implicated as a key regulator (Jia et al., 2023). Qi et al. (2025), based on a study of 'Hongyang' kiwifruit, found that malate content declined rapidly between 6 and 12 weeks after full bloom and was significantly negatively correlated with the expression of the plastidial AcPNAD-MDH1. CRISPR mutagenesis of AcSQBP9 reduced both malate and citrate contents while increasing AcPNAD-MDH1 expression, indicating that malate regulation also involves transcriptional control. Quinate metabolism is less resolved mechanistically, but kiwifruit studies have linked its accumulation to DAHPS, DHQS, and QDH expression, and consistently show high early abundance followed by decline as citrate becomes dominant (Fu et al., 2023).

4.2 Organic acid degradation during ripening

During ripening, organic acid decline in kiwifruit reflects increased respiratory utilization and broader metabolic reprogramming rather than simple dilution. Postharvest analyses show that citric acid declines progressively and tracks titratable acidity closely, identifying citrate degradation as the main cause of acid loss during ripening (Mao et al., 2023). In 'Xuxiang' fruit, Chai et al. (2024) found that the outer pericarp shows faster citric acid reduction than the core together with higher ATP, ADP, AMP, and energy charge, linking stronger acid decline to higher local respiration and energy metabolism. Across fruits more generally, citrate can be consumed through aconitase- and NAD-IDH-dependent pathways in mitochondria or diverted into the GABA shunt, and low mitochondrial aconitase activity can favor citrate retention whereas higher GABA-pathway activity promotes citrate degradation (Baiquan et al., 2018).

Malate decline during ripening is more variable than citrate decline, but when it decreases it is typically associated with decarboxylation and recycling into other pathways (Shu et al., 2024). Broader fruit metabolism studies indicate that vacuole-released malate and citrate can be redirected through gluconeogenesis, amino acid biosynthesis, and respiratory carbon metabolism during the transition from acid-dominated to sugar-dominated fruit composition (Iglesias-Sanchez et al., 2026).

In apple, malate decomposition is associated with NADP-malic enzyme and PEPCK activity, and suppressing these pathways during storage preserves acidity, supporting the general model that malate decarboxylation contributes to acid decline in fleshy fruit (Shu et al., 2024). Evidence in kiwifruit suggests this process is integrated with ethylene-responsive and TCA-linked ripening programs, although citrate appears to be the main driver of titratable acid loss in postharvest fruit (Fu and Chen, 2026).

4.3 Transport and compartmentation of organic acids

The final acidity of kiwifruit depends not only on metabolism but also on compartmentation, because malate and citrate are largely accumulated in vacuoles and their storage depends on tonoplast transport and vacuolar acidification (Huang et al., 2021). Reviews across fleshy fruits conclude that vacuolar storage is often the dominant determinant of cellular malate and citrate accumulation, even when biosynthetic pathways are active (Huang et al., 2021; Fu and Chen, 2026). In kiwifruit specifically, AcALMT1 has been functionally identified as a citrate transporter: its expression correlates with citrate accumulation, overexpression increases citrate content, and CRISPR mutagenesis of the upstream transcription factor AcNAC1 causes a dramatic citrate decrease without substantially affecting malate or quinate (Fu et al., 2023). This finding is notable because ALMT family members in other systems are more often linked to malate or fumarate transport, highlighting diversification of transporter function in fruit acidity control (Doireau et al., 2024).

Acid homeostasis also requires proton pumps and additional tonoplast carriers that establish the electrochemical gradient for organic acid sequestration (Huang et al., 2021; 2023). In other fruit systems, P-type ATPases such as PH5 and Ma10, together with V-ATPase and V-PPase, promote vacuolar acidification and enhance malate or citrate storage, indicating a transport logic likely relevant to kiwifruit as well (Wu et al., 2025). Tonoplast exchangers and channels such as tDT, ALMT9/Ma1, and related carriers further regulate the balance among citrate, malate, and other dicarboxylates by controlling import, export, and exchange across the vacuolar membrane (Doireau et al., 2024).