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Synergistic enhancement of *in-vitro* antioxidant activity in essential oil and post-distillation residue-derived oleoresin combinations of *Zingiber officinale* cultivars and development of a microencapsulated antioxidant rich controlled release nutraceutical

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Two widely cultivated ginger cultivars in Sri Lanka, named Ceylon and Rangoon (*Zingiber officinale*) were investigated to develop a valorized, high potency microencapsulated nutraceutical from ginger processing by-products. Essential oils (EOs) were extracted from fresh rhizomes by hydrodistillation; GC-MS profiling of EO confirmed zingiberene as the dominant volatile in both cultivars, with Ceylon exhibiting a monoterpene-enriched chemotype (eucalyptol 7.76%) and Rangoon a sesquiterpenoid-dominant profile (zingiberene 31.32%). Post-distillation residues (PDR) were subjected to Soxhlet extraction with acetone and ethanol to yield PDR-derived oleoresins; Ceylon consistently produced higher oleoresin yields while Rangoon yielded more EO, and acetone outperformed ethanol across both cultivars. Antioxidant screening (DPPH, FRAP, TPC, TFC, ORAC) established that PDR-oleoresins possessed substantially higher bioactivity (DPPH IC_{50}: 219-240 µg/mL; FRAP: 740-808 mg Trolox/g; TPC: 222-297 mg GAE/g; ORAC: 86-99 mg Trolox/g) relative to EOs (IC_{50} > 3,300 µg/mL; FRAP: 29-32 mg Trolox/g). Overall, Ceylon ginger exhibited superior antioxidant properties over Rangoon. Synergistic interactions between EO and PDR-oleoresin were evaluated across nine blend ratios (EO:Oleoresin 1:9 to 9:1); the Ceylon 4:6 blend achieved the highest synergy index (98.05%; Chou-Talalay CI = 0.020; DPPH IC_{50} = 7.480 µg/mL) and was chosen as the optimal blend by quadratic regression modelling. Microencapsulation of the optimal blend was optimized via lyophilization using Maltodextrin (MD) and Gumarabic (GA) wall matrices across five formulations. Formulation F3 (MD:GA 72:28) achieved 84.7% encapsulation efficiency, 1.78% moisture content, and 99.1% oil recovery; scanning electron microscopy revealed irregularly shaped microcapsules with a rough, porous wall surface and particle sizes of 20-100 µm. Antioxidant release of F3 under hot water brewing simulation (85°C) followed first-order kinetics (k_1 = 0.456 min^{-1}; $t_{½}$ = 1.52 min), with delivering approximately 82-fold higher antioxidant activity on an equal-mass basis relative to freshly chopped Ceylon ginger. These results demonstrate the successful valorization of ginger PDR into a protected, high-potency functional food ingredient.

Keywords:

Microencapsulation; *Zingiber officinale*; Antioxidant synergism; Controlled release

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