The brittleness of polylactic acid (PLA) can be improved through several strategies, as detailed in the retrieved documents:

1. Plasticization

- Adding **plasticizers** (e.g., lactide monomers, oligomeric lactic acid, glycerol, citrate esters, polyethylene glycol (PEG)) reduces brittleness by lowering the glass transition temperature (**Tg**) and increasing chain mobility (reference_161.pdf, p. 16; reference_30.pdf, p. 369).

2. Copolymerization

- Introducing flexible comonomers (e.g., caprolactone, glycolide) improves toughness by disrupting PLA's rigid structure (reference_156.pdf, p. 1051).

3. Blending with Toughening Agents

- **Rubber toughening** (e.g., blending with poly(butylene adipate-co-terephthalate) (PBAT), poly(ε-caprolactone) (PCL), or natural rubber) enhances impact resistance (reference_156.pdf, p. 1051).
- **Reactive blending** (e.g., with epoxy-functionalized polymers) improves interfacial adhesion and toughness (reference_156.pdf, p. 1051).

4. Nucleation Agents & Crystallinity Control

- Adding **nucleating agents** (e.g., talc, nanoclay) promotes smaller, more uniform crystallites, reducing brittleness (reference_30.pdf, p. 369).
- **Annealing** can optimize crystallinity, balancing stiffness and ductility (reference_161.pdf, p. 9).

5. Nanocomposites & Fillers

- Incorporating **nanofillers** (e.g., cellulose nanofibers, graphene) can improve toughness while maintaining strength (reference_30.pdf, p. 369).

6. Impact Modifiers

- **Core-shell rubber particles** (similar to high-impact polystyrene, HIPS) can significantly enhance impact strength (reference_156.pdf, p. 1051).

Key Considerations

- **Trade-offs**: Increasing toughness often reduces stiffness and strength.
- **Processing conditions** (e.g., extrusion speed, cooling rate) affect final properties.

For more details, see **reference_156.pdf (p. 1051), reference_30.pdf (p. 369), and reference_161.pdf (p. 16).**