



Engineering advance

## A comprehensive review of hybrid forward osmosis systems: Performance, applications and future prospects



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### ABSTRACT

Forward osmosis (FO) has been increasingly studied in the past decade for its potential as an emerging low-energy water and wastewater treatment process. However, the term “low-energy” may only be suitable for those applications in where no further treatment of the draw solution (DS) is required either in the form of pretreatment or post-treatment to the FO process (e.g. where the diluted DS is the targeted final product which can be used directly or simply discarded). In most applications, FO has to be coupled with another separation process in a so-called hybrid FO system to either separate the DS from the final product water or to be used as an advanced pre-treatment process to conventional desalination technologies. The additional process increases the capital cost as well as the energy demand of the overall system which is one of the several challenges that hybrid FO systems need to overcome to compete with other separation technologies. Yet, there are some applications where hybrid FO systems can outperform conventional processes and this study aims to provide a comprehensive review on the current state of hybrid FO systems. The recent development and performance of hybrid FO systems in different applications have been reported. This review also highlights the future research directions for the current hybrid FO systems to achieve successful implementation.

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**Abbreviations:** BSA, bovine serum albumin; BWRO, brackish water reverse osmosis; CA, cellulose acetate; CAC, citric acid; CQDs, carbon quantum dots; CTA, cellulose triacetate; DS, draw solution; ED, electrodialysis; EDTA, ethylenediaminetetraacetic acid; FDFO, fertiliser driven forward osmosis; FO, forward osmosis; FS, feed solution; GAC, granular activated carbon; rGO, reduced graphene oxide; HF, hollow fibre; ICP, internal concentration polarisation; IPN, interpenetrating network; LCST, lower critical solution temperature; LPRO, low pressure reverse osmosis; MBC, membrane brine concentrator; MD, membrane distillation; MDC, microbial desalination cells; MED, multi effect distillation; MF, microfiltration; MNPs, magnetic nanoparticles; MSF, multi stage flash; MW, molecular weight; NF, nanofiltration; OD, osmotic dilution; OMBR, osmotic membrane bioreactor; OMDC, osmotic microbial desalination cells; PA, polyamide; PAA, polyacrylic acid; PAFO, pressure-assisted forward osmosis; PRO, pressure-retarded osmosis; PV, photovoltaic; RO, reverse osmosis; ROSA, reverse osmosis system analysis; RSF, reverse solute flux; SPS, switchable polarity solvents; SWRO, seawater reverse osmosis; TDS, total dissolved solids; TEM, transmission electron microscopy; TFC, thin-film composite; TMA, trimethylamine; TOC, total organic carbon; TrOCs, trace organic compounds; UF, ultrafiltration; VMD, vacuum membrane distillation; WHO, world health organization; ZLD, zero-liquid discharge

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