Aquatic plants: an opportunity feedstock in the age of bioenergy

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There is a growing impetus to identify and develop bioenergy feedstocks that can be harnessed in ways that do not require major land-use intensification or use of food crops. Although invasive aquatic plants have long been regarded as an intriguing potential feedstock because of their high growth rate in natural water bodies, most contemporary management is based on plant control rather than utilization. This review presents a comparative life cycle overview of modern aquatic plant control and alternative bioenergy utilization programs, highlighting costs and benefits associated with both approaches. Given recent advances in harvester and bioenergy conversion technologies, it may be cost effective to incorporate utilization techniques in many water bodies, particularly if ancillary benefits associated with nutrient removal and greenhouse-gas reductions are given monetary credit. Pilot projects and site-specific evaluations are, however, needed to determine the ultimate scale in which bioenergy production from aquatic plants will be feasible.

Critical problems such as anthropogenic climate change, dwindling oil supplies and rural underdevelopment have sparked global interest in harnessing renewable energy sources. While biofuels, such as ethanol, and other forms of biomass-based energy (i.e., bioenergy) are widely regarded as being among the most promising renewable-energy pathways [1,2], there is significant concern that land-use changes implied by large-scale bioenergy production could pose substantial risks to both the natural environment [3–5] and human well-being [6].

Accordingly, there is a growing impetus to identify and develop bioenergy feedstocks that can be harnessed in ways that do not require major land-use intensification or use of food crops. Much attention, for example, has been given to potential environmental benefits associated with cultivation of perennial grasses for bioenergy production on marginal and/or degraded crop land [7–9]. Other pathways that are being extensively explored for their potential to reduce bioenergy's land footprint range from increased utilization of residues from existing crop and forestry lands [10,11], to the biotechnological development of algal species that can be cultivated with extremely high areal biomass yield rates [12,13]. However, major challenges and limitations identified for large-scale utilization of perennial grasses [14,15], residual biomass [16–18] and algal culture [19] make it clear that there is no 'silver bullet' solution to sustainable bioenergy production likely. Instead, there will have to be many solutions that are designed to take advantage of the specific resources available in different local and regional contexts.

This review makes the case that invasive aquatic plant biomass represents an untapped potential source of bioenergy that, while still having major challenges and limitations, is intriguing in the sense that a whole suite of socioenvironmental benefits can be seen to accrue in conjunction with increased utilization. Since invasive **aquatic plants** produce enormous amounts of biomass and adversely affect natural environments (i.e., areas without direct human impact), sustained removal of this biomass will generally have benefits for the nutrient balance and native ecology of affected aquatic ecosystems. Moreover, beneficial bioenergy utilization of what is essentially a nuisance waste can be seen as

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Key terms

Aquatic plants: Refers to plants that are biologically adapted to grow in wetlands, lakes, rivers and other water bodies

Eutrophication: Process of lake aging caused by accumulation of sediments and organic matter. Often exacerbated by anthropogenic loading of nutrients, such as phosphorus and nitrogen, in which case it is referred to as cultural eutrophication

Water hyacinth (*Eichhornia crassipes*): A floating aquatic plant that has become naturalized throughout the tropics and is commonly regarded as one of the world's most problematic invasive species. Owing to its prolific growth and ability to sequester many water-borne contaminants, water hyacinth has also been the subject of much research into biomass utilization and aquatic remediation

having the effect of correspondingly lessening the need for land, water, fertilizer and pesticide inputs associated with the production of other bioenergy feedstocks.

This review begins with a general discussion of invasive aquatic plants as a problem that has emerged within the context of the past century's rapid increase in both global commerce and anthropogenic **eutrophication**. Strategies employed to combat invasive aquatic plants are then explored, with consequences of the most common strategies examined in some detail through the use of a diagrammatic life cycle. Next, a comparative review and life cycle diagram is developed for management strategies based upon the harvest and utilization of extant invasive aquatic plant biomass for bioenergy production. The review concludes by suggesting public policy and research frameworks that could facilitate development of integrated bioenergy and utilization programs for the sustainable management of invasive aquatic plants in appropriate rivers, lakes and reservoirs.

To be clear, the context in which we propose to consider bioenergy production from invasive aquatic plants is in those water bodies in which such plants are already widely established and there is no feasible means for eradication. Since the changes to native ecology associated with invasive aquatic plants and their subsequent management are generally quite dramatic, we do not suggest that invasive aquatic plants should be introduced into natural systems where they are not currently found. Instead, we suggest that bioenergy utilization is a potential management alternative for what is, unfortunately, a ubiquitous environmental problem.

Invasive aquatic plants: a global problem

Invasive species are defined as non-native species that cause or could potentially cause significant economic and/or environmental harm in areas where they are introduced [20]. Commonly listed among the world's most damaging invasive species are freshwater aquatic plants, such as **water hyacinth (*Eichhornia crassipes*)**, water lettuce (*Pistia stratiotes*), hydrilla (*Hydrilla verticillata*), Eurasian water milfoil (*Myriophyllum spicatum*), common coontail (*Ceratophyllum demersum*), giant water fern (*Salvinia molesta*), alligatorweed (*Alternanthera philoxeroides*) and water pennywort (*Hydrocotyle ranunculoides*) [21]. In some cases, nutrient enrichment or other disturbances can trigger aquatic plant overgrowth from native species, with prominent examples including cattails (*Typha* spp.) in the Florida Everglades [22] and duckweed (*Lemna* spp.) in Lake Maracaibo, Venezuela [23]. Since such native species overgrowth is typically managed in a similar way as invasive overgrowth by non-native species, we suggest that the lines of reasoning developed in this review can be directly applied to problematic native aquatic plants.

The reach of invasive aquatic plants is truly global, stretching from the tropics (e.g., water hyacinth and water lettuce), through all temperate zones (e.g., common coontail and hydrilla) and even into sub-arctic regions (e.g., Eurasian water milfoil).

In all areas, overgrowth associated with aquatic plants often has quite detrimental socioecological consequences. If left unmanaged, the rapid growth and natural senescence of invasive aquatic plants can hasten the build-up of sediment nutrients and organic matter associated with lake eutrophication. In the most severe cases, waterways can become choked with vegetation mats to such an extent that navigation becomes impossible and underlying waters become anaerobic, thereby destroying valuable fisheries [24]. Development of anaerobic conditions in lakes with major aquatic plant problems is further associated with large increases in the emission of methane [25], a gas that has a global warming potential 21 times that of carbon dioxide. Some invasive aquatic plant populations also provide habitat for vector organisms that spread serious diseases among local human [26] and/or wildlife [27] populations. Annual economic costs from the control of invasive aquatic plants in the USA alone have been estimated at over US$1 billion [28].

Underlying causes

Invasive aquatic plants emerged as a major problem over the past century, owing to exponential increases in two anthropogenic forces: global trade and commerce, and nutrient enrichment of receiving waters, particularly with phosphorus (P) and nitrogen (N).

The impact of trade is straightforward, as plant species have been transported across great distances and introduced into new areas at rates far exceeding those that would have occurred without human assistance. While some invasive aquatic plant populations may be the result of intentional introductions for ornamental and/or agricultural use [29], unintentional spread has also occurred at a global scale through the careless disposal of imported aquarium plants or discharge of ship ballast contaminated with plant fragments [30]. Local and regional spread of nascent invasive plants typically results from the unintentional transport of fugitive plants in boat propellers and trailers [24] or, less commonly, intentional human acts [31].

Once introduced into a new ecosystem, invasive aquatic plants are characterized by their ability to produce extraordinary accumulations of standing crop biomass and, by extension, outcompete many native plant species [24]. Although such competitive advantage can, sometimes, be traced to an ecological release from co-evolved herbivore and pest species [32,33], nitrogen and phosphorus enrichment from fertilizer runoff, sewage discharge and other anthropogenic disturbances are often cited as important factors in promoting invasive overgrowth of aquatic plants. For floating plants, such as water hyacinth and water lettuce, rises in dissolved nutrient concentration associated with anthropogenic loading have been consistently shown to trigger increases in growth rate, thereby leading to invasive proliferation [34–36]. For rooted plants, such as hydrilla and Eurasian water milfoil, nutrient enrichment of sediments due to both legacy and ongoing nutrient loads is most commonly cited as a contributor to overgrowth problems [37,38]. Some studies have also linked moderately elevated levels of dissolved nutrients to increased growth rates and competitive ability of invasive submersed plants relative to native plants (as inferred by relative areal coverage and plant occurrence measures) [39,40], although extremely high loads of dissolved nutrients can lead to algal blooms that reduce even invasive submersed plants [37,39]. Given these relationships, we suggest that major aquatic plant problems can, at least in some cases, be viewed as a secondary, although quite severe, symptom of larger environmental changes that have occurred within increasingly human-dominated watersheds over the past century.

Aquatic plant control

Given the serious problems associated with invasive aquatic plants, it is not surprising that considerable resources have been dedicated to the development and implementation of integrated control programs. Although nutrient mitigation is sometimes noted as an aspirational goal for reducing invasive overgrowth for rooted [41] and, more commonly, floating invasive aquatic plants [42], modern aquatic plant control can be generally characterized by its reliance on one or more of the following methods:

- Manual removal
- Mechanical control
- Chemical control
- Biological control

Manual removal

The most basic form of aquatic plant control is manual uprooting of plants through hand-pulling and other forms of nonmechanized human labor. On the one hand, manual removal has important advantages, such as very low energy intensity, minimal impact to non-target species and, in some cases, the ability to eradicate nascent invasive plant populations [43]. Costs of manual removal are also quite minimal owing to the unskilled nature of the work and frequent use of volunteer labor [44]. On the other hand, the sheer scope and size of long-established aquatic plant invasions in many large water bodies makes manual removal an impractical option for efficient control. Moreover, manual removal is not an acceptable option in areas where workers could be exposed to high risks from dangerous wildlife, disease vectors and/or drowning [45].

Mechanical control

A wide variety of harvester and cutting machines designed to remove and/or destroy invasive aquatic plants have been used in water bodies over the past several decades [43,44]. Mechanical control provides the ability to manage aquatic plants at much greater spatial scales than manual labor, with typical applications including removal of aquatic plant biomass from navigation channels, irrigation canals, drainage ditches, dams and other critical infrastructure [43]. Together with chemical herbicide applications, mechanical methods are generally the most visible and active component of modern aquatic plant control management programs.

A major advantage provided by mechanical control is that biomass can be quickly removed from targeted areas, thereby allowing for rapid resumption of activities that were being affected by aquatic plant overgrowth. In cases where aquatic biomass is harvested and removed to land, there is an important additional benefit of exporting nutrients and organic matter from water bodies [46,47]. While the amount of nutrients removed during a typical harvesting program is often minor in relation to an overall watershed nutrient budget [43], the monetary cost per mass of nutrient removal can, in some cases, be considerably less expensive for aquatic plant harvesting as compared with other forms of nutrient control [47,48]. Thus, the mass of nutrients that is removed through harvesting can be seen as having the important economic benefit of correspondingly lessening the management costs associated with the achievement of nutrient reduction goals.

Another potential advantage of harvesting is that methods potentially could be developed that would maximize biomass removal rates for utilization potential. For example, a recent **life cycle analysis** describes a novel harvesting process for water hyacinths in which a cutting machine is used to cut manageable

> **Key term**
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> **Life cycle analysis:** A method of material accounting that attempts to quantify all inputs and outputs for a given process. Commonly used to determine relative impacts associated with energy consumption, greenhouse gas emissions, nutrient loading, water use and other resource factors

swaths through floating plant mats, which would then be towed by separate boats outfitted with grappling hooks into on-shore processing areas [49]. The cost of water hyacinth biomass recovered through this process is estimated at approximately US$40 per dry ton. By way of comparison, a recent study of switchgrass found that producer costs would average approximately US$50 per dry ton in major growing regions [50].

However, aquatic plant control researchers note that there are also important limitations to mechanical control. Primary among these are the high costs associated with the purchase, operation and maintenance of relatively complex machinery that is routinely subjected to harsh conditions [43]. Although widely perceived as being less ecologically harmful than the application of chemical herbicides, mechanical control can have undesirable environmental consequences, such as increased turbidity, inadvertent spread of viable invasive plant fragments and destruction of nontarget plants and animals [51]. In many situations, shredding or cutting methods are used instead of harvesting, mainly because the high water content and overall bulk of aquatic plants make it difficult and expensive to transport harvested biomass to on-shore areas [52]. To avoid this expense, cut or shredded plant matter is generally discharged onto the adjacent shoreline or directly back into the waterway. Although navigation channels and other uses can be maintained through such methods, the pulsed loading of senesced plant material from shredding and cutting operations has been associated with subsequent spikes in dissolved nutrients, major algal blooms and hypoxia-induced fish kills [53,54].

▪ Chemical control

Chemical herbicides are a mainstay of modern aquatic plant control programs, particularly in the USA and other developed countries. Although many different types of herbicides were historically used to control aquatic plants, increased regulatory requirements and environmental restrictions have led to the use of relatively few compounds in aquatic systems. Herbicides currently approved by the US Environmental Protection Agency for aquatic use include complexed copper, fluridone, endothall, 2,4-D, diquat, glyphosate, imazapyr, carfentrazone, penoxsulam and triclopyr [55].

The use of herbicides provides several aquatic plant control advantages. Perhaps most notably, herbicides can be applied using much smaller and flexible equipment – such as airboats, helicopters and even underwater sprayers – than the machines used for mechanical control [43]. This allows for effective control in areas that cannot be readily reached by harvester or cutter machines and, in many cases, will reduce the overall costs for similar levels of plant suppression [52]. It has also been found that nontarget animals may suffer less mortality from chemical control programs compared with mechanical control, largely because treated plant material is not removed, thereby giving animals adequate opportunity to escape into other habitat areas [43]. Furthermore, research has shown that some herbicide formulations can be applied in such a way that they are selective to the plant being targeted [56–58], meaning that desirable native plants suffer minimal-to-no damage.

However, there are also important disadvantages to chemical control. Senescence of plant material after herbicide application has often been shown to result in a pulsed increase of dissolved nutrients and mass loading of organic matter into sediment layers [59–61]. Near-term consequences from chemical control of large aquatic plant populations can, therefore, include major algal blooms, explosive growth of other invasive aquatic plants and, in severe cases, hypoxia-induced fish kills. Over the long term, build-up of killed plant material in sediment layers can also become a major contributor to internal nutrient-loading processes that exacerbate lake eutrophication [60,61]. Moreover, use of approved herbicides has, in some cases, been associated with unexpectedly severe harm to nontarget species [62,63], underscoring the fact that there is always some degree of uncertainty associated with the ecological effects from herbicide applications. Development of herbicide resistance due to mutation of targeted plant species is emerging as another major problem for some aquatic plant control programs [64]. Negative public attitudes toward unknown risks from chemical exposure are also well-recognized as a limitation to ongoing use of herbicides in public waters [43,55].

▪ Biological control

Biological control programs utilize introduced diseases, herbivores and/or pest species to retard the growth and biomass accumulation of invasive aquatic plants. The major advantage of a successful biological control program is that continuous control is achieved with minimal need for additional human inputs. In some cases, the introduction of biological controls can effectively end major problems with invasive overgrowth and effectively establish a competitive balance between native and non-native plant species [65,66]. However, the research and screening process for finding suitable biological control organisms is often quite lengthy and expensive [43]. Great care must be taken to ensure that newly introduced organisms are selective to targeted species, as severe damage to desirable native species has occurred with the release of non-selective biological control agents [67,68]. Several case studies have also shown that it can be quite challenging to establish self-sustaining populations of biological control organisms that seemed quite promising in screening phases [69,70]. Even in cases where biological controls are successfully established, the speed and spatial scale of invasive-plant suppression are often not sufficient for meeting overall control objectives [43].

Life cycle of modern aquatic plant control

Although manual removal and biological control are important components of many aquatic plant control programs, most large programs have a decided reliance on mechanical and/or chemical control components. An important benefit of chemical control strategies in particular is that, at least in some cases, invasive aquatic plant populations can be contained at low levels. This control function has significant socioecological value in terms of maintaining relatively intact native plant communities and supporting recreation activities otherwise prevented by aquatic plant overgrowth. However, several additional issues become apparent when these approaches are examined from a holistic life cycle perspective (Figure 1). First, the activity of aquatic plant control clearly represents a complete energy sink in which fossil fuels are consumed for herbicide production, equipment manufacturing and machinery operation. A secondary sink of embedded fossil energy can also be seen to occur with the fugitive release of major fertilizer nutrients, such as phosphorus and nitrogen, into dissolved forms and sediment deposits that are much more difficult to recover for beneficial use. Development of anoxic conditions that may cause fish mortality and the global warming potential of methane gas released in the aftermath of aquatic plant control operations are other important factors to take into account when tabulating life cycle costs.

Aquatic plant utilization

Recommendations to utilize harvested invasive aquatic plants for fertilizer, compost, paper-making, fuel production and other purposes date back to at least the early 20th Century [71]. In addition to the desire for controlling overgrowth, a primary rationale for attempting to utilize such plants is that they often show primary productivity rates significantly higher than terrestrial bioenergy feedstock candidates [72]. For example, water hyacinths have been shown to produce annual crop yields of 100 dry tons per hectare in natural lakes [49]. By way of comparison, the highest trial yields obtained for switchgrass in the USA are in the order of 25 dry tons per hectare [73]. The rapid emergence of the bioenergy economy would seem to provide a clear opportunity for implementation of programs that can direct the productivity of aquatic plants into beneficial uses.

Methods for beneficial use of harvested aquatic plants from wastewater treatment and/or phytoremediation have been demonstrated at small scales over the past several decades. A particularly notable pilot project using water hyacinth ponds for treatment of wastewater was performed throughout much of the 1980s at the Walt Disney World complex in Orlando, FL, USA. In this facility, excess plant material harvested from treatment ponds was utilized as a supplement to sewage sludge in the production of biogas [74]. In China's Lake Taihu, experimental water hyacinth block treatments of 40 m^2 were manually harvested using pitchforks, with animal feed suggested as the primary use of the biomass harvested at this scale [75].

Despite research into development of harvesting strategies that could potentially maximize utilization efficiency [49], very few large-scale aquatic plant

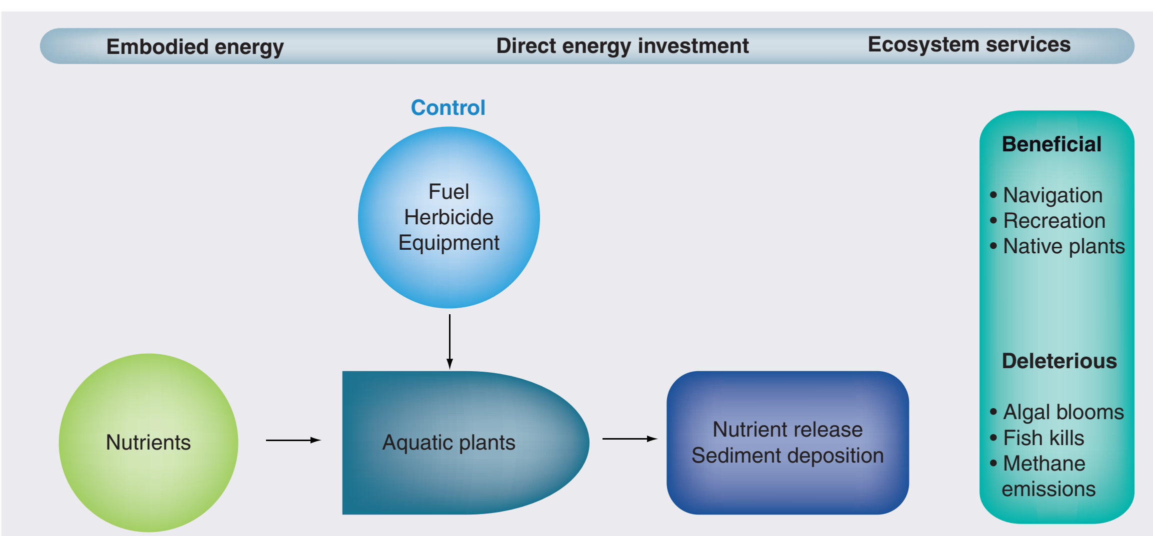

Figure 1. Life cycle for chemical and mechanical control of aquatic plants without biomass harvest.

utilization projects have been realized or attempted in natural water bodies. Such reluctance can be traced to three major issues that have been historically cited as primary disadvantages for utilization of invasive aquatic plants:

- The high up-front capital costs and overall complexity of instituting utilization programs relative to the operating costs of a typical control program;
- The perceived low value of products from aquatic plants relative to the expense of handling a feedstock that is over 90% water;
- The possibility that any demonstration of value for invasive aquatic plants could have the perverse effect of speeding their spread.

We acknowledge that all of these remain as important considerations, and this review does not imply that utilization is necessarily appropriate for all water bodies affected by invasive aquatic plants. Instead, we suggest that ongoing research into the bioenergy potential and complementary uses for aquatic plant biomass has advanced to such an extent that holistic re-evaluation of current control strategies may be appropriate for many water bodies. Thus, the intention of the review ideally is to provide an integrated overview of available research, thereby facilitating specific projects that can focus more directly on the unique circumstances of specific water bodies and surrounding communities.

Bioethanol

Biotechnological advances in the production of bioethanol from aquatic plants, with particular focus on water hyacinth, have been demonstrated over recent years. As with other cellulosic ethanol feedstocks, such as herbaceous grasses and crop residues, the general method for ethanol production from aquatic plants requires an acid hydrolysis pretreatment of dried biomass, followed by inoculation of hydrolyzed material with an appropriate fermenting organism [76,77]. As noted previously, a recent life cycle assessment suggests that at least one aquatic plant, the floating water hyacinth, could be harvested and processed in a manner that would make it cost competitive with switchgrass and other cellulosic ethanol feedstocks [49].

Ethanol yield values for aquatic plants show variability among studies, but are generally similar to those obtained from other cellulosic feedstocks [78]. At the lower end, an ethanol yield of approximately 0.05 g/g dry water hyacinth biomass was reported using *Pichia stipitis* as the fermenting organism [72]. A higher yield of 0.17 g/g dry water hyacinth was reported through the use of *Saccharomyces cervisiae* [79], while an even higher yield of 0.19 g/g dry water hyacinth was obtained with *Candida shehatae* [76]. It has been reported that the sugar content in the hydrolysate of water lettuce leaves is approximately 1.8-times higher than that of water hyacinth, suggesting that water lettuce could be an even more attractive ethanol feedstock than water hyacinth [79]. Subsequent experiments, however, showed that ethanol yields from dried water lettuce were roughly equivalent to those obtained from water hyacinth [80]. Although there is little published research about the ethanol potential from other major invasive aquatic plants, cellulosic conversion methods such as those demonstrated for water hyacinth and water lettuce should be transferable to dry matter obtained from other aquatic plant species. However, costs of dry biomass can be expected to be higher for rooted and submersed aquatic plants that are more difficult to harvest and process.

Key term

Anaerobic digestion: Biological process of breaking down organic matter that is performed by microbes adapted to live in oxygen-free conditions. The final product of these organisms, commonly called biogas, is a combustible mixture of methane, carbon dioxide and other trace gases that can be substituted for natural gas

Biogas

Production of biogas – a combustible gas composed of methane, carbon dioxide and other trace gases – using **anaerobic digestion** is a well-known process often applied to manure and agricultural wastes. There is an extensive literature describing the use of anaerobic digestion reactors for energy production from harvested aquatic plants, particularly within the context of developing countries. While much of this research has been directed toward water hyacinth [81–84], a variety of other aquatic plants have also received some attention for their biogas production potential [84–88]. Aside from the bioenergy benefits provided by substitution of biogas for fossil fuels, such as natural gas, a major advantage of biogas production is that residual material from anaerobic digesters can be readily removed and used as an organic fertilizer [89].

The most basic method for biogas production from aquatic plants involves processing the wet biomass into a slurry that is then loaded into the anaerobic digester [90]. However, use of aquatic plants in traditional single-stage slurry reactors can often cause major problems with clogging from spent biomass [71]. Two-phase and three-phase reactors that provide greater flexibility for managing spent biomass have been developed as an alternative that can help to avoid such clogging issues [81]. Some research suggests that digestion efficiency and gas production can be greatly improved in multistage reactors when aquatic plant biomass is mixed with manure [83].

Yields from different aquatic plant species, and even the same aquatic plant species grown in different conditions, can be quite variable. One comparative study showed that water hyacinth produced greater long-term biogas yields than both *Azolla* spp. and hydrilla growing in India's River Ganga [91]. In a survey of eight aquatic plants (*Azolla pinnata*, *Ceratopteris* spp., *Cyperas* spp., *Hydrilla verticillata*, *Nymphaea stellata*, *Salvinia molesta*, *Scirpas* spp. and *Utricularia reticulata*), an almost tenfold difference in biogas yield was found between the highest (*S. molesta*) and lowest producing (*Cyperas* spp.) plants [86]. Factors that generally influence biogas yields from aquatic plant biomass include particle size, volatile solids content, trace nutrients and inoculation. Targeted sampling to measure these variables can be used to make accurate estimates of expected biogas yield from local aquatic plant populations.

▪ Other bioenergy pathways

Although most aquatic plant energy research has focused on bioethanol and biogas, harvested biomass can be converted into usable energy through other pathways. For example, a recent paper describes potential energy yields from a complex process in which harvested biomass from *Typha* spp. is heated in an oxygen-poor environment to produce a syngas of carbon monoxide, methane and hydrogen that can be captured and used in an internal combustion engine [92]. Much less technological options, such as drying and briquetting of aquatic plants for use as a cooking fuel, have also been explored at small scales in some developing countries [45].

▪ Utilization life cycle

As shown in **Figure 2**, the life cycle of an aquatic plant utilization program has important differences from the aquatic plant control life cycle shown in **Figure 1**. First, management activities are not a complete energy sink, but instead will provide some renewable energy return from effort invested. While the actual net energy returns from utilization will probably vary quite significantly according to the morphology of water bodies, the biomass content of harvested aquatic plants, conversion technologies used and other factors, the possibility of any energy return from what currently amounts to an unwanted waste product is a clear benefit in terms of reducing land-use conversion pressure for other bioenergy feedstocks. Second, a clear benefit is achieved through the removal of biomass and corresponding nutrients from the water body. This removal not only has the potential to assist in ecological remediation of waters suffering from cultural eutrophication, but the anaerobic digestion process in particular provides a proven means for recycling nutrients into beneficial agricultural usages [88,89]. Subsequent use of such organic fertilizers can be credited for displacing natural gas used for chemical nitrogen fertilizers production by the Haber–Bosch process, as well as the fossil fuels used in

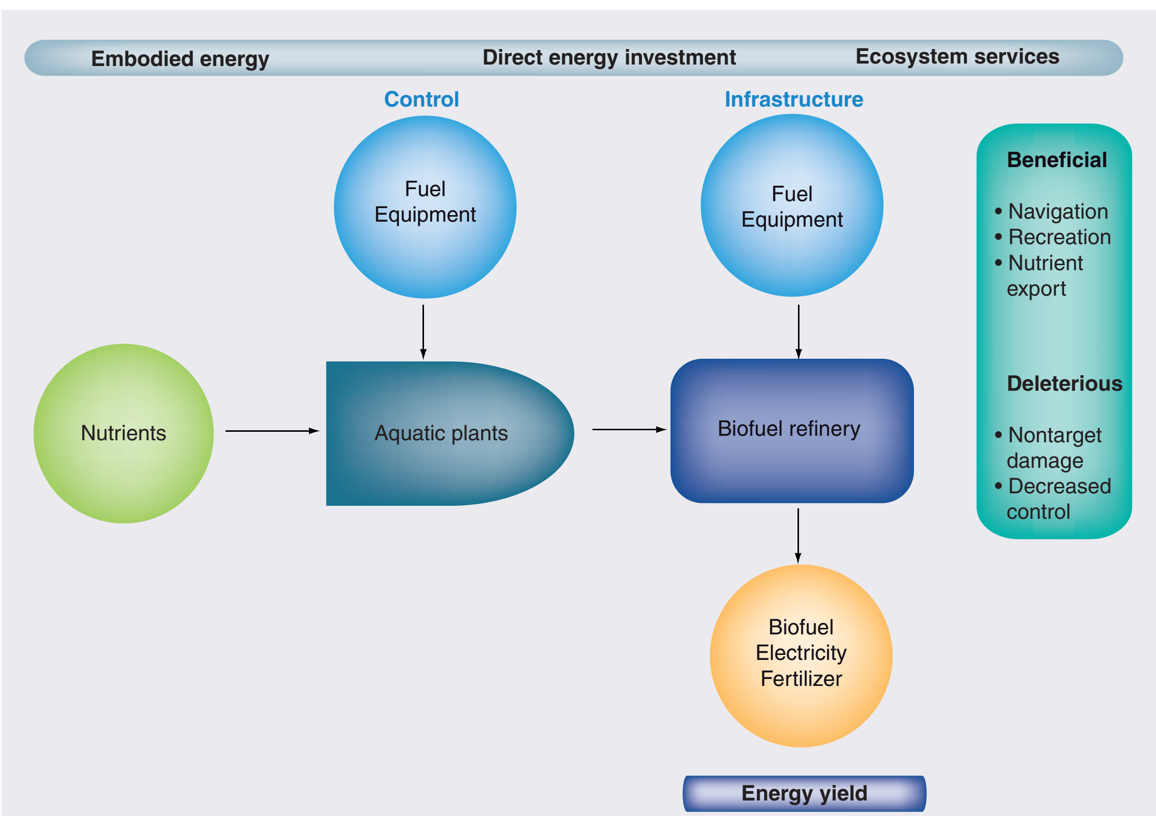

Figure 2. Life cycle of bioenergy production and fertilizer production from aquatic plant harvest program.

the strip-mining and beneficiation processes for production of phosphate. Re-establishment of oxygenated conditions and avoidance of anoxia-inducing biomass kills through harvesting of aquatic plant overgrowth also has the important benefit of avoiding emission of methane, a powerful greenhouse gas. As a labor-intensive process, utilization also has the potential benefit of producing green jobs during a time of job scarcity. The major concerns of utilization include damage to nontarget organisms during harvests and the potential difficulty of maintaining aquatic plant populations at minimal levels.

Future perspective

Since overgrowth from invasive aquatic plants is a source of such dramatic problems, public policy has understandably been tilted toward control programs that provide immediate relief from these problems at the least near-term cost. However, growing awareness of the following two issues should imply a rethinking of this paradigm at the level of aquatic ecosystem management:

- Invasive aquatic plants are virtually impossible to eradicate permanently once they become established;
- Long-term health of many aquatic ecosystems may be compromised by reliance on control programs that do not remove excess biomass.

Such a rethinking is further supported by broader-scale issues, such as the desire for renewable energy alternatives that can be produced with minimal land-use change and methods for reducing greenhouse gas emissions from all sources.

An obvious research need is for development of harvester machines and processing infrastructure that can deliver aquatic plant biomass to biorefineries in a timely and cost-efficient manner. As noted previously, one recent study suggests that field-scale projects involving harvest of water hyacinth and other floating aquatic plants (e.g., water lettuce and/or water pennywort) from eutrophic waters may already be economically justifiable in terms of the biomass demands of a bioenergy economy [49]. However, further work is needed to develop similar cost estimates for submersed aquatic plants such as hydrilla and Eurasian water milfoil. Since such species are already harvested solely for control purposes in some water bodies [41], there should be opportunity for pilot-scale projects that can quantify biomass yields per harvester effort, characterize the bioenergy potential through chemical analysis or direct laboratory testing and develop efficient methods for biomass drying and subsequent transport to a biorefinery.

Although research into more effective production methods is clearly important, public policy will play a major role in determining the extent and speed in which aquatic plant utilization programs may be adopted. One suggestion for incentivizing aquatic plant utilization is for governments to provide direct payment for mass removal of nitrogen, phosphorus and other water pollutants contained in harvested biomass. In some cases, harvest of aquatic plant biomass may be among the most cost-effective methods for permanent nutrient removal [48,49,93]. Similarly, emergence of a carbon market would provide the opportunity for monetary payments and/or tradable carbon credits for aquatic plant utilization programs that directly displace fossil fuel use with bioenergy production, indirectly displace fossil fuel use through fertilizer replacement and/or avoid methane emissions owing to biomass-induced anoxia. Direct subsidies to biorefineries for use of invasive plant material might also be considered by governments that currently allocate substantial funds for control of these same species. Justification for such subsidies would be directly derived from the sustainability value of the nutrient export, greenhouse gas reduction, fossil fuel replacement and invasive control services provided by the aquatic plant utilization process.

Ultimately, it is not our contention that aquatic plant utilization should be expected to replace all existing control programs or, even more remotely, serve as a stand-alone solution for growing bioenergy demands. Instead, we suggest that utilization options, such as those discussed in this review, should be carefully explored on a site-by-site basis to determine opportunities for enhancing local ecosystem services and energy security. Major management considerations aside from the energy-production and nutrient-export mechanisms discussed in detail by this review could include potential for spread into currently unaffected ecosystems in the surrounding region and the evapotranspiration demands of aquatic plants in the context of regional water balances. This latter concern about water balances may be especially important in the water bodies of arid or semi-arid regions of Africa [94]. For many regions and watersheds, however, we anticipate that ongoing development of policy frameworks designed to put economic value on restoration of ecosystem services and production of renewable energy can be expected to make invasive aquatic plants an increasingly attractive bioenergy feedstock opportunity.

Financial & competing interests disclosure

The authors have no relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript. This includes employment, consultancies, honoraria, stock ownership or options, expert testimony, grants or patents received or pending, or royalties.

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Executive summary

Invasive aquatic plants

- Global socioenvironmental issue that is exacerbated by nutrient loading of waters from anthropogenic activities.
- Represents a highly productive source of extant biomass that can be utilized without major land-use intensification.

Aquatic plant control

- Current paradigms based on chemical and mechanical control programs.
- Although often successful in the near term, can be viewed as unsustainable owing to heavy reliance on fossil fuel inputs and failure to recapture fugitive nutrients.

Aquatic plant utilization

- Major research advances in converting aquatic plants into bioenergy, particularly in the form of bioethanol and biogas.
- Not only offers the potential for bioenergy production, but also produces benefits by removing fugitive nutrients from aquatic systems.
- Biogas produced through anaerobic digestion has the further advantage of recycling nutrients back into agricultural systems, thereby displacing fossil fuels used for fertilizer production.

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