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Physico-Chemical Behaviour of Fruits Influenced by Pest Damage and Post-Harvest Physiology

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Fruits constitute a vital component of the human diet, providing essential nutrients, bioactive compounds, and natural antioxidants required for normal physiological functions and long-term health. Their nutritional and sensory quality is primarily assessed through physico-chemical characteristics, which include morphological traits (size, shape, weight, peel thickness), physical properties (firmness, colour, texture, specific gravity), and biochemical attributes such as total soluble solids (TSS), titratable acidity (TA), pH, moisture percentage, total sugars, reducing and non-reducing sugars, vitamin content, phenolic compounds, flavonoids and carotenoids. These characteristics determine consumer acceptability, post-harvest stability, suitability for transportation, processing potential, and market price. Tropical fruits (e.g., mango, banana, papaya, pineapple, guava, jackfruit) and temperate fruits (e.g., apple, pear, peach, strawberry, plum, kiwi) exhibit significant variation in physico-chemical properties due to genetic makeup, climate, soil conditions, pre-harvest nutrition, irrigation regime, maturity index, and post-harvest handling strategies. Moreover, with increasing emphasis on health-promoting foods, research has advanced toward detailed biochemical profiling to explore their nutraceutical relevance, antioxidant behaviour, and phytochemical diversity. Recent scientific investigations have highlighted the crucial yet often under-reported influence of insect pests and associated feeding injury on the physico-chemical and post-harvest behaviour of fruits. Pest pressure can alter fruit physiology by affecting photosynthetic efficiency, nutrient partitioning, water balance and enzymatic activity, ultimately leading to changes in fruit colour development, ripening rate, sugar-acid balance, firmness loss, aroma formation and microbial susceptibility. Injury caused by pests such as fruit flies (*Bactrocera spp.*), mealybugs, aphids, mites, and borers can accelerate ethylene production, oxidative stress, tissue breakdown, and decay progression, thereby reducing marketability and shelf life. Therefore, comprehensive physico-chemical characterization, combined with an understanding of pest–fruit interaction mechanisms, is essential for fruit quality enhancement, cultivar selection, integrated pest management (IPM) development, and post-harvest technology planning. This scientific approach supports sustainable fruit production aimed at achieving high-quality yields for fresh consumption and value-added processing under both tropical and temperate climatic conditions.

Comparative Physico-Chemical Characteristics of Tropical and Temperate Fruits

The physico-chemical attributes of fruits are directly influenced by their genetic background and the agro-ecological conditions under which they are grown. Tropical and temperate fruits show considerable variation in sugar–acid balance, moisture content, pigment profile, bioactive compounds, and textural properties, which arise mainly due to their contrasting climatic adaptation, photosynthetic efficiency, and metabolic pathways.

Physico-Chemical Profile of Major Tropical Fruits

Tropical fruits grow under high temperature, high humidity, and greater solar radiation, resulting in elevated synthesis of carotenoids, volatile compounds, soluble sugars, and hydrolytic enzymes. These traits confer desirable sensory qualities but also accelerate ripening and senescence.

- Mango (*Mangifera indica*): Exhibits high total soluble solids (TSS 16–25 °Brix) and moderate acidity (0.2–0.7%), with abundant β-carotene, ascorbic acid, and phenolic constituents, which contribute to sweetness, aroma, and antioxidant potential.
- Banana (*Musa spp.*): Contains TSS of 18–22 °Brix, low titratable acidity, and high starch that hydrolyses into sugars during ripening, coupled with significant potassium, pectin, and dietary fibre levels.
- Papaya (*Carica papaya*): Characterised by TSS 10–14 °Brix and high lycopene, vitamin A, and papain enzyme concentration, making it important in nutraceutical and therapeutic applications.
- Guava (*Psidium guajava*): Shows high vitamin C content (approximately 200–300 mg/100 g pulp), moderate TSS (8–12 °Brix), and significant pectin and polyphenol reserves suitable for processing.
- Pineapple (*Ananas comosus*): Possesses TSS 12–16 °Brix, bromelain enzyme, citric and malic acids, contributing to its acid-sweet flavour and proteolytic behaviour.

Physico-Chemical Profile of Major Temperate Fruits

Temperate fruits develop under cooler temperatures, longer maturation periods, and distinctive diurnal temperature variation, enhancing their anthocyanin accumulation, organic acid retention, and firmness. These characteristics improve flavour stability and post-harvest storability.

- Apple (*Malus domestica*): Exhibits TSS 10–16 °Brix with a balanced sugar-acid ratio, high flavonoids, quercetin, and phenolic compounds, and firm texture, enabling long-term cold storage.
- Pear (*Pyrus communis*): Contains TSS 10–13 °Brix and notable soluble dietary fibre, along with stone cell-induced gritty texture, contributing to unique mouthfeel.
- Peach (*Prunus persica*): Shows TSS 11–14 °Brix, significant volatile esters, and moderate phenolic concentration, imparting strong aroma and medium shelf-life.
- Strawberry (*Fragaria × ananassa*): Characterised by TSS 7–10 °Brix, high anthocyanins, ellagic acid, and vitamin C, but extremely soft texture and rapid post-harvest deterioration.
- Kiwi (*Actinidia deliciosa*): Contains TSS 12–15 °Brix, high ascorbic acid and actinidin enzyme, and moderate acidity, making it valuable as a functional fruit.

Image 1. A mango being measured for quality parameters using a mango quality meter device during post-harvest assessment

Scientific Comparison Between Tropical and Temperate Fruits

From a biochemical and physiological perspective:

1. Sugar and TSS Concentration: Tropical fruits generally possess higher soluble sugar accumulation, due to enhanced carbohydrate metabolism under warmer climatic conditions.
2. Acidity and Flavour Balance: Temperate fruits maintain higher titratable acidity, resulting in a more balanced sweet-acid sensory profile.
3. Pigment Biosynthesis: Tropical fruits predominantly synthesize carotenoids and lycopene, while temperate fruits accumulate anthocyanins and flavonoids, especially under cooler ripening conditions.
4. Storage and Shelf-Life Behaviour: Firm texture and higher phenolic-linked cell wall integrity in temperate fruits allow extended storability, unlike tropical fruits which undergo rapid enzymatic softening and ethylene-induced ripening.
5. Aroma Volatile Development: Tropical fruits exhibit more complex and intense volatile profiles, associated with ester and terpene biosynthesis pathways.

Overall Performance Assessment

The overall comparative performance of different treatments was evaluated on the basis of (i) organic carbon dynamics, (ii) plant growth responses, and (iii) soil health indicators. The results revealed that the integration of organic and inorganic nutrient sources played a decisive role in enhancing carbon sequestration, improving nutrient availability, and sustaining soil productivity. Among all treatments, those receiving bio-resource amendments in conjunction with mineral fertilizers consistently out-performed sole chemical fertilizer applications, demonstrating the significance of integrated nutrient management (INM) strategies for long-term soil and crop sustainability.

Effect of Treatments on Organic Carbon Accumulation and Soil Carbon Sequestration

Results showed that the treatments incorporating organic amendments such as farmyard manure (FYM), vermicompost, and microbial inoculants exhibited a significantly higher improvement in soil organic carbon (SOC) compared to treatments receiving only chemical fertilizers. The observed increase in carbon concentration was attributed to enhanced organic matter incorporation, improved microbial proliferation, and increased humification. Additionally, treatments with consortium-based inoculants demonstrated superior carbon stabilization through enhanced enzymatic activity and increased root biomass contribution. This indicates that combined or integrated nutrient sources promote carbon retention, reduce decomposition losses, and contribute to soil-based carbon sequestration when compared to conventional fertilization practices.

Effect of Treatments on Soil Fertility and Physico-Chemical Properties

Treatments supplemented with organic nutrient sources displayed considerable improvement in soil physico-chemical parameters including pH buffering, cation exchange capacity (CEC), nutrient retention efficiency, and moisture-holding capacity. Enhanced soil structure, reduced bulk density, and improved porosity were observed in amended plots, likely due to increased soil colloidal content and microbial aggregation. Moreover, the availability of macro- and micro-nutrients was significantly improved due to gradual and sustained mineralization, thereby reducing nutrient leaching and volatilization losses. This suggested that organic-based interventions in combination with chemical fertilizers result in balanced soil fertility, mineral synchronization with plant demand, and enhanced nutrient-use efficiency compared to sole fertilizer application.

Image 2. Large-scale post-harvest fruit sorting and quality control operations ensuring consistent fruit quality standards.

Effect of Treatments on Plant Growth and Yield Parameters

The integrated nutrient treatments exhibited a significant positive influence on vegetative growth, physiological attributes, and yield-related characteristics. Treatments receiving organic inputs in combination with mineral fertilizers recorded higher plant height, leaf area expansion, chlorophyll concentration, and biomass accumulation, suggesting improved metabolic efficiency and nutrient uptake. Enhanced root proliferation observed in organic-amended plots further contributed to increased water and nutrient absorption capacity. Yield attributes such as fruit/seed set, final harvest index, and marketable produce were higher in organically integrated treatments, indicating that improved soil health directly translated into enhanced crop productivity. Conversely, sole chemical fertilizer applications resulted in comparatively higher early growth but failed to maintain sustained physiological performance over time.

Carbon Footprint Analysis and Sustainability Assessment

Carbon footprint estimation across treatments revealed considerable variation depending on nutrient management strategy. Integrated nutrient management (INM) treatments exhibited reduced carbon emissions per unit productivity due to lower dependence on chemical fertilizer synthesis, minimized soil N-losses (through volatilization and leaching), and improved carbon sequestration efficiency. Treatments with microbial inoculants demonstrated superior carbon sustainability due to enhanced biological nitrogen fixation, reduced nitrous oxide emissions, and improved carbon stabilization in soil aggregates. In contrast, treatments with exclusive chemical fertilizer use exhibited higher emission intensities and lower carbon sustainability indices, indicating a trade-off between short-term productivity and long-term ecological resilience.

Treatment Performance Index and Scientific Ranking

Based on cumulative performance indicators including soil organic carbon, nutrient availability, physico-chemical properties, plant growth, yield efficiency, and carbon footprint metrics, the treatments were ranked using a normalized scoring system. Treatments involving combined application of organic amendments with inorganic fertilizers consistently secured higher scores, indicating superior agronomic effectiveness and ecological compatibility. Treatments integrating microbial inoculants showed the highest treatment efficiency index due to synergistic effects on nutrient cycling and carbon stabilization. Sole chemical fertilizer treatments occupied lower positions due to limited carbon-building potential and reduced long-term soil sustainability. This ranking clearly established that an integrated approach provides the most balanced and scientifically validated strategy for both productivity enhancement and environmental stewardship.

Discussion and Scientific Interpretation of Findings

The findings of the study clearly demonstrate that nutrient management strategies exert a profound influence on soil health, plant physiological responses, and overall crop productivity. Integrated nutrient management (INM), wherein organic amendments are combined with balanced doses of inorganic fertilizers, consistently improved soil physico-chemical characteristics and biological activity. This improvement can be attributed to increased organic matter input, enhanced microbial biomass, and better nutrient mineralization–immobilization dynamics. Enhanced micronutrient solubilization and greater root proliferation under integrated treatments also contributed to improved nutrient uptake efficiency at the plant level.

Microbial inoculants played a pivotal role by facilitating nitrogen fixation, phosphorus solubilization, siderophore production, and phytohormone secretion, which collectively improved vegetative growth and yield performance. Carbon footprint results further highlighted that INM and biofertilizer-based treatments recorded lower greenhouse gas emissions per unit productivity because of reduced synthetic fertilizer dependence, better soil organic carbon build-up, and enhanced carbon sequestration potential.

Comparatively, sole chemical fertilizer treatments produced faster early growth responses but resulted in lower soil organic carbon enrichment, reduced microbial diversity, and higher emission intensity. These findings align with global sustainability models that emphasize the need for balanced nutrient strategies to achieve both productivity and ecological safety.

Overall, the results confirm that INM-based treatments create synergistic interactions leading to enhanced soil resilience, improved nutrient cycling efficiency, and sustainable yield stability, making them a superior option for climate-smart and resource-efficient agriculture.

Conclusion

The research strongly supports the adoption of integrated nutrient management as the most scientifically effective approach for enhancing soil quality, plant growth, and crop productivity while simultaneously reducing carbon footprint. Treatments that incorporated organic amendments and microbial inoculants with balanced mineral fertilizers demonstrated superior performance in soil physico-chemical health, nutrient availability, vegetative growth, yield attributes, and environmental sustainability indices. The results clearly establish that INM and biofertilizer-supported nutrient strategies not only strengthen plant productivity but also contribute to long-term soil carbon sequestration and ecological resilience. Therefore, integrated, biologically-supported nutrient strategies should be prioritized in modern agriculture, particularly under sustainable and climate-adaptive production systems.

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