effectively absorb light and use resources, which would result in improved growth and production.

Table 9 Length-to-breadth ratio of swamp cabbage cultivars at different days after transplanting (DAT)

Cultivar	L/W Ratio		
	14 DAT	28 DAT	42 DAT
V1	0.58 a	0.57 NS	0.58 a
V2	0.39 b	0.50	0.44 b
V3	0.47 b	0.51	0.49 b
LSD (0.05)	0.8	0.10	0.06
CV (%)	8.40	9.50	6.41

Note: V1 = BARI swamp cabbage-1; V2 = La procesa swamp cabbage-1; V3 = Nice green swamp cabbage; NS = Non-significant. Means in the same column with different letter(s) are significant at the 0.05 level of probability

V1's genetic aptitude for effective resource utilization is highlighted by its increased length-to-breadth ratio (Rahman et al., 2020).

3.8 Root length

V2 showed intermediate roots, starting at 2.97 cm at 7 DAT and growth to 16.03 cm by 56 DAT. This shows its strong genetic advantage in the development of a robust root system. The V1 variety showed the longest roots, starting at 3.77 cm at 7 DAT and reached 20.80 cm times 56 DAT (Table 10). In the varieties, significant differences in the root length were observed, with V1 consistently exceeding the others in all growth phases. The table shows the progression of the root length of different swamps on different days after the transplant (DAT) and their corresponding regular length in different DAT . In contrast, V3 had the shortest roots in all stages, from 3.27 cm at 7 DAT to 14.77 cm to 56 DAT, which indicates a relatively limited capacity for the root extension.

Table 10 Root length of swamp cabbage at different days after transplanting (DAT)

Cultivar	Root length (cm)								Dry wt%
	7 DAT	14 DAT	21 DAT	28 DAT	35 DAT	42 DAT	49 DAT	56 DAT	56 DAT
V1	3.77 a	5.97 a	11.37 a	13.00 a	15.10 a	17.00 a	19.13 a	20.80 a	8.59NS
V2	2.97 b	4.87 b	7.37 b	10.00 b	14.17 a	15.20 b	15.70 b	16.03 b	8.36
V3	3.27 ab	5.63 ab	8.63 b	9.57 b	10.73 b	11.87 c	13.70 c	14.77 b	8.92
LSD (0.05)	0.50	0.90	1.75	0.75	1.08	0.89	0.95	1.06	1.59
CV (%)	7.55	8.22	9.62	3.46	4.05	2.95	2.95	3.07	9.22

Note: V1 = BARI swamp cabbage-1; V2 = La procesa swamp cabbage-1; V3 = Nice green swamp cabbage; NS = Non-significant. Means in the same column with different letter(s) are significant at the 0.05 level of probability

The root length plays a crucial role in determining plant power, nutrient absorption and overall productivity. V1 shows its suitability for maximizing growth and for determining under different soil and environmental conditions, which emphasized the importance of strong root systems for increasing agricultural productivity and resilience. These results match Haque et al. (2021) V1 consistently exceeded other varieties in the root length and emphasized its ability to access distant nutrient resources, which supports its growth under challenging conditions. The moderate root development of V2 indicates the adaptability of less demanding environments, while the shorter roots of V3 can restrict the efficiency of nutrient and water absorption, especially in resource-related environments.

3.9 Dry weight percentage of root

This indicates that despite the variations of the accumulation of dry matter, was relatively consistent. Despite the slight deviations, the percentage of dry weight in the tested varieties was relatively even. The percentage of dry weight at 56 DAT was between 8.36% (V2) and 8.92% (V3), observed without significant differences between the varieties (as NS). The consistency between varieties (known as NS) indicates similar physiological mechanisms that influence the accumulation of the dry matter.

3.10 Yield contributing characteristics

Variety V1 recorded the highest fresh weight (235.03 g), followed by V3 (219.53 g) and V2 (170.27 g). These differences are statistically significant, as stated by the LSD value of 13.13. In the types of swamps, significant differences in the fresh plant weight were observed after 56 days after the transplant (DAT) (Table 11). The superior performance of V1 could be attributed to its genetic features and adaptability to the experimental conditions.

Table 11 Yield, yield-contributing parameters, and dry matter percentage of swamp cabbage cultivars at 56 d after transplanting

Cultivar	Fresh wt./plant (g)	Yield/ha (ton)	Dry wt. %
	56 DAT	56 DAT	56 DAT
V1	235.03 a	34.83 a	12.33NS
V2	170.27 c	25.54 b	11.93
V3	219.53 b	32.93 a	11.54
LSD (0.05)	13.13	1.93	1.69
CV (%)	3.16	3.10	7.12

Note: V1 = BARI swamp cabbage-1; V2 = La procesa swamp cabbage-1; V3 = Nice green swamp cabbage; NS = Non-significant. Means in the same column with different letter(s) are significant at the 0.05 level of probability

The LSD value of 1.93 confirms the statistical significance of these differences. V1 and V3 provided the highest yields (34.83 or 32.93 tons/ha), exaggerated V2 (25.54 tons/ha). The yield per hectare also showed a significant differences between the swamps. V1 and V3 showed the highest yields and were in voting with their superior fresh weight per plant. These results reflect the trends that are observed in fresh plant weight. The variation of the yield per hectare (25.54-34.83 tons/ha) reflects the genetic potential and adaptability of the swamp cabbage types under the given conditions. The superior yield of V1 underlines the potential for high productivity in the context of the NFT system.

The consistency between varieties (known as NS) indicates similar physiological mechanisms that influence the accumulation of the dry matter. Despite the slight deviations, the percentage of dry weight in the tested varieties was relatively even. V1 had the highest dry weight percentage (12.33%), followed by V2 (11.93%) and V3 (11.54%). The percentage of dry weight showed a closer range (11.54%-12.33%) without significant differences between the varieties. Such trends in relation to yield and dry weight vote with the findings of Kowalczyk et al. (2014), which emphasized the influence of genetic characteristics and environmental factors on the productivity of the plants and the composition of the biomass In contrast to fresh weight and yield, dry weight percentage showed no significant differences between the swamps.

3.11 Quality parameters

The observed fluctuation indicates that the photosynthetic capacity of V2 is relatively unstable over time. Specifically, V2 (LP-1) exhibited the lowest SPAD values, increasing from 28.27 at 14 DAT to 34.20 at 28 DAT, followed by a decline to 29.70 at 42 DAT (Table 12). Significant differences in SPAD values were recorded among the cultivars at all growth stages (14, 28, and 42 DAT).

In contrast, V1 (BARI Swamp Cabbage-1) consistently showed the highest SPAD readings throughout the experimental period, with values of 32.87, 36.90, and 34.90 at 14, 28, and 42 DAT, respectively (Table 12), indicating superior and stable chlorophyll content. V3 (Nice Green) exhibited intermediate SPAD values (29.00, 31.13, and 31.60 at 14, 28, and 42 DAT, respectively), reflecting relatively stable photosynthetic performance across growth stages, although lower than that of V1.

Table 12 SPAD values of swamp cabbage cultivars at different days after transplanting (DAT)

Cultivar	SPAD values		
	14 DAT	28 DAT	42 DAT
V1	32.87 a	36.90 a	34.90 a
V2	28.27 b	34.20 b	29.70 c
V3	29.00 b	31.13 c	31.60 b
LSD (0.05)	1.56	2.16	1.36
CV (%)	2.67	2.54	1.69

Note: V1 = BARI swamp cabbage-1; V2 = La procesa swamp cabbage-1; V3 = Nice green swamp cabbage; NS = Non-significant. Means in the same column with different letter(s) are significant at the 0.05 level of probability

3.12 Content of chlorophyll-a

In every growth phase, there were remarkable variations in the amount of chlorophyll-A in the swamps (14, 28, 42 and 56 DAT). V2 V2 (LP-1) had the maximum chlorophyll a concentration at 14 DAT (0.61 mg/100 g), but its values drastically decreased during the day and reached 0.52 mg/100 g at 56 DAT. The second best performer in this parameter was V3 (nice green), which showed steady intermediate values and its chlorophyll a concentration to 0.60 mg/100 g at 56 DAT (Table 13) at 56 DAT (0.75 mg/100 g) had V1 Bari Swamp Cabbage-1 the highest chlorophyll a level, which is on the larger photosynthetic Efficiency (Appendix XIII) indicates.

These findings suggest that V1 may be better suited for long-term cultivation due to its ability to maintain higher chlorophyll-a levels over time. Since chlorophyll-a directly contributes to the light reaction, it is essential for photosynthesis. V1’S enhanced photosynthetic efficiency and biomass production potential are indicated by its increased chlorophyll-a content. The steady performance of V1 is consistent with research by Ahmed et al. (2021), which emphasized how genetic variables influence chlorophyll content.

Table 13 Content of chlorophyll-a in swamp cabbage cultivars at different days after transplanting (DAT)

Cultivar	Chlorophyll-a mg/100 g			
	14 DAT	28 DAT	42 DAT	56 DAT
V1	0.41 a	0.44 a	0.34 a	0.75 a
V2	0.61 a	0.26 c	0.20 c	0.52 c
V3	0.34 c	0.39 b	0.32 b	0.60 b
LSD (0.05)	0.03	0.02	0.01	0.07
CV (%)	2.76	2.75	2.01	4.74

Note: V1 = BARI swamp cabbage-1; V2 = La procesa swamp cabbage-1; V3 = Nice green swamp cabbage; NS = Non-significant. Means in the same column with different letter(s) are significant at the 0.05 level of probability

3.13 Content of chlorophyll-b

V2 exceeded V1 and V3 with the largest chlorophyll B concentration at 42 DAT (0.19 mg/100 g) .With the values of 0.17 to 0.21 mg/100 g, the variety differences at 56 DAT were no longer significant (Table 14). The amount of chlorophyll-B varied between the varieties, but the changes were not as large as the chlorophyll-A. V2 continuously showed more chlorophyll-B levels in earlier stadiums, which indicates that it could withstand more low levels in early growth.

Table 14 Content of chlorophyll-b in swamp cabbage cultivars at different days after transplanting (DAT)

Cultivar	Chlorophyll-b mg/100 g			
	14 DAT	28 DAT	42 DAT	56 DAT
V1	0.11 b	0.15 NS	0.12 b	0.21 NS
V2	0.23 a	0.17	0.19 a	0.20
V3	0.11 b	0.17	0.11 b	0.17
LSD (0.05)	0.08	0.04	0.02	0.04
CV (%)	7.22	11.70	8.02	10.77

Note: V1 = BARI swamp cabbage-1; V2 = La procesa swamp cabbage-1; V3 = Nice green swamp cabbage; NS = Non-significant. Means in the same column with different letter(s) are significant at the 0.05 level of probability

Chlorophyll-b is an auxiliary pigment that increases the spectrum of light absorption. V2's higher chlorophyll-b content at 42 DAT suggests that it may be tolerant of low light conditions. This trend may be supported by the findings of Khan et al. (2020), who emphasized the role of chlorophyll-b in light gathering and plant resilience.

3.14 Content of β-carotene

At every stage but 42 DAT, there were notable variations in the cultivars' β-carotene concentration .The greatest β-carotene content (0.22 mg/100 g) was reported by V2 at 14 DAT, however, this advantage was lost by 56 DAT, when V1 and V3 overtook it with values of 0.24 mg/100 g and 0.23 mg/100 g, respectively. While V1 showed a dramatic increase at 56 DAT, which indicates its potential for an increased nutritional value when the harvest subsequently, V3 contributed comparatively constant levels in the growth stages (Table 15).

Table 15 Content of β-carotene swamp cabbage cultivars at different days after transplanting (DAT)

Cultivar	β-carotene mg/100 g			
	14 DAT	28 DAT	42 DAT	56 DAT
V1	0.17 b	0.11 b	0.11 ab	0.24 a
V2	0.22 a	0.15 a	0.12 a	0.16 b
V3	0.14 c	0.11 b	0.09 b	0.23 a
LSD (0.05)	9.42	0.01	0.02	0.02
CV (%)	2.67	5.88	9.18	4.97

Note: V1 = BARI swamp cabbage-1; V2 = La procesa swamp cabbage-1; V3 = Nice green swamp cabbage; NS = Non-significant. Means in the same column with different letter(s) are significant at the 0.05 level of probability

A precursor to vitamin A, β-carotene is essential to human health. Their improved performance at 56 DAT shows the potential of V1 and V3 as nutrient-rich cultivars. Our results are consistent with those of Rahman et al. (2019), who emphasized the genetic basis for β-carotene accumulation in green vegetables. V3 is a strong choice for systems that prioritize stable nutritional quality over extended growth periods, as seen by its consistent performance.

3.15 Ascorbic acid content

With 14 DAT (1.77 mg/100 g), V1 Bari Swamp Cabbage-1 had the highest ascorbic acid content, while V3 (beautiful green) had the best ascorbic acid retention at 56 DAT (1.92 mg/100 g). On all days after the transplant (DAT) there were remarkable differences in the ascorbic acid level between swamp cabbage varieties (Table 16). These results suggest that V3 can be a better choice for the production of nutrient-rich plants, especially for the ascorbic acid content. V3 was better than other varieties at 56 DAT and demonstrated its ability to capture himself over time. The ascorbic acid content of V2 (LP-1) was greatest at 28 DAT (1.98 mg/100 g), followed by V3 (2.00 mg/100 g).

Table 16 Ascorbic acid content of swamp cabbage cultivars at different days after transplanting (DAT)

Cultivar	Ascorbic Acid mg/100 g			
	14 DAT	28 DAT	42 DAT	56 DAT
V1	1.77 a	1.76 b	2.06 NS	1.72 b
V2	1.47 b	1.98 a	2.03	1.62 c
V3	1.50 b	2.00 a	2.01	1.92 a
LSD (0.05)	0.12	0.09	0.08	0.05
CV (%)	3.71	2.48	2.22	1.51

Note: V1 = BARI swamp cabbage-1; V2 = La procesa swamp cabbage-1; V3 = Nice green swamp cabbage; NS = Non-significant. Means in the same column with different letter(s) are significant at the 0.05 level of probability

This factor is important to find out the health advantages of the harvest. The potential of V3 for nutritional applications is highlighted by the reported variations of the ascorbic acid level between varieties. V3 and other varieties can be particularly useful in markets in which nutritional quality and yield are given the same weight (Ahmed et al., 2022).

4 Discussion

The present study demonstrated clear varietal differences in growth, yield, and quality traits of swamp cabbage cultivated under a Nutrient Film Technique (NFT) hydroponic system, highlighting the strong influence of cultivar selection on hydroponic performance. The superior growth and yield performance of BARI Swamp Cabbage-1 (V1) suggests that this cultivar possesses higher adaptability to NFT conditions, likely due to its efficient nutrient uptake, vigorous vegetative growth, and effective utilization of water and dissolved nutrients. Similar cultivar-dependent responses under hydroponic systems have been reported in leafy vegetables, where genotypic variation significantly influences growth dynamics and biomass accumulation.

The consistently higher plant height, leaf area, and fresh weight observed in V1 may be attributed to its enhanced photosynthetic capacity and rapid canopy development, which allow more efficient light interception under protected cultivation. NFT systems provide continuous nutrient availability and oxygenated root zones, which favor cultivars with high metabolic activity and rapid nutrient absorption. Previous studies on hydroponically grown leafy vegetables have reported that cultivars with larger leaf areas and faster growth rates tend to produce higher yields due to increased photosynthate production and translocation.

Although Nice Green (V3) produced a slightly lower yield than V1, it exhibited superior quality attributes, including higher vitamin C, chlorophyll-a, and β-carotene contents. These findings suggest that V3 prioritizes biochemical and nutritional compound accumulation rather than maximum biomass production. Enhanced chlorophyll content indicates efficient photosynthetic pigment synthesis, while increased β-carotene and vitamin C levels reflect improved antioxidant capacity. Similar trade-offs between yield and nutritional quality have been reported in hydroponically grown leafy greens, where certain cultivars exhibit enhanced phytonutrient concentration under controlled nutrient and environmental conditions.

The relatively lower and fluctuating performance of La Procesa Swamp Cabbage-1 (V2) indicates moderate adaptability to NFT hydroponic cultivation. Variability in SPAD values and yield suggests less stable chlorophyll synthesis and photosynthetic efficiency over time. This may be due to cultivar-specific differences in nutrient absorption efficiency or root system architecture, which are critical factors in NFT systems where nutrient delivery is continuous but shallow.

Overall, the effectiveness of the NFT system observed in this study supports its potential for year-round swamp cabbage production with efficient water and nutrient use. NFT hydroponics minimizes soil-related constraints, reduces water consumption, and allows precise nutrient management, making it particularly suitable for regions with limited arable land, poor soil fertility, or urban and peri-urban environments. The present findings are consistent with earlier reports that hydroponic systems enhance yield stability and quality of leafy vegetables when appropriate cultivars are selected.

Authors' contributions

Afrin Fardous designed and conducted the experiment. Md. Sifat Ullah analyzed the DAT and prepared the manuscript. Shreef Mahmood provided technical guidance and reviewed the manuscript. All authors read and approved the final manuscript.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Controlled Environment Techniques for Year-Round High-Quality Strawberry Production

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Abstract This study systematically summarizes and analyzes the key environmental factors and precise control technology paths for achieving high-quality year-round production of strawberries, including environmental factors such as temperature, light, humidity, carbon dioxide concentration and nutrient supply. The study found that reasonable day-night temperature difference (18 °C-25 °C), precise lighting measures (such as LED light source to control the ratio of red and blue light), humidity (60%-80%) and carbon dioxide concentration optimization and precise substrate nutrient management have significant effects on improving strawberry yield and fruit quality. Typical cases show that in different regions such as temperate and subtropical zones, efficient year-round high-quality cultivation of strawberries can be achieved through the comprehensive application of facility cultivation and intelligent environmental control systems. In addition, the integration of facility intelligence and green energy systems, and the integration of smart agricultural management technologies of AI and big data will further improve the economic and ecological benefits of year-round strawberry production. This study provides important theoretical support and technical paths for promoting the transformation of the strawberry industry from traditional cultivation to a year-round efficient, stable and environmentally friendly production model.

Keywords Strawberry; Year-round cultivation; Environmental control; Facility agriculture; Smart agriculture

1 Introduction

Strawberry (*Fragaria* × *ananassa*) is one of the most valuable horticultural crops in the world, and is widely favored for its unique flavor, rich nutrition and outstanding economic value. As the demand for high-quality strawberries continues to rise throughout the year, planting systems and environmental control strategies are also constantly innovating.

The worldwide strawberry sector is undergoing a significant shift from focusing solely on yield to equally valuing both quality and productivity. Advances in breeding methods, improvements in cultivation practices, and the growing adoption of climate-controlled farming have all contributed to robust development in strawberry production. Growing techniques have evolved beyond conventional outdoor farming to incorporate various smart greenhouse setups, strengthening the industry's resilience while overcoming natural weather and geographical constraints. Rising consumer expectations for premium, distinctive-flavored strawberries are fueling innovation in both research and farming applications. Currently, parallel progress in genetic enhancement and precision growing techniques has endowed strawberries with wide environmental tolerance and strong market competitiveness, reinforcing their strategic importance and economic worth in contemporary agriculture (Mezzetti et al., 2018; Hernández-Martínez et al., 2023; Kouloumprouka Zacharaki et al., 2024).

Faced with the structural demand changes brought about by consumption upgrades, consumers are increasingly eager for sustainable, localized, high-quality fresh fruits throughout the year, which in turn puts forward more stringent requirements on the production side. At present, producers need to deal with multiple challenges, including precise control of light, temperature and humidity, and build intensive pest and disease control mechanisms and efficient water and fertilizer utilization models. To meet the above needs, modern planting facilities are constantly emerging, including fully functional smart greenhouses, high-coverage facility arch sheds, and flexible soilless cultivation systems. However, these technical means still face certain bottlenecks in the application process, such as high energy consumption, excessive environmental metabolic load, and high requirements for temperature control stability (Lu et al., 2023; Mousavi et al., 2023; De Oliveira Bernardo et al., 2024; Kouloumprouka Zacharaki et al., 2024).

In the 1980s, strawberries were introduced from Japan to Zhejiang for cultivation and gradually became one of the most representative high-efficiency specialty industries in the province. Currently, Zhejiang has emerged as a major production base for facility-grown strawberries nationwide, with an annual planting area of 6,000 hectares, an output of 120,000 tons, and a value exceeding 2.8 billion yuan. Two key production areas have initially formed: Hangzhou and Ningbo, with Jinhua City standing out as the largest in the province and among the top in China, earning the title of "China's Strawberry Hometown". From December to February of each year, strawberries enter a concentrated market period, leading to significant price drops and partial sales stagnation in some regions, resulting in unstable planting benefits. To address this, Zhejiang has adopted measures such as planting early, mid, and late-season varieties to extend the strawberry supply period and balance market availability; employing practical techniques like trellis-based three-dimensional cultivation, soilless cultivation at the grassroots level, and integrated water and fertilizer management; and selecting a mix of red, pink, and white strawberry varieties to diversify fruit types and enhance appeal (Figure 1). These efforts aim to achieve year-round strawberry cultivation and improve planting economic efficiency.

Figure 1 Strawberry Base of Jinhua Yudi Family Farm Co., Ltd. (Photoed by Guojia Ni)

This study aims to systematically sort out and evaluate the environmental control technology paths required to achieve high-quality year-round supply of strawberries, and conduct in-depth discussions on the actual performance of greenhouse structural engineering design, soilless substrate performance optimization, automation equipment integration, and sensor monitoring digital technology. At the same time, we will also focus on the ability of these technologies to achieve a balance between yield, quality and sustainable development goals, strive to provide a theoretical basis for the iteration of related technologies, and provide a feasible reference for the strawberry industry to achieve efficient, environmentally friendly and sustainable development.

2 Physiological Basis and Environmental Requirements for Year-round Cultivation of Strawberries

2.1 Characteristics of vegetative and reproductive growth of strawberries

The root system of strawberry plants is shallowly distributed, and the typical fibrous root system responds quickly to small changes in the rhizosphere environment and the physical and chemical properties of the substrate. Although this type of root structure is conducive to water and fertilizer absorption, it also means that it is more vulnerable to high-frequency environmental disturbances. Strawberries show a significant ability to switch between stages during their life cycle, and have a flexible physiological mechanism for regulation between vegetative growth and reproductive development. Although this switch gives the plant a strong adaptability potential, its sensitivity to fluctuations in external factors also increases. Among all growth regulatory factors, the combination of light and temperature plays a leading role: high temperature accompanied by long day conditions promotes plant vegetative growth and enhances biomass accumulation; while low temperature and short day conditions effectively trigger flower bud differentiation and promote the development of reproductive organs (Koskela and Hytönen, 2018; Rivero et al., 2022).

Special focus should be given to controlling root zone temperature. Research indicates that keeping roots slightly cool helps flower development while boosting overall plant growth and improving adaptation to environmental shifts (Sakamoto et al., 2016). During unfavorable weather, proper watering and shade can effectively minimize stress and maintain steady plant development (Cordoba-Novoa et al., 2022).

The transition from vegetative growth to reproductive growth in strawberries is strictly regulated by environmental factors. Short days and cool temperatures usually induce flower bud differentiation, while long days and high temperatures are more conducive to the germination of vegetative runners (Koskela and Hytönen, 2018). The photoperiod after flowering also affects fruit development and quality: short days may inhibit flower bud differentiation and fruit development, resulting in deformed fruits; long days help plants enhance photosynthesis and accumulate more nutrients, thereby improving fruit quality (Figure 2) (Ren et al., 2024). The physiological processes behind these growth transitions are also affected by both genetic factors and hormonal regulation - this also ensures the feasibility of year-round production through environmental regulation (Koskela and Hytönen, 2018; Chen et al., 2023).

Figure 2 Effects of different photoperiod treatments on the first inflorescence of strawberry fruit appearance (Adopted from Ren et al., 2024)

2.2 Variety requirements and selection criteria for year-round production

Modern strawberry cultivars are mainly divided into two types: photoperiod-insensitive (day-neutral) varieties and short-day varieties. Day-neutral varieties can achieve year-round continuous production under environmentally controlled conditions because their flowering and fruiting are not restricted by a specific photoperiod (Rivero et al., 2022). In contrast, the reproductive development of short-day varieties strictly depends on specific light and temperature conditions. If the environment is not properly regulated, it will be difficult to achieve off-season cultivation (Koskela and Hytönen, 2018).

For year-round production, choosing suitable varieties is crucial, considering their light requirements, consistent yields, and market quality. Day-neutral types adapt well to various conditions with stable outputs, whereas short-day varieties, though producing superior fruit in ideal settings, struggle with environmental changes (Koskela and Hytönen, 2018; Rivero et al., 2022). Different cultivars also react distinctly to control methods like LED lights, root cooling, and humidity adjustments, directly impacting both yield and fruit quality in controlled environments (Sakamoto et al., 2016; Rivero et al., 2022; Ren et al., 2024).

3 Technical Approaches to Regulating Environmental Factors in Strawberry Cultivation

3.1 Temperature control technology

Temperature plays a central role in strawberry development, directly influencing plant metabolism, final yields, and fruit quality. Research confirms most strawberry varieties grow best between 18 °C-25 °C. Certain high-performing types achieve optimal results with daytime temperatures of 20.5 °C-27.4 °C combined with slightly cooler nights (Tang et al., 2020; Sugiyanto and Kasih, 2024). Keeping temperatures within these ranges supports healthy plant functions, encourages flowering, and enhances fruit appearance. Proper temperature management helps overcome seasonal limitations while balancing quality and productivity.

In cold periods, a variety of heating systems are required to maintain the optimal temperature: hot water pipes and air furnaces are traditional ways to heat greenhouses, while geothermal and air source heat pumps are energy-saving alternatives. Using water heated by heat pumps (air or geothermal) to heat the substrate can keep the root zone temperature stable at around 18.4 °C throughout the year, increasing yield by 21% to 36% compared to the control group. Geothermal systems can especially reduce electricity consumption and enhance production sustainability (Jo and Shin, 2022; Moritani et al., 2023). In winter cultivation, using positive temperature coefficient films to heat the root zone can accelerate flower bud germination, increase fruit yield and improve quality (Jo and Shin, 2022).

In warm climates or when solar radiation is strong, efficient cooling is also critical: natural ventilation and forced exhaust fans are commonly used to exhaust hot air to maintain a suitable temperature; evaporative cooling systems can further reduce greenhouse temperatures, especially in areas with higher ambient temperatures (Yin et al., 2023; Lei, 2024). Smart greenhouse systems integrate sensors and automatic control functions to dynamically adjust cooling (and heating) measures based on real-time temperature data to achieve dual optimization of plant growth and resource utilization (Mubarakah et al., 2023 ; Tarigan, 2023; Lei, 2024).

3.2 Light and photoperiod management

When natural sunlight is inadequate, artificial lighting becomes essential for quality strawberry production. LED systems now outperform traditional lights due to their adjustable spectra, energy savings, and durability, making them ideal for modern growing facilities. Evidence shows using LED lights at 132~235 μmol/m^2/s intensity for 16 hours daily can boost yields over 30% while improving water efficiency and fruit traits (Hidaka et al., 2015; Park et al., 2023; Kaur et al., 2024).

Compared with traditional high-intensity discharge lamps (HID), LED systems have obvious advantages in light quality control and energy saving and consumption reduction (Hidaka et al., 2015; Guiamba et al., 2022; Tang et al., 2023). In addition, when supplementary lighting measures are combined with carbon dioxide concentration management, the yield of strawberries can be increased by more than 50%, and the soluble solids content of the fruit is also increased simultaneously, showing the significance of the synergistic effect (Qiu et al., 2023).

Light environment optimization technology also includes shading regulation and spectrum management. The use of new shading materials such as OPV components can accurately adjust the photosynthetically active radiation (PAR), which can ensure normal fruit development and promote the accumulation of soluble solids within the light intensity range of 387-437 μmol/m^2/s (Tang et al., 2020). Specific light quality ratios have a significant regulatory effect on the growth and development of strawberries: a 7:3 ratio of red to blue light can promote plant morphology and yield formation; while blue light and far-red light affect flowering time and stolonogenesis by regulating the expression of photosensitive pigment-related genes (Díaz-Galián et al., 2020; Guiamba et al., 2022; Prisca et al., 2022; Yang et al., 2024). Spectral regulation can also activate secondary metabolic pathways and significantly increase the content of functional components and antioxidant activity in fruits (Díaz-Galián et al., 2020; Warner et al., 2021).

3.3 Humidity and CO_2 regulation

Maintaining a relative humidity range of 60%-80% is most beneficial to the growth and development of strawberries. This range can not only ensure normal transpiration, but also effectively reduce the risk of disease. Greenhouse cultivation practice shows that 65%-75% relative humidity is the best control range: too high humidity will inhibit transpiration and assimilate transport, and too low humidity will lead to water stress, both of which are not conducive to plant growth and fruit quality improvement (Miyoshi et al., 2023; Kaur et al., 2024).

Carbon dioxide application technology has shown significant advantages in improving the photosynthetic efficiency of strawberries, and has become an important means of high and stable yields in greenhouse cultivation. Relevant studies have shown that by artificially increasing the carbon dioxide concentration in the greenhouse, the strawberry yield can be increased by more than 23%, and when this technology is used in conjunction with supplementary lighting measures, not only the yield benefits, but also the fruit sugar content and overall sensory quality are improved simultaneously (Qiu et al., 2023). Especially in autumn and winter, limited by natural light conditions, carbon dioxide regulation technology shows stronger application potential in off-season production, providing a feasible solution for the stable supply of high-quality strawberries.

4 Strawberry Cultivation Substrate and PrecisionNutrient Management

4.1 Substrate type selection and optimization technology

Soilless strawberry growing is key in modern farming, using water-based and media-based methods. These approaches prevent soil diseases while improving fruit quality and yields (Rathod et al., 2021; Hutchinson et al., 2025). Tests show mixing worm compost with coconut fiber (0.5:0.1 ratio) creates better water/nutrient conditions for plant growth (Tang et al., 2024). Different media serve different purposes - rockwool helps fruiting while coconut fiber supports leaf growth (An et al., 2025). Container size matters too - 830 cm^3 coconut fiber pots work well for 6-month crops (Lee et al., 2023). Adding organic materials like manure boosts soil life and fruit flavor (Bai et al., 2025).

4.2 Precision fertilization and nutrient regulation technology

IoT-based watering systems now automate fertilizer and water delivery. Sensor systems cut chemical use by 38% and water by 26% (Bonelli et al., 2024; Hutchinson et al., 2025). Changing nutrient mixes during growth stages, especially adjusting N/K and K/Ca ratios, improves plant health and fruit quality (Yu et al., 2023). Combining root and leaf feeding with balanced NPK reduces waste while nourishing plants (Kumar et al., 2025).

4.3 Comprehensive optimization strategy for substrate and nutrient management

Combining good media with smart watering gives best results. Water-holding mixes (like worm compost-coconut blends) with sensor systems grow stronger plants (Bonelli et al., 2024; Tang et al., 2024; Hutchinson et al., 2025). Mixing organic (compost) and mineral fertilizers maintains both yields and soil health (Yadav et al., 2010; Barooah and Datta, 2020; Prasad et al., 2022; Bai et al., 2025). For water systems, keeping pH stable with buffers like MES helps roots take up nutrients (Yafuso and Boldt, 2024).

5 Facility Design and Year-round Control Model

5.1 Comparison of greenhouses, multi-span greenhouses, and smart cultivation systems

Modern greenhouse structures have become an important basic platform for promoting year-round strawberry cultivation due to their excellent environmental regulation performance. With the support of temperature control systems and artificial light sources, single greenhouses can still maintain stable yields in areas with drastic climate fluctuations, showing high adaptability and management flexibility. Multi-span greenhouses have more advantages in spatial organization, airflow balance and expansion capabilities. At the same time, the operating cost per unit area is relatively low, which is more suitable for large-scale deployment (Miyoshi et al., 2013; Wai et al., 2022; Thanthong et al., 2024). However, its regulation efficiency in dealing with extreme meteorological conditions is still limited by the insulation structure and the degree of automation integration, and the system resilience has certain limitations (Hernández-Martínez et al., 2023).

Intelligent cultivation systems (such as plant factories) represent the forefront of facility agriculture development. Such systems rely on IoT sensor networks and efficient automatic control platforms to achieve real-time feedback and precise regulation of light intensity, temperature and humidity, water supply and gas environment. In specific application scenarios such as urban agriculture and high-value crop cultivation, its high-density and high-efficiency advantages are particularly prominent. However, the high initial construction investment and complex operation and maintenance requirements are still the key issues that need to be weighed during the promotion and application process (Samaranayake et al., 2022; Wai et al., 2022; Mubarakah et al., 2023; De Oliveira Bernardo et al., 2024).

The automated environmental management platform is regarded as the nerve center of modern facility planting. The monitoring system composed of a distributed sensor network continuously collects multidimensional parameters such as temperature, humidity, light, and substrate moisture content, and realizes model-driven dynamic regulation through a cloud computing platform. The prediction system built with machine learning algorithms such as random forests and support vector regression can effectively avoid low temperature stress and improve photosynthesis efficiency and energy utilization (Chen et al., 2022; Samaranayake et al., 2022; Mubarakah et al., 2023; De Oliveira Bernardo et al., 2024; Wang et al., 2025). Comprehensive practice shows that the system has significant advantages in maintaining fruit consistency and can reduce labor management costs by more than 30%.

5.2 Seasonal crop rotation and soil fatigue mitigation technology

Innovative environmental control technology provides solutions for off-season production. Through the combined application of shading system and phase change energy storage device, greenhouse facilities can maintain a suitable cultivation temperature of 18 °C-25 °C in the high temperature season, successfully realizing the commercial cultivation of summer strawberries (Miyoshi et al., 2013; Thanthong et al., 2024). This technical system can not only stabilize the yield level, but also show good adaptability in ensuring fruit quality.

Multi-dimensional comprehensive management strategies are required for the prevention and control of continuous cropping obstacles. Physical disinfection technology (steam sterilization, solar disinfection) can effectively reduce the base number of soil pathogens; scientific rotation systems and intercropping of non-host crops can block the transmission chain of pests and diseases (Kang et al., 2024); regular disinfection of facilities can prevent the cross-transmission of pathogenic microorganisms (Hernández-Martínez et al., 2023; Kang et al., 2024). Deeply integrate traditional prevention and control methods with modern facility systems to provide technical support for the sustainable development of the strawberry industry.

6 Comprehensive Case Study on Environmental Control for High-quality Strawberry Cultivation Throughout the Year

6.1 Representative case study on regional year-round environmental control

In Japan and some temperate regions of Europe, large greenhouses are equipped with advanced environmental control systems - covering temperature, light, and carbon dioxide regulation - to achieve stable and high yields of strawberries throughout the year. Taking Japan's industrial greenhouses as an example, it uses a moving bed system and comprehensive environmental control methods (light supplementation, carbon dioxide enrichment, and precise temperature control), and the yield is doubled compared with traditional systems. These facilities improve yield and fruit quality by optimizing planting density and environmental parameters, especially when June-bearing varieties are selected and customized light supplementation solutions are used (Hidaka et al., 2016). China's solar greenhouses use opaque photovoltaic (OPV) panels to shade the sun, combined with solar heating, to maintain the temperature at 20.5 °C-27.4 °C and the light intensity (PAR) at 387~437 μmol/m^2/s, which increases the yield by 1.2 times compared with the unshaded control group, and the soluble solids content of the fruit is also higher (Tang et al., 2020).

The core of environmental control in tropical and subtropical regions is to alleviate the problems of overheating and humidity. Covering technology (especially black plastic mulch) and shade nets have been proven to regulate soil temperature and humidity - in the humid tropical regions of India, such measures can increase fruit yield by 68% and improve the content of phytochemicals (Misra, 2023). The Saudi Arabian experimental area adopts a 20 m × 8 m layout to test the effects of different colored shade nets on plant growth (Figure 3). In greenhouses, colored shade nets (e.g., beige or green) can optimize light quality and temperature, with beige shade nets achieving optimal yields and improving plant physiological characteristics (Alhelal et al., 2024). These improvements allow strawberry to achieve off-season and year-round production under otherwise limited climatic conditions.

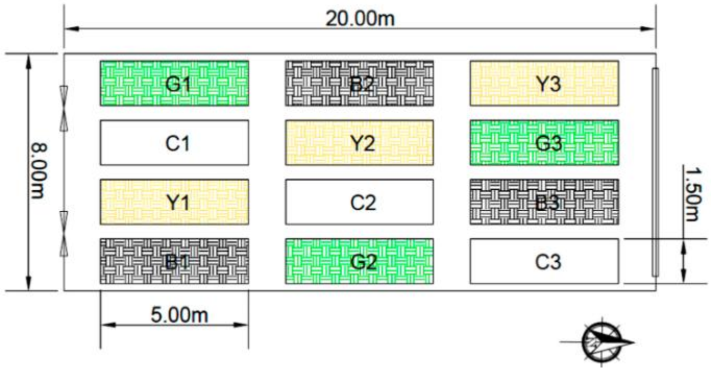

Figure 3 The distribution of the colored shading nets blocks, blocks with black shading nets (B), blocks with green shading nets (G), blocks with beige shading nets (Y), and the control blocks (C) (Adopted from Alhelal et al., 2024)
Image caption: Each shading net covered three blocks (replication) with dimensions of 5 m × 1.5 m × 3.5 m (Adopted from Alhelal et al., 2024)

6.2 Evaluation of the impact of environmental control on strawberry yield and quality

The precise environmental control technology system (covering light environment regulation, temperature and humidity management, and intelligent water and fertilizer system) has a continuous promoting effect on the formation of strawberry yield and quality improvement. LED artificial lighting technology can not only improve the yield level, but also significantly increase the content of anthocyanins, polyphenols and antioxidant activity in fruits, thereby enhancing the functional nutritional quality of strawberries (Warner et al., 2021; Pérez-Romero et al., 2024). The sensor irrigation system under hydroponic conditions dynamically optimizes the supply of water and fertilizer to achieve a synergistic improvement in resource utilization efficiency and yield (Hutchinson et al., 2025). In the organic production system, although the application of biostimulants and compost tea varies from year to year and from variety to variety, it can generally improve the yield composition and the accumulation of fruit flavor substances (Pérgola et al., 2023; Kilic, 2024; Nakielska et al., 2024; Ciriello et al., 2025).

7 Integration of Environmentally Sustainable Technologies

7.1 Potential of green energy systems in year-round strawberry cultivation

The use of renewable energy such as solar energy has become a key path to reduce the environmental load of facility strawberry production. The results of life cycle analysis show that photovoltaic (PV) systems and solar thermal-photovoltaic (PV/T) systems have shown significant advantages in energy efficiency and carbon emission reduction. Among them, photovoltaic technology is particularly outstanding, which can reduce cumulative energy consumption by 50%, and its environmental impact index is reduced by 16% and 6% respectively compared with traditional energy modes (Hosseini-Fashami et al., 2019). This type of energy configuration not only provides stable and clean power support, but also effectively alleviates the potential pressure caused by greenhouse system operation on the ecosystem. It has been verified in facility agriculture scenarios in many places (Romero-Gámez and Suárez-Rey, 2020).

7.2 Eco-friendly integrated pest and disease control system

Developing effective yet natural pest control methods is crucial for sustainable strawberry farming. Using helpful bacteria (like *Bacillus*) along with organic boosters such as humic acid can raise strawberry production by up to 79% while fighting fungal infections (Nakielska et al., 2024; Ranasingha et al., 2024). The effectiveness depends on plant types and local conditions, requiring customized solutions. Specially made compost tea both strengthens plants and blocks diseases, working especially well in organic systems that protect nature while growing crops (Pérgola et al., 2023). Unlike chemical sprays, these natural methods help keep soil microbes healthy and create better farming conditions long-term.

7.3 Innovative application of smart agricultural management platform

New digital tools are changing how strawberries get grown. Connected sensors and smart computers work together to automatically adjust temperature, moisture, light and air conditions for ideal growing. In Ecuador, the

AgroTec 4.0 system increased harvests by 15% using 20% less water while growing better berries (Abdo-Peralta et al., 2024). Remote monitoring systems also cut labor needs by over 30% while making production more reliable (Mubarakah et al., 2023; De Oliveira Bernardo et al., 2024; Jyoti et al., 2025).

8 Concluding Remarks

Growing top-quality strawberries year-round depends on carefully managing light, warmth, water and food for the plants. Modern indoor farms - like smart greenhouses, tunnel houses and vertical farms - use special equipment to control growing conditions. These systems combine climate control, special grow lights and soil-free methods to produce steady harvests all year. Even in tight city spaces, growing strawberries in water or stacked setups with adjustable lighting works well for continuous production.

While these indoor methods have improved greatly, some big problems remain. Crazy weather from climate change, tougher bugs and diseases, and the need to save resources are pushing farmers toward smarter systems. Networks of sensors connected to cloud computers help monitor and adjust growing conditions perfectly. Matching farm setups to local weather, plant types and what customers want makes the whole system work better and earn more money.

Looking ahead, work should focus on better smart tools and systems that handle weather changes well. Important areas include: using clean power, creating self-adjusting control systems, and adding natural pest control methods. Building earth-friendly farms that use resources wisely will help the strawberry business last long while cutting pollution and handling challenges better.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Feature Review Open Access

Nutrient Regulation for Improving Pear Fruit Size and Sugar Content

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Abstract The size and sweetness of pears (*Pyrus* spp.) influence people's preferences and market prices. This study explored the effect of dietary regulation on pear fruits, with a focus on three major nutrients - nitrogen, phosphorus and potassium, and also involved trace elements, such as boron, zinc and copper. It analyzed the roles of these nutrients in fruit cell division, the transport of water and nutrients within plants, sugar changes, and the energy distribution between leaves and fruits. The results show that potassium is a key factor, which can activate sugar transportation-related genes (such as SUT and SWEET), allowing more sugar to enter the fruit and making pears larger and sweeter. When growers apply bio-organic fertilizers simultaneously or spray trace elements on the leaves, the sugar-acid ratio is further optimized and the flavor of the pears is also better. Actual cases have also verified this point: increasing the application of potassium fertilizer can boost the yield of pears, while supplementing boron and zinc improves the appearance of the fruit, making it more market-attractive. It indicates that the best way to manage pears is to apply fertilizers in a balanced manner, in stages, and by combining organic and mineral fertilizers. This study provides fruit farmers with more scientific and targeted guidelines for pear tree management.

Keywords Pear (*Pyrus* spp.); Nutrient regulation; Sugar accumulation; Potash fertilizer; Bio-organic fertilizer; Precision fertilization

1 Introduction

Pears (*Pyrus* spp.) are one of the world's most important fruits. Their size and sweetness decide how popular they are, and how much they sell for. In local markets and in exports, big and sweet pears are always in demand. They bring farmers more money and keep the pear industry steady and growing (Liu et al., 2019; Zhang et al., 2024). But just planting more trees or only chasing higher yields is not enough to keep the pear industry strong. People now want better fruit, not just more fruit. This change is pushing farmers to rethink how they grow pears. To make the fruit taste better and look better, farmers need to keep looking for new ways and new tools.

The economic value of pears is high, but growing big and sweet fruit all the time isn't easy. Things like genetic differences, lack of nutrients, bad weather, and plant diseases, can make pears smaller or less sweet (Sete et al., 2019; Zhang et al., 2024). Too much fertilizer or using it the wrong way can make the problem worse. It not only hurts the quality of the fruit, but also causes harm to the environment (Prasad and Bora, 2015).

N, P and K, along with trace elements like boron, zinc and copper, are all important for pear growth. Among them, K is the most critical. It helps plants make, move and store sugar, which makes the fruit sweeter and helps pears grow bigger (Shen et al., 2016; Zhang, 2019). N and P also help fruit develop and boost yield, but their effect on sugar levels is not always the same. This means, farmers need to manage them carefully (Sete et al., 2019; Li et al., 2024). Trace elements, like boron and copper, are often sprayed on the leaves. They help flowers turn into fruit, support sugar buildup, and improve the overall quality of the pears (Gilani et al., 2021; Sajid et al., 2022).

For pears to grow smoothly and become sweet, nutrients and sugar must be transported smoothly from the "source" (leaves) to the "reservoir" (fruits). In this process, P not helps plants build nutrient transport channels, activates key transport genes such as *SUT*, *SOT* and *SWEET* (Shen et al., 2018; 2019; Gu et al., 2021; Wang et al., 2022a). These genes work together to transport sugar and minerals to the fruit. When they operate in balance, the fruit can grow larger at the right time and accumulate more sugar.

This study explores how to better manage macronutrients and trace elements, incorporating the use of bio-organic fertilizers to enhance nutrient regulation. It integrates concepts from plant physiology, molecular research, and agricultural management methods, to identify practical approaches to improve pear quality. Through more scientific management, pear yields can be increased while also enhancing taste and nutritional value. This not only increases income for farmers, but allows consumers to enjoy higher-quality pears.

2 Physiological Basis of Fruit Size Formation

2.1 Mechanisms of cell division and expansion

N and P are key nutrients that influence pear cell growth and division, which directly determine the final fruit size. It has been reported that, providing adequate nitrogen and phosphorus during early fruit growth, can increase the length, width, weight, and overall volume of pears by promoting cell division and expansion (Arba et al., 2017). Field trials have found that pear yield and quality are optimal when farmers apply approximately 337.5 kg of nitrogen and 262.5 kg of phosphorus per hectare (Li et al., 2024).

The nutritional status of plants also affects the function of hormones in the body. Hormones such as auxin (IAA), zeaxin nucleoside (ZR), gibberellin (GA), and abscisic acid (ABA) are all related to the number of cell formation and fruit size (Tian et al., 2021; Liu et al., 2024). Research shows that higher levels of ZR and a more ideal balance of IAA/ABA, ZR/ABA and GA/ABA help to produce more cells and promote fruit enlargement. On the contrary, ABA inhibits cell division (Tian et al., 2021).

Nutrient regulation of plant hormones helps maintain a balanced growth process. Furthermore, external application of plant growth regulators (e.g., gibberellins and cytokinins), can further promote cell division and expansion, resulting in larger pear fruits and improving their quality (Mosa et al., 2022; Al-Saif et al., 2024; Liu et al., 2024).

2.2 Vascular structure and sink strength modulation

For pear fruits to grow big and sweet, the sugar in the leaves must be smoothly delivered to the fruit. However, if the transport function of the transport channel, that is, the vascular tissue, is poor, sugar will block the road (Shen et al., 2019; Wang et al., 2022c. The role of K can be manifested at this time: it can make the vascular tissues of petioles and fruit stalks more developed, and also make sugar transport genes, such as *SUT* and *SOT*, more active. Thus, glucose, fructose, sorbitol and sucrose will accumulate rapidly in the fruit (Shen et al., 2019). With the enhancement of transportation capacity, the "reservoir strength" of fruits will also be stronger, the ability to absorb and store sugar will be better, and the fruits will be larger and sweeter (Cheng et al., 2018).

Of course, potassium is not the only key. Calcium (Ca) and boron (B) are also indispensable. Calcium can make the cell walls and cell membranes more stable, supporting the continuous growth of fruits. Boron maintains cell wall structure and vascular function at the back (Pessoa et al., 2022). Only when both calcium and boron are sufficient can the vascular system remain smooth, allowing sugar and nutrients to continuously flow into the fruit, and enabling the pear to grow to the desired size and quality.

2.3 Interactions between nutrition and environmental factors

Water and temperature play a big role in how well pear trees take in and use nutrients. When there isn't enough water, sugars and nutrients can't move into the fruit. When it gets too hot, the tree's normal metabolism is thrown off, and even its nutrient needs can change (Shen et al., 2019). Pear trees will try to adjust by doing things, like boosting root activity or changing how transport proteins work. But if these fixes go on for too long, the fruit won't grow well, and the pears will end up smaller (Shen et al., 2019; Nishio et al., 2021).

Nutritional imbalance is also a problem. Too little fertilizer, or the wrong mix, can slow cell division, and block the growth of vascular tissue. It also weakens the "sink strength", which makes fruits smaller and less sweet (Shen et al., 2019). On the other hand, using fertilizer the right way—with a good balance of N, P, K, Ca and B—can ease these stresses, and help pears grow better and taste better (Nishio et al., 2021).

3 Regulatory Mechanisms of Sugar Accumulation in Pear Fruit

3.1 Metabolic pathways of sucrose and sorbitol

In pear fruit, sugar accumulation primarily occurs via sucrose and sorbitol, a common transport pathway in Rosaceae plants. Sorbitol dehydrogenase (SDH) converts sorbitol to fructose, a step that directly impacts sweetness. Numerous studies have found that, the application of bio-organic fertilizers that enhance SDH expression significantly increases fructose content (Wang et al., 2022a; Jiang et al., 2023).

Sucrose breakdown involves not only one enzyme. Invertase hydrolyzes sucrose into glucose and fructose, and its activity varies with fruit development. Acid invertase (AI) is more active in the later stages, helping to accumulate hexoses, while sucrose synthase (SS) and sucrose phosphate synthase (SPS) are more important early in the fruit (Kou et al., 2017; 2018; Min et al., 2020). Interestingly, some studies suggested that in developing pears, sucrose synthase may even play a greater role in sucrose breakdown than invertase (Reuscher et al., 2016).

Nutrient supply, especially potassium (K), boosts the activity of genes like *SDH*, *S6PDH*, *SPS*, and *SUS* in leaves and fruits. This helps sugar build up in the fruit (Shen et al., 2018; Wang et al., 2022a). Sugar itself can also “push back” and activate SDH. When sorbitol, glucose, or sucrose is sprayed on the plant, SDH expression and activity go up even more. Researchers also found that, transcription factors like PbrbZIP15, PuMYB12, and PuWRKY31, as well as epigenetic changes such as histone acetylation, affect how sugar metabolism and transport genes are expressed (Li et al., 2020; Gao et al., 2023; Jia et al., 2024).

3.2 Key nutritional factors influencing sugar content

Potassium (K) is very important for helping pears move and store sugar. It makes the plant’s veins grow better and turns on sugar transport genes like *SUT* and *SOT*. This helps sugars move smoothly from the leaves, or the “source”, to the fruit, or the “sink” (Shen et al., 2018; 2019). When the plant has plenty of potassium, the leaves and fruit hold more sorbitol, sucrose, and total sugar, which makes the fruit sweeter. Mg hasn’t been studied as much, but it also matters because it helps leaves keep up photosynthesis and might work together with potassium to move sugars. Shen et al. (2019) found that when potassium is low, the plant makes more magnesium transporter proteins to make up for it a little.

For pears, Boron (B) and zinc (Zn) are important micronutrients. They help sugars build up by keeping cell walls strong, cell membranes stable, and enzymes working well. B is key for sugar transporters and vascular tissues to work normally. While Zn helps enzymes that take part in carbohydrate metabolism (Pessoa et al., 2022; Zhang et al., 2022). When pears get enough boron and zinc, sugar moves and gathers more easily, which makes the fruit taste better and improves its quality.

3.3 Interactive regulation with photosynthesis and source-sink dynamics

The nutritional status of leaves, especially the potassium (K) content, has a significant impact on photosynthesis. After the increase of potassium, the photosynthetic efficiency of leaves is enhanced, sugar production is also greater, and the "raw materials" transported to the fruit are naturally more abundant (Shen et al., 2018). The addition of organic and bio-organic fertilizers can also enhance photosynthesis and promote the expression of genes related to glucose metabolism, making the accumulation of sucrose in fruits more obvious (Wang et al., 2022a).

The way fruits get sugar is not simple. Phloem unloading and sugar storage rely on sugar transporters, like SUT, SOT, SWEET, and TMT, along with metabolic enzymes. Transcription factors such as PuWRKY31 and PbrbZIP15, plus epigenetic changes, also take part in this process (Li et al., 2020; Gao et al., 2023; Jia et al., 2024). There are also genes like *PbCPK28* and *PbTST4*. Their natural variations can change how well sugar moves into the vacuole, which then affects how sweet the fruit becomes (Cheng et al., 2018; Li et al., 2023).

4 Nutrient Metabolic Regulatory Network in Pear Fruit

4.1 Signal transduction and transcription factor regulation

In the metabolic regulation of pears, transcription factors (TFs), like members of the bZIP, WRKY, and MYB families, all play a role. Take PpbZIP44 as an example, it can directly regulate the genes involved in the biosynthesis of carbohydrates, amino acids and flavonoids, redistribute the metabolic flow direction, and allow more fructose and phenylalanine to accumulate in the fruit (Wang et al., 2023). Members of the WRKY family, such as PbWRKY26, regulate organic acid metabolism by activating malate dehydrogenase-related genes, and ultimately affect malic acid levels and fruit acidity (Yang et al., 2023). MYB is more involved in the regulation of secondary metabolites and structural components, and has an impact on both flavor and quality (Xue et al., 2023).

Nutrient signals and hormone signals are closely linked in pears. For example, MeJA treatment can start changes in carbohydrate and amino acid metabolism. This process involves ceRNAs, miRNAs, and transcription factors (Yuan et al., 2024). ABA signaling has its own chain of control. It is shaped by DNA methylation, and transcription factors like PbZFP1. These signals affect how metabolic genes work, which then sets the pace for fruit ripening and the overall metabolic state (Gu et al., 2024).

4.2 Mechanisms of carbon-nitrogen balance regulation

Nitrogen supply not only determines the growth of leaves, but also affects the expression of genes related to sugar metabolism, thereby influencing the balance between carbon and nitrogen compounds. Transcriptome analysis revealed that, nitrogen-responsive transcription factors and metabolic genes were co-expressed with sucrose biosynthesis genes, suggesting that there was not an indirect relationship between nitrogen status and sugar accumulation, but a direct regulatory connection (Lu et al., 2020; Wang et al., 2023).

Lü et al. (2020) conducted a comparative transcriptome analysis of three developmental stages of the low-sucrose cultivar ‘Korla’ and the high-sucrose cultivar ‘Fengshui’, identifying seven key genes closely related to sucrose synthesis (*SPS*, *SUS*, *FRK*, and *PGI*, etc.) along with 42 transcription factors. They constructed a regulatory model linking signals, transcription factors, and target genes to explain how gene regulation and metabolic flux jointly drive differences in sweetness (Figure 1). This provides a valuable reference for understanding the molecular basis of sugar accumulation under nitrogen influence and also demonstrates that by regulating the expression of relevant genes, carbon–nitrogen metabolism can be coordinated to optimize fruit quality.

The balance of nutrients, especially the carbon-to-nitrogen ratio, also affects how pear trees work inside. Studies using different “omics” methods show that when this ratio changes, it can turn certain genes on or off. These genes are linked to how the plant handles sugars and amino acids. As a result, the amount of sugar, organic acids, and amino acids in the fruit also changes (Wang et al., 2023; Yuan et al., 2024).

5 Fertilization Strategies for Improving Fruit Quality

5.1 Balanced fertilization schemes for coordinated trait improvement

Studies have shown that moderate application of nitrogen fertilizer can increase fruit quantity and yield. However, excessive application not only fails to further improve fruit quality, but may also lead to nutrient excess and environmental risks (Chen et al., 2018; Sete et al., 2019; Liang et al., 2022). Especially, the role of potassium fertilizer is more prominent. It can not only enhance fruit hardness, soluble solid content and storability, but also promote sugar accumulation, thereby comprehensively improving fruit quality (Brunetto et al., 2015; Shen et al., 2016; Sete et al., 2020).

The optimal NPK ratio should be adjusted based on local soil conditions and tree needs. For example, studies have shown that in North China, moderate irrigation combined with high nitrogen application yields the best results (Liu et al., 2023; Li et al., 2024). Balanced fertilization can also increase the mineral and vitamin C content of fruit, improving flavor and nutritional value (Gill et al., 2017).

Slow-release and controlled-release fertilizers give the trees a steady flow of nutrients through the whole growing season. This cuts down on nutrient loss and helps the plant use the fertilizer better. These fertilizers can make pears have more soluble solids, more vitamin C, and a better sugar–acid balance. They also save money on fertilizer and are better for the environment (Shen et al., 2018). For example, studies show that bagged controlled-release fertilizers, compared to regular compound fertilizers, make the fruit taste better and boost its nutrition, giving farmers a good option for growing high-quality pears.

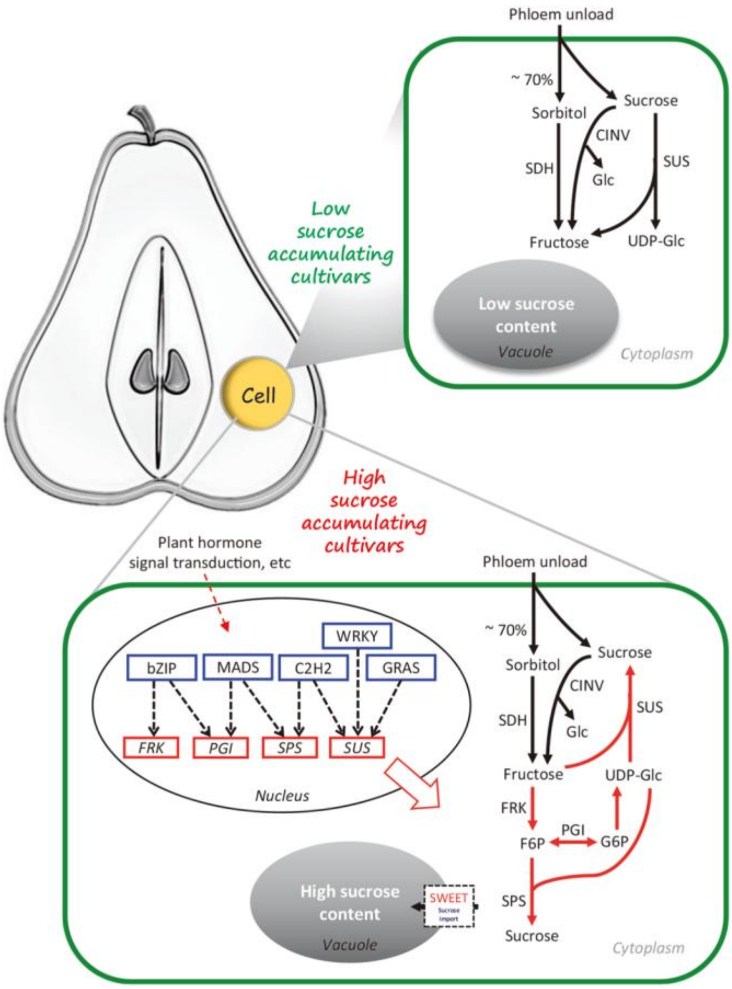

Figure 1 A proposed model of sucrose content difference in pear fruits. Several types of TFs are involved in the upregulated transcription of *FRK*, *PGI*, *SPS* and *SUS* genes in the nucleus, and high sucrose then accumulates in vacuoles. Sucrose accumulation is affected by multiple signals, such as plant hormones. CINV, cytoplasmic invertase or neutral invertase; Glc, glucose; SDH, sorbitol dehydrogenase (Adopted from Lü et al., 2020)

Image caption: The figure illustrates the metabolic pathways at the cellular level in high- and low-sucrose cultivars. In high-sucrose types, the upregulation of genes such as *SPS*, *SUS*, *FRK*, and *PGI* promotes sucrose synthesis and its accumulation in vacuoles within fruit cells, while being regulated by transcription factors like bZIP and WRKY as well as plant hormone signals. In contrast, low-sucrose types lack this efficient pathway, resulting in limited sucrose deposition (Adapted from Lü et al., 2020)

5.2 Timing and methods of nutrient application

The advantages of foliar fertilization are quite obvious, especially when there is a deficiency of trace elements. It works quickly and can also enhance the hardness, sugar content and soluble solids of fruits. It works best during critical periods, when the fruit is developing (Gilani et al., 2021; Sajid et al., 2022; Seo et al., 2024; Yuan et al., 2024). However, root (soil) fertilization remains the main force. It provides a large amount of nutrients and supports the entire process of pear trees from vegetative growth to reproductive growth (Jiang et al., 2020; Colpaert et al., 2021). When the two methods are used in combination, the improvement of nutrient absorption and fruit quality will be more obvious. When soil nutrient supply is insufficient or stress occurs, foliar spraying becomes more important (Zargar et al., 2019).

The timing of fertilization is also very important. Giving the right nutrients during flowering, fruit setting, and fruit expansion helps pears grow bigger and build up more sugar (Liu et al., 2019; Jiang et al., 2020). For example, nitrogen fertilizer added in spring mostly goes to the young fruits. Fertilizers used in summer and autumn are stored in the roots, and later moved through the plant (Colpaert et al., 2021). During fruit setting and expansion, spraying regulators and trace elements can improve both the quality, and the yield of the pears (Gilani et al., 2021; Li et al., 2023).

5.3 Use of organic and biological inputs

Organic fertilizers, like compost, farmyard manure, and biogas slurry, can make the soil better by improving its structure, helping it hold water, and boosting microbial activity. This helps pears grow bigger, get sweeter, and store longer (Wang et al., 2022a; Ye et al., 2020; 2022; Butcaru et al., 2024). Bio-organic fertilizers with helpful microbes can go even further-they help pears make more sucrose, balance sugar and acid better, and improve overall fruit quality by affecting the genes that control sugar and acid metabolism (Kang et al., 2021; Wang et al., 2022a; b). Using organic fertilizers for many years, also builds up organic matter in the soil and makes nutrients easier for the trees to use, helping orchards keep producing in the long run (Butcaru et al., 2024).

Soil microbial inoculants like *Bacillus subtilis* and *Trichoderma* can help pear trees take in more nutrients. They boost enzyme activity, improve soil health, raise fruit yield, and keep the sugar-acid balance better (Kang et al., 2021; Shi et al., 2023; Yanwei et al., 2025). These biofertilizers change the microbes around the roots, encouraging good bacteria and fungi to grow. This helps nutrients move through the soil and supports plant growth (Wang et al., 2022b; Yanwei et al., 2025). When organic matter is used together with these inoculants, the effect is even stronger. It can stop leaves from dropping too early, raise yields even in bad weather, and make the fruit better in quality.

6 Variety Differences and Nutrient Regulation Adaptability in Pear

6.1 Nutrient response characteristics of different pear varieties

Different pear species take in nutrients and store minerals in their own ways. This changes how big and how sweet the fruit becomes. *Pyrus bretschneideri*, *P. pyrifolia*, and *P. ussuriensis* each have different patterns of sugar buildup, organic acid levels, and mineral content. For example, *P. ussuriensis* fruits have more potassium, calcium, and magnesium than *P. pyrifolia* or *P. bretschneideri*. Wild pears also usually hold more minerals than the pears grown in orchards (Liu et al., 2023).

Metabolomic studies, further elucidate these differences, revealing distinct patterns in phenylalanine metabolism, and other pathways related to fruit quality between white pears and sand pears (Zheng et al., 2022). Northeast pears exhibit higher potassium efficiency and greater tolerance to potassium-deficient environments, which is associated with the regulation of genes like *PbNRT2.4*, that is upregulated under potassium deficiency or exogenous sugar conditions (Yang et al., 2025).

The sensitivity of different varieties to nutrient management also varies. The high sugar type "Fengshui" upregulates sucrose synthesis related genes under nutrient supply, while the low sugar type "Korla Fragrant Pear" shows another expression pattern (Lü et al., 2020). Some varieties with larger fruits and higher sugar to acid ratios, like "Niitaka" and "Hanareum", have stronger nutrient absorption and accumulation abilities for sugars, amino acids, and minerals, making them suitable for both fresh and processed consumption. Some varieties can exhibit stronger tolerance or metabolic compensation ability, when they are deficient in potassium or iron (Melaouhi et al., 2022; Liu et al., 2025).

6.2 Breeding basis of traits related to nutrient regulation

Modern breeding increasingly values high-sugar and large-fruit traits, which are underpinned by both genetic and metabolic factors. QTL mapping and transcriptome analysis have identified a number of important loci and candidate genes, related to sugar accumulation and fruit enlargement, including *PpSUT*, *PpSDH*, *SPS*, *SUS*, etc. (Lu et al., 2020; Zhang et al., 2021; Jiang et al., 2023). Metabolomics studies supplemented more information, to help breeders screen varieties with better performance in sugar, organic acids and polyphenols (Zheng et al., 2022). The pollination effect (xenia), can also change fruit size and sweetness, indicating that breeding strategies cannot ignore the interaction between genetic background and reproductive biology (Qiao et al., 2025).

Selecting genotypes with high nutrient utilization efficiency is also a key point. The ability of different rootstock and scion combinations to absorb and utilize nutrients such as nitrogen and potassium varies. Rootstocks such as "Pyrodwarf" and "OHF", have differences in the levels of required nutrients (Jamshidi et al., 2016). Some genotypes exhibit higher nutrient absorption efficiency, such as the nitrogen-efficient "971" selection and potassium-efficient Northeast pear, which is of great significance for sustainable production and quality improvement (Sete et al., 2020; Liu et al., 2023; Yang et al., 2025).

6.3 Genotype × nutrient interaction mechanisms

QTL mapping has identified many key sites related to sugar, organic acid and nutrient utilization efficiency. For instance, in pyrifolia, qSugar-LG6-Chr7 and qSugar-LG12-Chr3 are closely related to the total sugar content. The candidate genes include sorbitol dehydrogenase (PpSDH) and sucrose transporter (PpSUT). They play a core role in sugar accumulation (Jiang et al., 2023). GWAS analysis also identified more loci related to fruit quality, involving genes such as stone cell formation, organic acid and sugar accumulation (Zhang et al., 2021), providing a genetic basis for breeding material selection.

Research has also found that different genotypes respond differently to fertilization systems. Some varieties are particularly sensitive to potassium supply. For example, a comparative study of "Crown" pear shows that potassium treatment can change gene expression and sugar accumulation, indicating that the fertilization plan must match the genotype (Shen et al., 2019). In addition, the improvements in sugar content, fruit size and metabolic characteristics brought about by bio-organic fertilizer or canopy structure adjustment vary among different genotypes (Wang et al., 2022a; Liu et al., 2024).

7 Case Studies of Nutrient Regulation in Pear Production

7.1 Practices for pear fruit enlargement

In the pear industry, rational nutrient regulation is key to increasing fruit yield and commercial value. In recent years, researchers have focused on the role of traditional chemical fertilizers and single nutrients, and also incorporated sustainable inputs, such as organic fertilizers and bio-organic fertilizers, into their experiments to explore more efficient and environmentally friendly pathways to increase yield. Wang et al. (2022a) demonstrated that the application of bio-organic fertilizers (BF) provides a new practical example for increasing pear fruit size. Field trials showed that, BF treatment significantly increased per-plant yield (by 10.6%) compared to chemical fertilizers. The fruit also increased in both longitudinal and transverse diameters, resulting in larger fruit size without affecting firmness (Figure 2).

In field trials of Asian pear varieties, including ‘Yali’ and ‘Xinli No. 7’, increasing potassium (K) fertilizer application rates has been shown to effectively improve fruit size and quality. Potassium fertilizer increases potassium concentrations in leaves and fruits and enhances net leaf photosynthetic rate, thereby promoting fruit growth. High levels of potassium fertilizer can upregulate the expression of genes involved in sugar metabolism (such as *AIV*, *S6PDH*, *SPS*, *SUS*, and *SUT*), promote soluble sugar accumulation, and increase fruit size during ripening (Shen et al., 2018; 2019).

Multiple foliar potassium sprays during fruit development, such as three sprays of 1.5%-2.0% potassium nitrate (KNO_3) or potassium sulfate (K_2SO_4) during the fruiting period, can further enhance these effects (Prasad and Bora, 2015). Economic analysis also shows that high-potassium fertilization can increase yield by 16%-17%, improve soluble solids and sugar content, and enhance market value and crop profitability. However, the amount and timing of fertilizer application must be precisely controlled to avoid over-investment or diminishing returns (Shen et al., 2016).

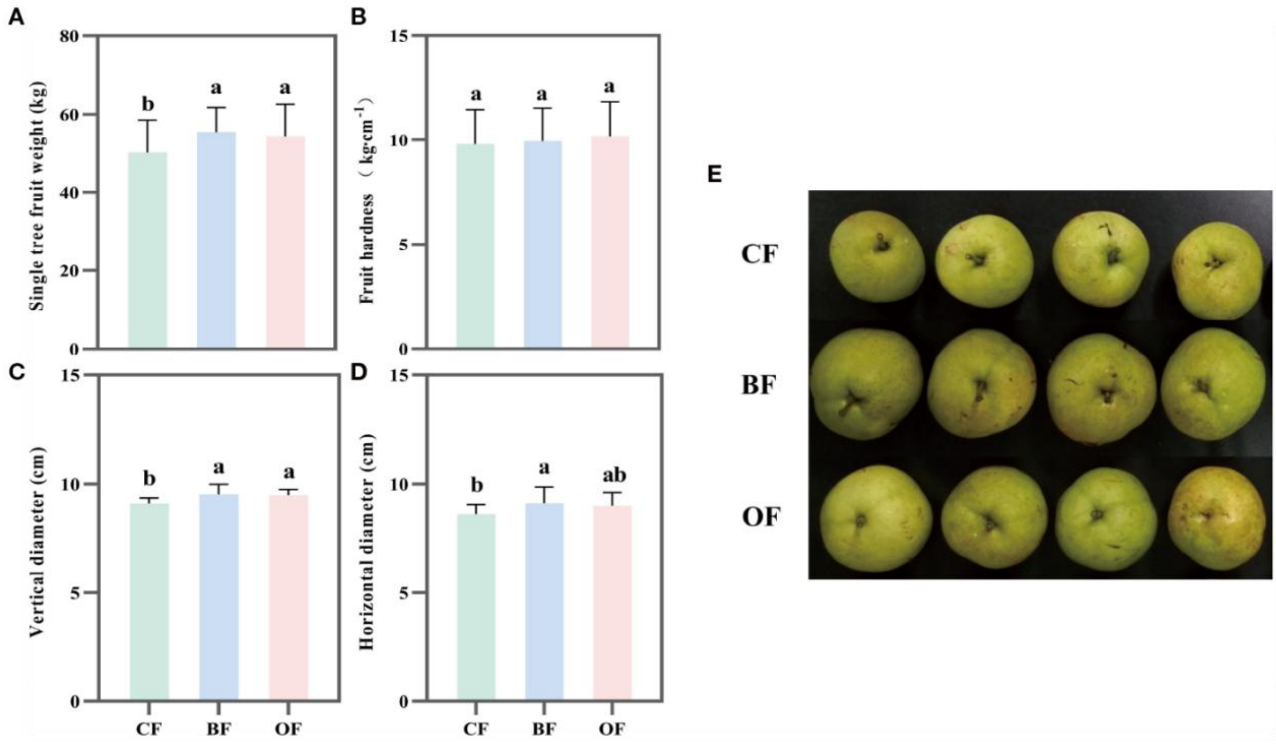

Figure 2 Effect of different fertilization treatments on fruit weight per tree (A), fruit hardness (B), fruit vertical (C), horizontal (D) diameter and phenotype (E) of Pear. CF: chemical fertilizers application; BF: bio-organic fertilizers application; OF: organic fertilizers application. Values followed by different letters differ significantly (Duncan's test, $P< 0.05$, $n=5$) (Adopted from Wang et al., 2022a)

7.2 Enhancement of pear flavor quality

The flavor and commercial value of pears mainly depend on the balance of sugar and acid, as well as the accumulation of secondary metabolites. In recent years, the role of transcription factors in the regulation of fruit quality has attracted much attention. As research has found, PpbZIP44, a member of the S1-bZIP family, plays a key role in the multiple metabolic regulation of fruits.

Wang et al. (2023) demonstrated that PpbZIP44 can alter the accumulation patterns of sugars, organic acids, amino acids, and flavonoids by transient overexpression and RNA interference in pear fruit, as well as by establishing a stable transgenic system in tomatoes. The experiments showed that overexpression of PpbZIP44 increased fructose in the fruit by 38%, decreased sorbitol by 26%, and reduced citric acid and malic acid by nearly 40% and 30%, respectively. This significantly increased the sugar-acid ratio, thereby improving flavor and marketability (Figure 3).

More importantly, PpbZIP44 regulates sugar conversion, proline decomposition, and the synthesis of aromatic amino acids and flavonoids by directly binding to the promoters of genes (e.g., *PpSDH9*, *PpProDH1*, *PpADT*, and *PpF3H*), promoting the flow of carbon towards fructose and flavonoid accumulation, while weakening the formation of some lignin. Thereby reducing the negative impact of "stone cells" on the taste. Metabolomic and transcriptomic analyses further confirmed that these treatments could enhance gene expression related to carbohydrate metabolism, ultimately achieving sweeter fruits and higher market acceptance (Wang et al., 2022a; Wang et al., 2023; Jia et al., 2024).

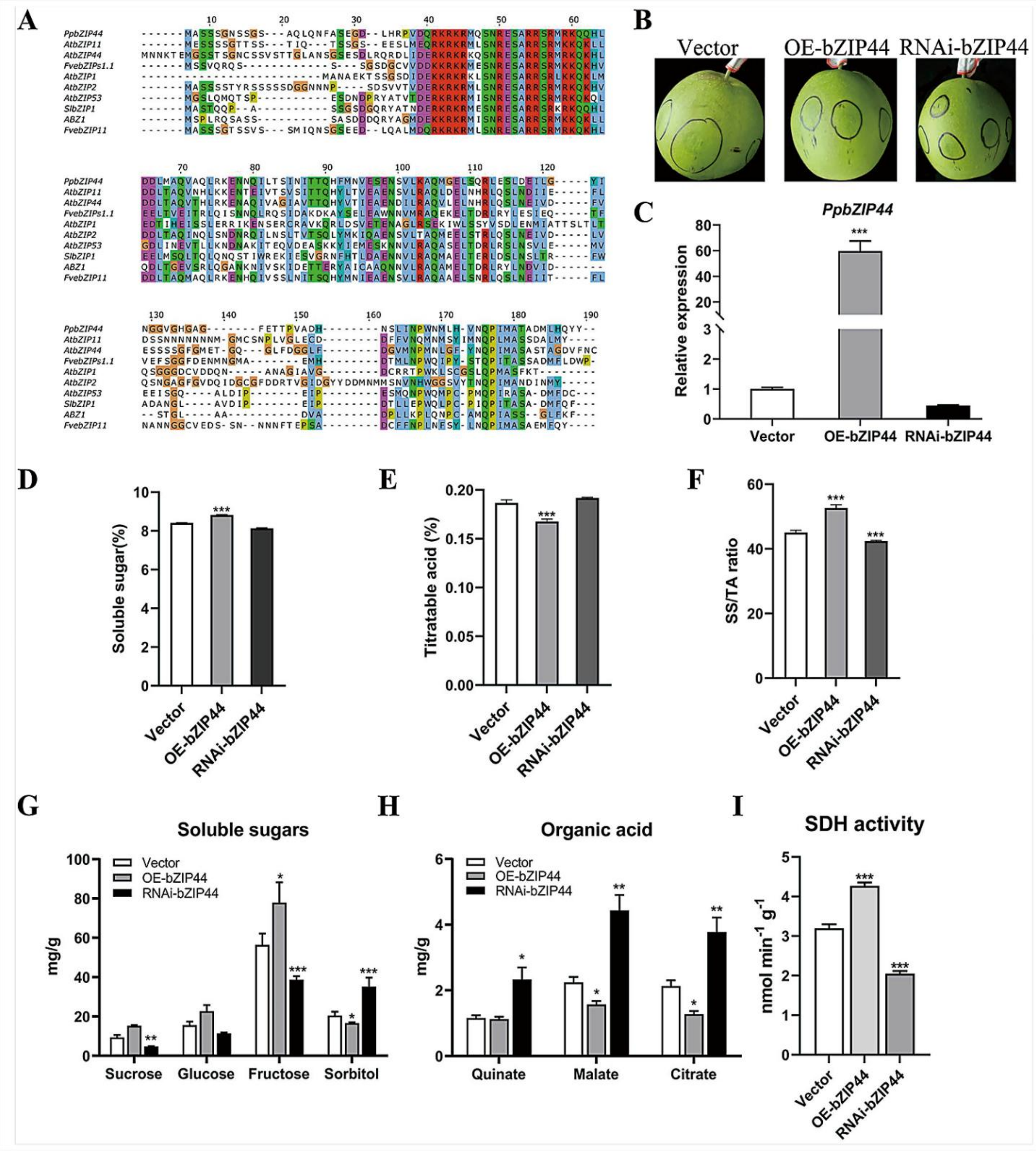

Figure 3 Transient transformation of *PpbZIP44* in pear fruits. A. Multiple protein sequence alignments of PpbZIP44 and other S1-bZIP proteins in different species. B. Transient assays in 'Sucui 1' pear using overexpression (OE-) or RNAi (RNAi) or empty vector (Vector) of PpbZIP44. C. The expression levels of PpbZIP44 in the fleshy tissue around the infiltration sites of transformed pear fruits using qRT-PCR. The content of total SS (D) and TA (E), SS/TA ratio (F), individual soluble sugars contents (G), individual organic acids contents (H), and SDH activity (I) in transformed pear fruits and control pear fruits. Bars represented the mean value ± SE (n ≥ 3). The asterisks indicated values that were determined by the Dunnett t test to significantly differ from their empty vector or WT control (*P < 0.05, **P < 0.01, ***P < 0.001) (Adopted from Wang et al., 2023)

8 Conclusions and Perspectives

When talking about pear quality, it's hard not to bring up nitrogen, potassium, and different trace elements. These nutrients pretty much decide the fruit's shape, size, and even how it tastes. Sugar doesn't come from just one process-it's built through a whole network that also involves plant hormones like ethylene, gibberellins, and abscisic acid, plus many working genes. New research in genomics and molecular biology is now finding more and more of these key genes and pathways, giving clues on how to manage nutrients more precisely in the future.

Smart fertilization methods-like giving a balanced mix of nutrients, applying them in stages, and using both organic and mineral fertilizers-can help pears grow bigger and taste sweeter. In practice, this means adjusting the right nutrient ratios, spraying leaves at key growth times, and using new genomic research to plan fertilizer use for each specific variety.

However, the shortcomings of reality cannot be ignored either. Many studies still remain at the level of a few varieties or general mechanisms, and the understanding of the differences among various pear varieties is not deep enough. In the fields, the situation is always more complicated: soil differences, climate fluctuations, and even pests and diseases can all alter the effectiveness of fertilization. This gap makes the achievements in the laboratory not always smoothly enter the orchard, and it also reminds us that future management strategies must be flexible and adapted to local conditions.

Next, a more promising direction is to truly integrate molecular and genomic data into nutrition management and build a smarter system. Genomic selection, marker-assisted breeding, and even real-time monitoring technologies can all be incorporated. The ultimate goal is not only to make pears larger and sweeter, but also to take into account the environment and sustainability. Precise fertilization, organic improvement, and the breeding of new varieties that efficiently utilize nutrients may enable the pear industry to strike a balance between economic benefits and ecological protection.

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The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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