

Closing phosphorus cycle from natural waters: re-capturing phosphorus through an integrated water-energy-food strategy

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Phosphorus (P) reserve, largely derived from phosphate rock, is essential for crop growth to support the growing world population. However, a significant proportion of phosphorus used as a fertilizer runs into natural waters, causing eutrophication and ecological damage. Moreover, most P in the food is eventually discharged as waste after being digested by human and animals. Thus, industrial activities have created a one-way flow of non-renewable P from rocks to farms to lakes, rivers and oceans.

It has been suggested that P reserve can only support global food security for up to 125 years (*Gilbert, 2009*). Due to technological and economic reasons, existing wastewater treatment and environmental stewardship laws permit a relatively high level of P (~0.3 mg/L) to be discharged into natural environment, which will cause eutrophication. Phosphorus recovery has become an important issue for agricultural sustainability and aquatic ecology. Existing technologies for re-capturing P from concentrated wastes still remain unsustainable due to high chemical and energy costs (*Zhou et al., 2017; Zhang et al., 2017*). We predict that in the near future we have no option but to find cost-effective and sustainable methods to re-capture P from the natural waters where it currently ends up.

Harmful algal bloom has become an important issue in eutrophic natural waters, which represent a great threat to public health and cause ecological degradation (*Conley et al., 2009*). However, microalgae are exceptionally effective in turning low levels of dissolved P into concentrated particulate P, and at very much faster rates than the geological mineralisation processes that created our P reserves. Recent developments have made it possible to remove large scale harmful algal blooms through flocculation using ecologically friendly geo-engineered materials (*Pan et al., 2006; Li and Pan. 2013; Li et al., 2015; Shi et al., 2016; Yuan et al., 2016*). This principle makes it possible to harvest algal biomass and take P out of natural waters cost-effectively by combining with conventional air floating technologies. We predict that there will be a tipping point to make it feasible to re-capture from natural waters when the supplying of food, water and energy to the growing global population becomes unsustainable, and microalgae utilization technologies may greatly accelerate this process.

In addition to harvesting harmful algae biomass from natural waters, microalgae can be cultured using nutrient rich wastewater and industrial waste gas containing CO₂. After purification of *water* and gas, microalgae can be turned into biofuel for *energy* through pyrolysis (*Clarens et al., 2011*). It is also possible to produce electricity by using/decomposing organic pollutants through bio-fuel cells. The remaining algal residues can be turned into multi-functional hollow sphere bio-

hydrochar through hydrothermal treatment (Bi and Pan, 2017; Bi and Pan, 2014), which can be applied to soils to remove toxic metals and promote agriculture that provides safe food. Although technologies in the individual processes are still not economically viable, a combined strategy to yield *integrated water-energy-food* (iWEF) products may be a way to solve this problem, thereby powering a green and sustainable economy triggered by commercialization, which will eventually close the P cycle (Fig. 1). In the near future of less than a hundred years when the P rock reserve is exhausted, human food and activities may have to be driven by the reserve of iWEF which will rely on scattered P in waters.

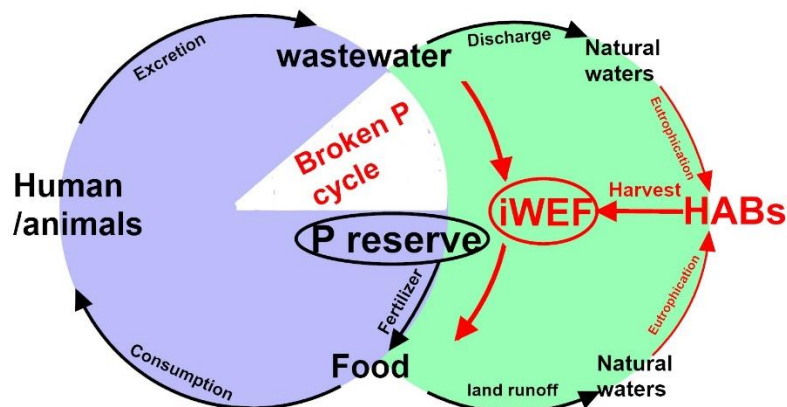


Fig. 1 Traditional broken phosphorus cycle (black words) and closed phosphorus cycle from natural waters (red words)

Therefore, it is concluded that the P discharged into natural waters causes increasing harmful algal blooms worldwide and the broken biogeochemical P cycle. However, microalgae are very effective in turning low levels of dissolved P into concentrated particulate P. As innovative technologies develop, re-capturing P from natural waters is expected to be a tipping point of closing the P cycle. Microalgae biotechnology to turn industrial wastewater and waste gas into integrated water-energy-food (iWEF) products may accelerate our endeavour for environmental sustainability and solve the viability and feasibility problems that hindered green industry from exploiting P re-capturing.

The authors declare no competing financial interest

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