

Methodology

Biological Mechanisms

Cambium Alignment and Contact

The success of graft union formation fundamentally depends on precise alignment of the cambium layers, the thin meristematic tissue responsible for secondary growth in plants [?, ?]. The cambium, located between the xylem and phloem, contains actively dividing cells that generate new vascular tissue. For successful grafting, the cambium layers of rootstock and scion must be brought into direct contact, enabling cell-to-cell communication and tissue integration.

The cambium contact area can be quantified as:

$$C(t) = C_0 + \int_0^t r_c(\tau) \cdot A(\tau) d\tau \quad (1)$$

where $C(t)$ is the cambium contact area at time t , C_0 is the initial contact area (determined by technique quality), $r_c(\tau)$ is the cambium growth rate, and $A(\tau)$ is the available contact area.

Callus Formation

Following cambium contact, callus tissue forms at the site of graft union formation.

Grafting Techniques

Whip and Tongue Grafting

Whip and tongue grafting (also called splice grafting) is among the most precise methods, suitable for rootstock and scion of similar diameter (5-25 mm) [?, ?]. The technique involves:

1. Making matching 30-45° angle cuts on both rootstock and scion
2. Creating interlocking tongues (notches) on both pieces
3. Aligning cambium layers precisely
4. Securing with grafting tape or wax
5. Protecting from desiccation

Success rates typically range from 75-90%, depending on species compatibility and execution quality.

Cleft Grafting

Cleft grafting is suitable for larger diameter rootstock (10-50 mm) and is particularly useful for top-working established trees [?]. The procedure involves:

1. Making a vertical split in the rootstock
2. Preparing wedge-shaped scion with 2-3 buds

Compatibility Theory

Phylogenetic Distance Model

Phylogenetic distance is the strongest predictor of graft compatibility [?, ?]. Closely related species share similar vascular anatomy, biochemical pathways, and growth patterns, enabling successful union formation. Compatibility decreases exponentially with phylogenetic distance:

$$P_{phyl}(d) = e^{-k \cdot d/d_{max}} \quad (4)$$

where $P_{phyl}(d)$ is the phylogenetic compatibility (0-1), d is the phylogenetic distance, d_{max} is the maximum distance for compatibility, and k is a decay constant (typically $k \approx 2.0$).

Cambium Match Model

Similar cambium thickness indicates better alignment potential and reduced stress at the union interface:

$$P_{camb}(r_s, r_r) = 1 - \min \left(1, \frac{|r_s - r_r|}{\tau \cdot r_r} \right) \quad (5)$$

Success Factors

Environmental Conditions

Optimal environmental conditions are critical for graft success:

- ▶ **Temperature:** 20-25°C optimal, 15-30°C acceptable range
- ▶ **Humidity:** 70-90% relative humidity optimal
- ▶ **Light:** Moderate indirect light, avoid direct sun exposure
- ▶ **Season:** Late winter to early spring for temperate species

The environmental suitability score can be calculated as:

$$E(T, H) = E_T(T) \cdot E_H(H) \quad (8)$$

where $E_T(T)$ and $E_H(H)$ are temperature and humidity suitability functions, respectively.

Technique Quality

The quality of technique execution significantly impacts success rates. Key factors include:

- ▶ Precision of cuts and alignment
- ▶ Speed of operation (minimizing desiccation)
- ▶ Proper sealing and protection
- ▶ Removal of air bubbles

Computational Framework Biological Process Simulation

Our simulation framework models the temporal dynamics of graft healing using a system of differential equations:

$$\frac{dC}{dt} = r_c \cdot (1 - C) \cdot E(T, H) \cdot P_{total} \quad (9)$$

$$\frac{dF}{dt} = r_f \cdot C \cdot (1 - F) \cdot E(T, H) \cdot P_{total} \quad (10)$$

$$\frac{dV}{dt} = r_v \cdot F \cdot (1 - V) \cdot E(T, H) \cdot P_{total} \quad (11)$$

where r_c , r_f , and r_v are growth rate constants for cambium contact, callus formation, and vascular connection, respectively.

Success Probability Prediction

The overall graft success probability combines compatibility, technique quality, environmental conditions, and seasonal timing:

Implementation Details

The computational toolkit implements these models through modular Python packages:

- ▶ `graft_basics.py`: Core grafting calculations and compatibility checks
- ▶ `biological_simulation.py`: Simulation framework for healing processes
- ▶ `compatibility_prediction.py`: Compatibility prediction algorithms
- ▶ `species_database.py`: Database of species compatibility information
- ▶ `technique_library.py`: Encyclopedia of grafting techniques
- ▶ `graft_statistics.py`: Statistical analysis of grafting outcomes
- ▶ `graft_analysis.py`: Factor analysis and outcome evaluation

All implementations follow the thin orchestrator pattern, with business logic in `src/` modules and orchestration in `scripts/` files, ensuring maintainability and testability.

Validation Framework

To validate our models and predictions, we use:

1. **Literature Review:** Comparison with published success rates and compatibility data
2. **Synthetic Data Generation:** Realistic trial data based on known biological parameters
3. **Statistical Validation:** Hypothesis testing and correlation analysis
4. **Cross-Validation:** Model performance on held-out data

The validation framework ensures that predictions align with established horticultural knowledge and biological principles.