3.3 Environmental, water, and nutrient management during the seedling stage

During the seedling stage, propagation success depends not only on the method used but also on precise control of the nursery environment, water supply, and nutrient regime. In cutting propagation, temperature, relative humidity, and light intensity are critical determinants of rooting and survival, while irrigation water and nutritional status also influence early establishment (Suárez Padrón et al., 2022). In grafted seedlings, protected greenhouse or shade-house systems are commonly used to stabilize temperature and moisture and to support rapid healing of the graft union. Citrus management studies also show that generalized irrigation and fertilization schedules are often inefficient because plant demand varies with substrate condition, growth stage, and local environment, making real-time monitoring and precision management preferable to uniform input application (Zhang et al., 2017).

Water and nutrient management should aim to maintain steady seedling growth without causing leaching, salt stress, root hypoxia, or excessively soft vegetative growth. Citrus studies show that heavy rainfall or over-irrigation can increase nutrient leaching, while flooding and waterlogging reduce aeration and damage fine roots. Fertigation and soluble fertilizers can improve nutrient-use efficiency when carefully managed, but excessive inputs are harmful; high fertigation rates may acidify the soil solution and increase ammonium accumulation (Quaggio et al., 2019). Likewise, a citrus pot study showed that very high nitrogen reduced total biomass from 14.24 to 6.95 g per plant, largely through direct and indirect inhibition of root growth (Niu et al., 2024). This result demonstrates the risk of excessive nitrogen in citrus seedlings, but it should not be converted into a direct fertilizer threshold for fingered citron. Practical nursery management should therefore emphasize moderate and split fertilizer application, good drainage, and irrigation scheduling based on substrate moisture rather than fixed routines (Srivastava et al., 2026). Evidence across citrus systems further supports coordinated water, nitrogen, and potassium management to improve resource-use efficiency (Zhang et al., 2026). For fingered citron seedlings, fertilizer rate and irrigation frequency should ultimately be adjusted according to substrate properties, seedling vigor, and local nursery conditions.

4 Seedling Quality Evaluation and Nursery Stock Management

4.1 Morphological and growth indicators of seedlings

Morphological and growth indicators are the most practical basis for routine nursery evaluation because they are rapid, simple, and usually nondestructive, even though they do not capture every aspect of field performance (Wang et al., 2026). Across seedling quality studies, the most commonly used indicators are seedling height, stem or root-collar diameter, height-to-diameter ratio, shoot and root dry mass, total biomass, shoot-to-root ratio, root length, root volume, and lateral root development (De Melo et al., 2018; Robonen et al., 2023). For citrus seedlings specifically, useful shoot indicators include plant height, stem diameter, leaf number, leaf area, branch number, sprout length, and sprout diameter, while root evaluation includes root length, root diameter, root number, fibrous root number, and root dry matter (Cruz et al., 2019; Xu et al., 2020; Kaur et al., 2024). Morphological markers such as leaf form, leaf size, and thorniness can also help distinguish seedling types or identify off-types in citrus breeding and nursery populations, although morphology alone is not always sufficient for definitive identification (Kurt and Koyuncu, 2024).

Among these indicators, stem diameter is consistently one of the strongest single predictors of overall seedling quality because it correlates well with biomass-based indices and later establishment potential (Robonen et al., 2023). Root traits add essential information because aboveground morphology alone does not always predict post-planting performance, whereas large root volume, high root fibrosity, abundant first-order laterals, and greater root system development tend to support better establishment, water uptake, and nutrient absorption (Figure 1) (Cruz et al., 2019; Pecoraro Sanches et al., 2026). Citrus studies also show that stronger shoot growth is positively associated with stronger root growth: seedling height and diameter correlate with root length, root diameter, root number, photosynthetic rate, stomatal conductance, and chlorophyll status, while vigorous rootstocks develop more absorbing roots and greater biomass accumulation (Kaur et al., 2024; Dattola and Gullo, 2026). Accordingly, these indicators can provide a reference framework for fingered citron seedling evaluation, but species-specific grading thresholds should be developed and validated for fingered citron rather than copied directly from other nursery systems (Kamanga et al., 2026).