## 3 Advances in Marigold (*Tagetes* spp.) Production Technology

The increasing commercial demand for marigold flowers in ornamental horticulture, the pharmaceutical industry, poultry feed, and natural pigment extraction has accelerated research on improving production technologies. Advances in breeding, biotechnology, cultivation practices, nutrient management, and post-harvest handling have substantially enhanced flower yield, quality, stress tolerance, and production efficiency. Modern production systems increasingly integrate conventional breeding with molecular approaches, tissue culture, precision cultivation, and sustainable crop management to develop high-performing cultivars capable of meeting industrial demands while improving resource-use efficiency (Hussein et al., 2011; Kumar et al., 2016).

### 3.1 Advancement in hybrid seed production

The discovery of male sterility has greatly expanded opportunities for efficient hybrid seed production in marigold by eliminating the need for labour-intensive manual emasculation. Both genic male sterility (GMS) and cytoplasmic male sterility (CMS) systems have been successfully utilized in breeding programmes. Apetaloid female lines are controlled primarily by GMS and are widely used in commercial hybrid seed production because they are easily distinguishable during flowering. In contrast, petaloid female lines are governed by CMS, although partial fertility may occasionally occur, resulting in gynodioecious or gynomonoecious reproductive systems (Sindhuja et al., 2018; Sukwiwat et al., 2023). These male sterile systems facilitate efficient cross-pollination, increase hybrid seed purity, and reduce production costs, thereby significantly improving commercial hybrid seed production (Dedhia et al., 2022).

### 3.2 Conventional breeding advances

Conventional breeding has played a central role in improving marigold cultivars through mass selection, pedigree selection, pure-line selection, hybridization, and mutation breeding. Mass selection has been successfully employed to develop open-pollinated cultivars such as 'Calcutta Orange' and 'Arka Pari', whereas pedigree and pure-line selection have improved flower yield, colour intensity, carotenoid content, plant architecture, and resistance to diseases such as Fusarium wilt (Ayiecho and Nyabundi, 2025; Venkatesan and Ramesh Kumar, 2025). Hybridization has resulted in superior $F_1$ hybrids, including 'Arka Abhi', 'Arka Shubha', and 'Arka Agni', characterized by larger flowers, improved shelf life, and enhanced transportability. Mutation breeding using gamma rays and ethyl methanesulfonate (EMS) has generated valuable genetic variability, including novel flower colours and improved ornamental traits, thereby providing useful breeding materials for future cultivar development.

Biotechnological approaches, particularly tissue culture, provide opportunities for rapid multiplication and conservation of superior gomphrena germplasm (Figure 3). Successful callus induction has been achieved using hypocotyl explants cultured on Murashige and Skoog (MS) medium supplemented with appropriate concentrations of sucrose, NAA, and BA. These protocols facilitate efficient shoot regeneration and root development, thereby supporting large-scale propagation and conservation of elite genotypes (Ruiz and Valadez, 1985). Nevertheless, commercial application remains constrained by relatively high production costs, specialized laboratory requirements and the need for efficient acclimatization protocols.

### 3.3 Modern biotechnology

Modern biotechnology has substantially accelerated marigold improvement by complementing conventional breeding approaches. Marker-assisted selection enables the identification of quantitative trait loci associated with economically important traits such as flower size, yield, and male sterility, thereby increasing breeding efficiency. The development of SCAR markers has facilitated the rapid identification of desirable male sterile lines for hybrid seed production (Joshi et al., 2024). Genome editing using CRISPR-Cas9 also offers considerable potential for improving flower colour, pest resistance, and abiotic stress tolerance. Although its application in marigold remains limited, successful modification of ornamental traits in related species demonstrates promising opportunities for future genetic improvement (Verma et al., 2023; Nishihara et al., 2024). Furthermore,