Newsletter for the Community of Duckweed Research and Applications, edited by the ISCDRA

DUCKWEED FORUM

ISCDRA
International Steering Committee on Duckweed Research and Applications

Volume 10 (1), issue 36 suppl., pages 50 - 73 (2022)




Duckweeds: The underlying engine of the New Circular Economy

Cover page

Duckweeds: The underlying engine of the New Circular Economy

This montage showcases the large-scale growth of duckweed in the context of its role in circular economy. From top left: A handful of duckweed from an outdoor growth facility; project Prism at Mirzapur, Bangladesh; the Ball-Valve design for Agriquatics India; pilot at Terraqua Barranca project, Peru. Photo credit: Dr. Paul Skillicorn, USA; montage by Eric Lam, Rutgers University, NJ, USA.

In this issue

The 4th International Steering Committee on Duckweed Research and Applications Members

All prior Duckweed Forum issues: http://www.ruduckweed.org/

Letter from the ISCDRA:

Dear *Duckweed Forum* readers,

As we are bringing this special supplement to you this month, in which we are sharing with you a special contribution by Paul Skillicorn and Rebecca Torres on usage of duckweed for creating Circular Economy, the world is experiencing another major upheaval that deserves special attention, the war in Ukraine. Death of many innocent people, many casualties, millions of refugees and thousands that perished on both sides of the fighting. Yet, it seems that the worst is yet to come.

We, the members of the International Steering Committee for Duckweed Research and Applications, are extremely saddened by this turn of events. At a time after two years into a global pandemic that witnessed the loss of over 6 million people worldwide to a contagious virus, the eruption of this war is especially shocking. We have learned how interdependent we all are on this planet in terms of our well-being and our future destiny and need to keep working together on existential threads such as pandemic control and Climate Change mitigations, raising our hope of safeguarding this earth of ours for the future generations.

Our solidarity to all the people / scientists, both in Ukraine and in Russia. Our thoughts and prayers are with you, the scientists in the countries that are involved in the conflict, whose lives and work have been drastically altered by the war in Ukraine.

May peace come in the near future for the sake of all humanity.

Members of the 4th ISCDRA

Election of the 5th ISCDRA: Reminder to vote

Election of members to the 5th International Steering Committee on Duckweed Research and Applications is open until April 30, 2022.

Link to the e-ballot:

https://forms.gle/E7ahPkcPhS8umByR6

Eligibility for voting: You must belong to at least one of the categories listed below to be eligible to vote.

- Attended any of the past two ICDRA meetings.
- Will attend ICDRA 2022 in Germany.
- A principal investigator who is working with duckweed in his/her laboratory.
- A researcher/postdoc/student who is working with duckweed in their research (i.e. not just reading about it, but actually doing a project).
- An entrepreneur who is working to commercialize a duckweed-based technology and/or product.
- A research scientist who is working on a commercial venture that aims to develop a duckweed-based technology and/or product.
- A venture capital principle who has invested significantly into duckweed-based technology and/or product.
- A worker in a commercial venture involved with a duckweed-based technology and/or product.
- An administrator in a University or Funding Agency who has sufficient interest in the duckweed community to provide funding for one or more duckweed-based activity/project/venture.

List of candidates for the election to 5th ISCDRA is the following:

Eric Lam (New Brunswick, USA)

Sowjanya Sree K (Kerala, India)

Klaus Appenroth (Jena, Germany)

Tsipi Shoham (Tel Aviv, Israel)

Marcel Jansen (Cork, Ireland)

Jiaming Zhang (Hainan, China)

Ingo Schubert (Gatersleben, Germany)

Duckweeds: The underlying engine of the New Circular Economy


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Abstract:

The term Circular Economy is shown to be more an aspirational semantic fiction than a practical reality. Here, we reflect on the reasons why this is so, and review advanced methods whereby energy and nutrients can be extracted from municipal and agricultural wastes as a primary mechanism by which to leverage the value of those extracts to create The New Circular Economy. Specifically, we outline an approach to achieving a New Circular Economy drawing centrally on duckweed-related nutrient stripping of a highly digested blend of municipal solid wastes and wastewater volatile solids as well as the wastewater itself. The circle is closed with value-added, zero-waste monetization of harvested duckweeds in the production of locally grown, absolutely fresh proteinaceous foods, vegetables, herbs and vine fruit as well as advanced, renewable materials. The potential for widespread application in Africa, in particular, is noted. This is enabled by fewer entrenched engineering firms and regulatory agencies, as well as the absence of an existing capital-intensive installed base that is comprised of decades-old waste treatment and elimination technologies, as well as their attendant expensive support services. We conclude that implementation of The New Circular Economy is feasible and practicable, and that it can transform the circumstances of communities that adopt its use.

Introduction:

The circular economy and the wastewater, municipal solid wastes and agricultural residuals conundrum

This article examines the potential for intensive, circumstantial cultivation of duckweeds – variously called Lemnaceae, Lemnoideae, water lentils, lemna, green gold, *oro verde* and *shobuj shona* (Torres et al., 2011) – to provide the underlying engine for an evolving "new" circular economy. This is enabled by increasing acceptance in academia, government, finance and the business community of what duckweeds are, what they can do and how they can be profitably harnessed to assist in the cleanup of a variety of common endemic waste streams that afflict every community on earth.

The industrialized nations of The West and East Asia, and the rapidly developing BRIC (Brazil, Russia, India and China) nations have already heavily committed to established paradigms for treatment of wastes, however it is Africa which holds the greatest potential for developing this profitable New

Circular Economy. In doing so, African villages, towns and even cities can begin embracing a more sustainable economy: one which better serves both human welfare and the encompassing environment.

The Circular Economy has, in recent years, become a fashionable buzzword that loosely accompanies *Sustainable Development* and *Climate Change Mitigation* in the media and public discourse. This has also brought it into the political and public policy arenas as a direction being promoted by governments and NGOs, alike. In 2010, the Ellen MacArthur Foundation was established with the explicit mission of promoting the circular economy, which along with the World Economic Forum, they define as (World Economic Forum, 2021 and Ellen MacArthur Foundation, 2010):

> A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models.

Academia is following suit, with a growing number of conferences and research endeavors liberally using the term as an umbrella for courses and research projects ranging broadly from industrial ecology (Frosch and Gallopoulos, 1989; Graedel, 1996; Lifset and Graedel, 2001) and recycling (Boulding, 1966; Georgescu-Roegen, 1971; Daly, 1996; Ring, 1997; Ayres, 1999) to cleaner production (Stevenson and Evans, 2004; Ghisellini et al., 2016; Lieder and Rashid, 2016) and the performance economy (Stahel, 2010; EMAF, 2013).

In recent years, a number of authors have pointed out that, despite expansive use of the term *The Circular Economy*, it has failed to gain widespread application in practice. This criticism speaks both to a failure by industry and government to embrace the broad notion of turning all wastes into valued resources and the generally poor results of recycling practices that have been widely adopted. Recycling of paper and plastics – now almost universally considered to be normal practice – is being criticized because most of the paper and plastics that are successfully isolated at the individual household, business and street disposal container level, are shown not to be recycled (Rahman et al., 2014; Nelles et al., 2016; Faraca and Astrup, 2019; Faraca et al., 2019; Liu et al., 2020; Volmer et al., 2020; Honma and Hu, 2021). This problem was exacerbated when China, Southeast Asian and more recently South Asian and African nations began refusing to take delivery of waste plastics collected as "to be recycled." This unsorted material was typically incinerated in those nations or simply disposed of in ways that were inflicting significant damage to their respective environments and proximate ocean areas (Clapp, 1994; Gupta et al., 2018; Burlakovs et al., 2019; Parts, 2019; Iroegbu et al., 2020; Huang et al., 2020; Sharma et al., 2020; Gündoğdu and Walker, 2021; Wen et al., 2021).

More fundamental is the growing realization that nutrient-rich volatile and chemical wastes contributed by municipal and industrial wastewater and solid waste streams; urban yard and park residuals, as well as agricultural wastes, residuals and runoff, are not contributing to the Circular Economy (Su et al., 2013; Pagotto and Halog, 2016; Voulvoulis, 2018; Kisilev et al., 2019; Zhang and Liu, 2019; Guerra-Rodríguez et al., 2020; Mavhungu et al., 2020; Smol et al., 2020; Deksissa et al., 2021; Zhang and Liu, 2022). Nutrient-bereft mining wastes aside, it is these wastes, more than any other, that are responsible for polluting practically every river, stream, lake, pond, aquifer and coastline in disparate countries such as Egypt, Nigeria, Ethiopia, Kenya, Uganda, India, Bangladesh, Nepal, Indonesia, Malaysia, Thailand, Laos, Cambodia, Vietnam, Myanmar, The Philippines and China – as well as densely populated and heavily farmed areas in more industrialized nations (van der Schans et al., 2009; Shivayogimath et al., 2012; Pagotto and Halog, 2016; Yohannes and Elias, 2017; Rajeshkumar et al., 2018; Hassouna et al., 2019; Shishir et al., 2019; Mayanglambam, and Neelam, 2020; Mathewson et al., 2020).

"Why have we been unable to tap the nutrients and energy inherent in municipal, industrial and agricultural waste streams?" is a question increasingly being posed by Circular Economy advocates (Alleman and Prakasam, 1983; Gündoğdu and Walker, 2021;Wen et al., 2021). Critics point to regulatory agencies, legacy infrastructure system design, the critical mass and inertia of those systems, and the extreme inflexibility of engineering firms responsible for advocating their installation. Several prevalent systems features in this criticism are: landfills; clarifier sludge handling and disposal; anaerobic digestion; composting and activated sludge-mediated "mechanical" treatment of clarified liquid waste streams (Wong and Law-Flood, 2011; Wang et al., 2015; Kehrein et al., 2020; Meilinger and Monstadt, 2021).

In the industrialized world – and increasingly globally – regulatory agencies established to protect both the environment and the consumer continue to tighten disposal and discharge standards for volatile solid wastes and wastewater, as well as urban and agricultural runoff and drainage flows. This has resulted in an investment in infrastructure system designs that favors ease of management and testing of output, at the expense of nutrient and energy recovery and generation of positive cashflows by incorporation of new technologies that will require more effort in adaptation (Sherman et al., 2020).

Problematic solid wastes – mixed, damp or wet volatiles and dirty plastics – are generally landfilled or, increasingly, incinerated. Each approach to treatment and disposal, in some fashion, can be made to yield some energy – albeit inefficiently. In both instances, the inherent nutrients are almost completely lost (Themelis et al., 2011).

Where separation of volatile solid wastes and dirty plastics is achieved, volatiles are increasingly being subscribed by commercial purveyors of anaerobic digestion – notably in the EU. Anaerobic digestion has accordingly seen a steady improvement in energy recovery (Anyaoku and Baoutian, 2018). This is achieved by parsing and phasing what has typically been a single batch process. In more advanced systems, front-end pre-processing of influent solids incorporate fine grinding, thermal, sonic and/or acid treatment to enhance volatile material breakdown and cell lysis. This allows more efficient hydrolysis, which can also be parsed to favor, sequentially, thermophilic and mesophilic anaerobes in successive stages. Following hydrolysis, however, even advanced digester systems still use a single mixed batch process to move through the essential acidogenesis, acetogenesis and methanogenesis steps that result in production of targeted fatty acids, biogas and a residual, nutritious sludge. In the best systems, biogas is cleaned up, CO_2 is removed and the resulting "green methane" is used to produce both electric power and thermal energy. This typically results in a positive cashflow that exceeds operations and maintenance costs, while also paying, over time, for the initial capital expenditure. What is not done, however, is to monetize the resulting sludge – which is typically densified, desiccated and landfilled at great expense and in a manner designed to meet the dictates of regulatory agencies. In these circumstances, effectively, half the immense potential of the circular economy is not realized (Paul Skillicorn, 2020, personal observation).

While advanced biogas digesters do contribute positively to The Circular Economy, activated sludge systems are notable for their failure to do so. Indeed, their energy consumption uses far more electricity than is produced by both attached (digestion of activated sludge biosolids and influent volatile solids) and discrete (municipal, industrial and agricultural volatile solid wastes digestion) digester complexes (Mizuta and Shimada, 2010; Banerjee et al., 2011; McCarty et al., 2011; Smith et al., 2014)

Energy intensive activated sludge systems are designed specifically to get rid of targeted nutrients: ammonia, phosphates and nitrates. Nitrogen is released to the atmosphere as a consequence of nitrification and denitrification. Phosphorus and other nutrients are picked up by the mixed liquor bacteria which are continuously harvested from the system as waste activated sludge, concentrated (thickened), desiccated and then typically land applied. More advanced wastewater treatment systems also incorporate anaerobic digesters capable (as above) of generating some useful methane from waste activated sludge (Zhang et al., 2010; Wang et al., 2014).

Some municipal wastewater treatment operations do recover digester wastes and produce blended "flower garden only" fertilizers. *Milorganite*, produced in Milwaukee, has effectively saturated that market in the US (Kadish, 1928). All others that have attempted to produce a comparable commercial product have been forced to abandon the business. Other municipalities, notably Austin, Texas, have sought to produce a commercial compost product, by blending digester sludge (originating as waste activated sludge) with treated sewage-irrigated hay (grass). These fields are actually fertilized with procured, commercial chemical fertilizers. The resulting compost, as with Milorganite, is restricted to non-edible crops due to heavy metals and persistent toxin vectors present in the compost (Awal et al., 2021). Austin's system fails to turn a profit, and the city is accordingly considering landfilling its digester sludge. Critics also point out that producing compost is a notably inefficient mechanism for recovering energy from municipal wastes. The composting process is exothermic, emitting very significant amounts of heat – all of which is lost to the atmosphere in a world that is overheating (Lin et al., 2018; Ajmal et al., 2020).

The replacement value of the installed base of activated sludge systems in the United States is estimated at around $2 trillion (Owen, 2020). That activated sludge base supports an industry – ranging from engineering firms to electricity generators and distributors – with a fee-derived cashflow of around $200 billion per year (Stensel and Makinia, 2014; Orhon, 2015; Owen 2020). In the US and elsewhere, the solid waste industry is comparable in size, if not larger. The size and cost of both industries in the EU is estimated to be more than double that of the US (Zessner et al., 2010; Trica et al., 2019). Asia, excluding South Asia, is double that again. India is embarked on a commitment to "advanced landfills and activated sludge" that is estimated at approximately the same replacement value as the US installed base (Wild et al., 2010; Gross and Park, 2018). Wrestling The Circular Economy into this ossified $32 trillion arena – one that wastes, indeed throws away, both energy and nutrients – is a bridge too far.

As futile as it may seem, attempts at extricating value from wastewater and its sludge byproducts continue. Prominent among these has been Singapore's efforts to recycle activated sludge treated wastewater into its municipal water supply system – incorporating a final reverse osmosis (RO) step preparatory to merging the two hydraulic flows (Cammak, 2019). This endeavor underestimated the frequency with which even the best activated sludge systems "go down." In Singapore, pushing untreated wastewater (down time effluent) through RO filters resulted in clogging of those systems and frequently repeated need to close the recycling system down (Angelakis and Snyder, 2015). The cost of these interruptions, to consumers and the utility, have been immense. The "fix" in the works is to significantly expand the RO systems, lower throughput and massively increase buffer storage of treated water. There has been much grumbling as to the cost/benefit of this amended system. Accordingly, no other water deficit nations have elected to follow suit (Icke et al., 2020; Asif and Zhang, 2021; Siagian et al., 2021).

Approving irrigation of crops and even municipal landscaping with treated wastewater has gained some momentum. As with Singapore's attempts at complete recycling, these programs suffer from injection of untreated wastewater into the recycling system (Shelef et al., 1987). Incorporation of RO and major buffer storage is not an option for virtually free agricultural irrigation water (Murtaza et al., 2010). Austin's wastewater recycling "Purple Pipes" system aside, these endeavors tend to be limited to countries where regulatory surveillance and the authority behind that surveillance is limited. India, for instance, routinely calls for "treated wastewater" (sic: virtually untreated raw wastewater) to be distributed to farmers (Gupta et al., 2009; Pescod and Arar, 2013; Bougnom et al., 2019). Studies conducted around the perimeter of cities such as Prayagraj (sic: Allahabad) of smallholder farmers that have long-subscribed to this practice have shown virtually all vegetables sold in local markets to be contaminated with heavy metals, pathogenic bacteria and viruses (Gadi et al., 2013; Yadav et al., 2013).

In agriculture, advances in mechanization and a broad subscription to concentrated animal feeding operations (CAFOs) allows unprecedented aggregation of wastes. The low margins that are prevalent in agriculture, however, have placed a premium on very low costs when it comes to treatment of wastes, and regulatory "allowance" when it comes to enforcement (Nicole, 2013). The latter is typically achieved through underfunding and understaffing of attendant regulatory agencies (MacMullen, 2007; Walton et al., 2020). In turn, the farmer's reflex is "don't mess with the system." With returns on asset value that average below 4% in the US, farmers are not inclined to give consideration to investing even more capital into energy and nutrient retrieval systems so that "perhaps" they could better leverage the value of their various waste streams. This "don't mess with the system" sentiment is heavily reinforced by the powerful agribusiness conglomerates that have formed within each agricultural vector (Durham and Karan, 2011). In North Carolina, to pick one example, Smithfield Foods, now controlled by the Chinese, has absolute control over the swine and pork industry. They own the pigs, which they distribute to farmers to grow (Furuseth, 2001, Ladd and Edward, 2002). They also provide the feed and they own the slaughterhouses and processing facilities. They guarantee the capital loans that go to their captive farmers. They are, in this manner, able to extract virtually all the value out of the system, leaving to farmers just enough to survive (Skillicorn and Torres, 2000; Torres et al., 2006). Poultry, beef and dairy follow comparable models. Their political donations and lobby groups maintain virtually absolute compliance in the state legislatures and state executive departments: "The food supply must not be constrained" (Carrell et al., 2016; Ball-Blakely, 2017; Handen-Nader et al., 2021).

It is ironic, therefore, that in a state like North Carolina, which is emblematic of adoption of factory farming as a rural development strategy, and where regulatory authorities continue, inexorably, to tighten the regulatory noose on towns, cities and industry, that agricultural wastes are allowed immense discretion when it comes to disposal – or lack of it (Skillicorn and Torres, 2001; Harrison, 2020; Calhoun and Cecala, 2021). The swine fecal wastes from three conjoined counties – all of it collected and contained, but little treated – are equivalent to what would be discharged by a municipal population of 60 million people (Wing and Johnston, 2014). These two generalized waste streams – high costs on the municipal side and very low costs in agriculture – end up merging in the state's streams, rivers and coastal estuaries (Mallin and Cahoon, 2003, Hamstead and BenDor, 2007). The damage is done and yet neither contribute anything close to their potential to The Circular Economy (Riggs et al., 2007; Skillicorn and Torres, 2001).

Duckweeds as a potential engine for the circular economy

Duckweeds are today gaining recognition as "The Next Super Crop and Superfood" (Bates, 2019). This is exemplified by recent venture capital funding of duckweed projects that promise a plant-based protein that can compete successfully with chicken, pork, beef, mutton and egg whites for the average consumer's palate. Duckweeds are now widely acknowledged to rank among the world's most productive vascular plants (Liu et al., 2021). Their protein content, "complete" amino acid profile and continuous, clonal reproduction are being celebrated as the "perfect plant" (Kucala et al., 2021). They are being advocated by the popular media as a solution to the problem of explosive demand for soybeans (to feed the aquaculture and CAFO industries in China and Vietman) destroying the Amazon rainforest (UN Environment Programme, 2019). Engineers and biologists have engaged the task of developing fully automated, vertically arrayed production systems that incorporate high tech lighting (pulsed LEDs) and misted, aerosol hydraulics and fertilization. Systems incorporating this thinking are already becoming available to the industrial marketplace: producing a green, fresh plant, sealed in a bottle – a product of axenic culture that has not experienced a bacterium or virus, touched a human being or, indeed, seen the light of day (Green

Onyx, 2019; Tsipi Shoham, 2019 personal communication). Duckweed's elegant, sparse genome has become a focal point for advocates of CRISPR-engineered clonal production of everything from pharmaceuticals like insulin to superfoods, super-lipids and bioenergy. This is amplified by NASA's renewed interest in using duckweed to recycle human wastes in space (Leman, 2020). Indeed, it is this latter revival that speaks directly to duckweeds' potential for driving The New Circular Economy.

Duckweeds in Wastewater Treatment:

While Wolverton (1976), in his work with NASA, is given formal credit for conceiving duckweed-based treatment of wastewater, the Louisiana study by Culley and Epps (1973) wherein they grow duckweed on diluted swine waste and examine the feed value of the harvested duckweed, was the first such study reported in the scientific literature. The first reported attempts at treating human wastewater with duckweed were conducted by Skillicorn and Gilman, working collaboratively in India and Bangladesh from 1976 through 1978 (Prism Group, 1996). Culley and Epps (1973) were subsequently joined by Rusoff (1980), Rejmankova and Hillman (Culley et al. 1981), collectively launching a notably productive decade-long examination of duckweed's application to the task of treating wastewater and producing animal feed.

In the early 1980's Skillicorn and Gilman then shifted their focus to Peru, where with funding from USAID, Johns Hopkins University, The International Potato Center (CIP) and Canadian CIDA, they launched a 10-year study examining "The Safety and Efficacy of Sewage Grown Duckweed as feed for broilers, layers and chicks" (Skillicorn and Gilman, 1985; Haustein et al. 1990, 1992, 1993, 1994). The continuing effort also included feeding trials on swine, goats, guinea pigs and dairy cattle. More importantly, it expanded from production of duckweeds in existing facultative municipal wastewater treatment lagoons in Lima, to construction, under Torres' supervision, of a one-off dedicated "denticular design" municipal wastewater treatment plant treating a raw sewage flow of 100 L/s produced by Ferreñafe, an agricultural town of 25,000 located about 8-hours drive north of Lima. Working independently through The Prism Group, Skillicorn also expanded his duckweed work in India, and, in particular Bangladesh, where he established the Mirzapur Duckweed Farm and R&D Center, the Shobuj Shona Project (Skillicorn, 2003) and The Mirzapur Agriquatics Wastewater Treatment Plant, which became, upon commissioning in 1989, and has remained ever since, the world's only fully self-supporting (no fees or subsidies) municipal wastewater treatment system (Alaerts et al., 1996).

In the 1980s, a group in Israel, headed by Ben Gurion University-based Gideon Oron and Daniel Porath, began working seriously with application of duckweed to the treatment of municipal sewage. Their 1985 and 1987 articles published in Water Science and Technology reported a 3-10 day detention time, "acceptable effluent quality for reuse," and dry weight production averaging 14 g/ m^2 of a duckweed clone having a crude protein content of "above 30%" (Oron & Porath 1985, 1987). Louw Wildschut and Andre de-Vegt, both from Wageningen University in The Netherlands, collaborated with Gideon Oron and Dan Porath in their early work. Collectively, they represent the advent of a strong commitment to duckweed-based treatment of wastewater by Wageningen University and neighboring IHE Delft (UNESCO Institute for Water Education), that continues today.

The first commercial applications of duckweed-based wastewater treatment date to the early 1980s, when Delman Hogan, working with Lemna Corporation principal Viet Ngo, began testing designs for floating plastic containment structures that could be easily deployed and then used to position a complete duckweed mat cover over an existing facultative lagoon. This invention was granted US patent 4,536,988 on Aug 27, 1985. The Lemna Corporation continued to improve the system and was issued US patents 5,096,577 and 5,180,501 on March 17, 1992 and January 19, 1993 respectively. The improved systems allowed almost instantaneous deployment on any existing, permitted facultative lagoon and enabled "float-over" harvesting of the duckweed mat contained within the barrier system by either dragged or self-propelled harvesting devices (www.ci.devils-lake.nd.us/departments/lemna.html). The primary purpose of "The Lemna System," was to precipitate algae by providing a natural system occluding light penetration into the final lagoon or lagoons of facultative wastewater treatment complexes that are generally unable to meet permitted TSS (total suspended solids) standards. The largest Lemna Corporation system to be installed was the Devil's Lake tertiary polishing system, which at 58 acres became the second largest duckweed-based wastewater treatment system in the world (ranking behind the 65-acre Ferreñafe wastewater treatment plant). The Lemna Corporation went on to install a reported 66 municipal wastewater treatment systems throughout the US (Viet Ngo, 2014, personal communication). With most facultative lagoon systems now having been replaced by activated sludge mechanical treatment systems, the Lemna Corporation no longer offers its retrofit system. Despite its demise, the "Lemna System" is now included in most mainstream wastewater treatment textbooks such as those published by Academia Press (Tchobanoglous, 1991) and The Water Environment Federation (Chin, 2012). Hobbs (1970) provides a comprehensive operators manual.

It is noteworthy that The Lemna System business model, on one side, allowed municipal clients a relatively inexpensive quick-fix to difficult regulatory problem (exceeding permitted discharge limits). On the other, it gave The Lemna Corporation a high margin, quickly deployed capital equipment sale. Monetizing the harvested duckweed was given little consideration. In most circumstances the duckweed was simply "dumped." Some communities, typically unsuccessfully, endeavored composting it.

In Australia, Robert Bell, working initially with Ronald Leng and his duckweed program based at the University of New England in Armidale, New South Wales, produced a look-alike design to the successful systems then being installed by The Lemna Corporation in the US. A pilot, and several small commercial systems were commissioned – treating both municipal and CAFO wastewater (Leng et al., 1995). With Leng's retirement from academia, Bell went on to found BioTech Waste Management (BTWM), a company devoted strictly to duckweed-based treatment of wastewater. BTWM's first commercial system involved installing a duckweed-based secondary system to polish, and bring to permitted standards, the discharge of the Pasaveer primary system then being used to treat the wastewater of Harrington, a small coastal town in NSW (Willet, 2005). BTWM has now installed over a dozen systems in Australia and has progressed to marketing its new system designs, which now also include treatment of mine tailing effluents, throughout South and Southeast Asia. BTWM is the first purveyor of commercial, municipal duckweed-based wastewater treatment systems incorporating use of the harvested duckweed as a feedstuff in diets for livestock and fish (Robert Bell, 2014 personal communications).

In the Netherlands, several faculty based at Wageningen University and the adjacent IHE Delft embraced "the duckweed system" for secondary and advanced tertiary treatment of wastewater in the mid-80s. Key among these were Professor Guy Alaerts, who went on to head up the Wastewater Treatment Section of the World Bank, and his colleague Professor Huub Gijzen. Dr. Gijzen already had an international reputation for his contributions to the design, testing and optimization of the low cost, full flow-through UASB (up-flow anaerobic sludge bed) anaerobic digester system. He came to believe and subsequently promote, world-wide, duckweed-based nutrient removal as "completing the wastewater treatment package" (Gijzen, 2001). As with their academic colleagues in the US, Israel and Australia, Alaerts and Gijzen also embraced value-added, on-site use of the harvested duckweed as feed for livestock, poultry and/or fish. A commitment by both to onsite production of fish, in particular, as an integrated element of "sustainable wastewater treatment," followed Alaerts' formal review of the Skillicorn-designed Mirzapur system in 1996 (Alaerts et al., 1996; Gijzen and Veenstra, 2000; El-Shafai et al., 2004). Wageningen faculty and graduates have, during the last 25 years, been responsible for promoting, installing and overseeing management of duckweed-based wastewater treatment systems in Jordan, Yemen, Indonesia, Kenya, Uganda, Tanzania, Ethiopia, Egypt, Gaza, West Bank, Colombia and elsewhere (El-Shafai et al., 2004; Skillicorn, 2014 personal communication).

Elsewhere, discrete groups in The United States, France, Spain, Brazil, Peru, Ecuador, Chile, Canada, Mexico, Pakistan, Malaysia, Philippines, Indonesia, Iran, Egypt, Lebanon, Taiwan, Vietnam, Venezuela and Cuba, as well as several groups in both India and China have either built, are building, or are planning on building duckweed-based wastewater treatment systems to treat CAFO, industrial and/or municipal wastewater and sewage. This was communicated to the authors in personal conversations held during 2013 to 2015 with prominent duckweed industry entrepreneurs, including: Geary, Landesman, Tiarks, Selset, Mohnot, Lam, Ikramullah, Powell, Sharma, Ramasamy, and Mercovich, among others. With minor exception, these tended to be unsophisticated systems in which existing waste flows (raw or partially treated municipal, industrial, CAFO and/or agricultural runoff) were contained, with collection areas landscaped to allow harvesting and minimize wind effects. Harvested duckweeds were typically fed wet as a portion of rations to poultry, swine, dairy cattle and even goats and sheep. The more sophisticated systems – notably those in Southeast Asia – tend to duplicate, after a fashion, the system described in Skillicorn's book published by The World Bank (1993): Duckweed Aquaculture (Robinson, 2001; Phuong, 2003; Landesman, 2010; Dokulil, 2011; Louyer, 2013). A number of these latter systems, notably those described by Jena (2010), Iqbal (1999) and Drechsel (2012) are producing fish for sale in local commercial markets. Few systems have elected to make the investments in system efficiencies and drying or mass disposal of duckweed that are required to move beyond a backyard approach to duckweed-based wastewater treatment.

Despite these advances, treatment of wastewater with duckweeds has recently stalled. In the industrialized world and BRICs, there is strong resistance by engineering firms to any "irregular" systems that fall outside their perceived approach to "modernizing" by adopting more "advanced" mechanical systems. The combination of entrenched notions of modern wastewater treatment, regulatory hostility towards decentralized alternatives to the accepted "standard" technologies, and the lack of political will to seriously invest in new approaches – hinders adoption. By contrast, the Global South, particularly rural and smaller urban communities in Africa, offer the best opportunity for building this New Circular Economy. Achieving a genuine "new" circular economy is feasible and immediately possible in contexts that lack an entrenched engineering and regulatory fraternity that has vested interests in maintaining the current expensive, inefficient, and wasteful status quo.

Our purpose for the remainder of this article, is to lay out, in very practical terms, a New Circular Economy that draws its strength from advanced, phased-sequenced anaerobic digestion of volatile solid wastes and duckweed-based wastewater treatment. In doing so we will engage a discussion of sustainability and sustainable development, which have become foci for global aspirations relating to Africa, as it moves through the 21st century.

The New Circular Economy:

Wastewater and Municipal Solid Waste (MSW) Treatment

The EPA estimates that Americans generated 276 million tons of recyclable wastes in 2017; with only 97 million tons of those wastes either recycled or composted in some fashion: 38% (USEPA, 2018). Paper, metal, glass and plastics are the most commonly recycled materials. Steel, is more "successfully" recycled, with 69% of new steel sold in the US in 2019 comprising recycled material. Recycling steel is also efficient and relatively clean because it can all be done electrically (Donovan Bennett, 2020). In 2018, The EPA estimates that only 31% of all glass disposed of was effectively recycled (USEPA, 2018). Estimates vary, but Americans are reported to consume around 85 million tonnes of paper and paper products each year. The EPA also reports that 68% of paper and carboard materials that were submitted for recycling (68% of 46 million tonnes) ended up finding their way into some form of new paper product material (USEPA, 2018). Doing the math, 36% of all paper products can be assumed to have genuinely been recycled. Plastic is the most problematic of commonly recycled materials, with only 9% genuinely recycled in 2017 (Krosofsky, 2021).

The US now submits around 70 billion M^3 of raw sewage to wastewater treatment plants each year. Around 0.1% of that wastewater, or 70 million tonnes, comprises volatile solid wastes (Infrastructure Report Card, 2021). This is comparable in volume to the estimated 70 million tonnes of food wastes and yard trimmings collected by MSW services. If we take the water out of MSW volatile wastes, we cut that number on a dry weight basis, in half: 35 million tonnes.

Our vision for a New Circular Economy takes all volatile wastes, wastewater, polluted drainage water and agricultural runoff, collects them, segregates them, as necessary, and puts them to work in a leveraged (solar energy and photosynthesis) fashion. Plastics, but not metals, glass and/or construction aggregate and debris are also included. Nothing is thrown away – no pollutants, energy, nutrients or water – and what is finally released to the environment as water vapor or discharge is always potable as to quality. The New Circular Economy, by definition, makes a very significant net profit. It revitalizes urban periphery agriculture and its value-added derivatives. It provides new, vital sustenance to communities and formal expressions of those communities: neighborhoods, villages, towns and cities. This vision, The Skillicorn Technologies Circular Economy model, is described in some detail in the document STLTBCC C Form (2021) submitted as a requirement to the US Securities and Exchange Commission. The sections which follow, draw from and summarize The Skillicorn Technologies Circular Economy model.

In a typical US community, The New Circular Economy would require that what are now considered to be "landfill wastes," be segregated into: volatiles (including food wastes and lawn and yard trimmings); dirty plastics; and "other materials." Typically, dirty plastics tend to be mixed with wet and damp volatiles. These are amenable to crude separation, resulting in a stream of: a) volatiles with only minor inclusion of plastic fragments – notably foamed plastic and thin film plastics; and b) very dirty plastics, including thin film, foamed, unrecyclable containers and other mixed unrecyclable plastic wastes. The latter will typically be heavily soiled by wet, decaying and odiferous volatiles.

Ideally, all sewered homes and institutions should be fitted with utility-supplied robust, high capacity garbage disposal grinders that would work to grind up everything from food wastes (including recalcitrant 'garbage can' items such as avocado and mango seeds), yard trimmings, paper and cardboard wastes to dirty, foamed, irregular and thin film plastics, and simply flush them all collectively down the sewer. These wastes, accounting for around 70% of what is now laboriously (and expensively) assembled, loaded and trucked to landfills and waste combustion facilities (USEPA, 2021), would efficiently be transported to "the new circular economy" wastewater treatment plants where plastics would be separated out and volatiles would be further reduced, broken down and digested. The paper, in particular, would contribute valuable carbon, which is now deficient for efficient anaerobic digestion.

Adding these materials to "sewered transport" can be expected to approximately triple the volume of what now passes through the sewers. At the household, neighborhood and community levels, this can be easily accommodated by existing, installed sewerage infrastructure (USEPA, 2002). Since all water in The New Circular Economy is completely recycled, there is no "water cost," and even tripling local pumping costs adds little to existing sewerage costs. It is dramatically less expensive than operating fleets of garbage trucks, separation facilities, landfills and incinerators. The "other materials," which would include everything from e-wastes to disposed furniture do not represent significant volume, cannot be extracted for energy or nutrients, and are not dealt with in this brief article. We assume, as is common practice, that materials of interest will have been screened to remove metallic, large woody, cementitious, glass and aggregate materials. Wet and damp volatiles containing some plastic fragments which today are mixed together in garbage collection, would be finely ground and blended with incoming sewage primary solids – the latter preferentially removed from influent raw sewage by simple, robust, small footprint mechanical screening (e.g., Salnes continuous screen filters). Care must be taken to ensure that a balance between available carbon (C) and nitrogen (N) (range: 25:1 to 30:1) (Yen and Brune, 2002; Wang et al., 2012; Tanimu et al., 2014; Sylvestre et al., 2015) is maintained at a ratio targeted at optimizing subsequent anaerobic digestion operations.

Three basic waste streams (of interest) are generated by contemporary human settlements: 1) screened, ground "dirty" plastics; 2) screened, ground volatile solids (including sewage volatiles, and also some finely ground plastics); and 3) clarified raw wastewater containing some soluble BOD (biochemical oxygen demand) and COD (chemical oxygen demand). The dirty plastics are desiccated and then contributed to the plastics sequestration facility. The finely ground and macerated volatile solids are passed to the pretreatment front end of the anaerobic digester array. The clarified wastewater is dispatched to arrays of soluble BOD reactors designed, in particular, to carry out efficient hydrolysis of soluble protein molecules (STLTBCC, 2021).

Sequestration of plastics is achieved by producing robust foamed panels. These utilitarian panels incorporate: 1) dirty plastics that have been blended with damp volatile MSW solids and/or wastewater, then separated; 2) unrecycled and unrecyclable plastics that have been segregated from other MSW fractions and then coarsely ground; and 3) purchased foaming agents designed to react with fractions of #s 1 and 2 (above). These panels can be precisely molded for many purposes. It is particularly advisable to use them to produce plug n' play, in- water floating solar PV power plants. The expected demand for such products by power plants is so great, it could potentially accommodate all plastic wastes, worldwide. Alternatively, these same waste plastics foaming approaches have considerable potential for the manufacture of structural insulated panels (SIPs) that can contribute to the local housing industry (STLTBCC, 2021).

Screened, macerated volatile solids that have been contributed for pretreatment, preparatory to anaerobic digestion, are first finely ground then subjected to ultrasonic treatment and perhaps steam explosion (to effect lysis) before being passed on a continuous basis to one of a series of parallel swirled hydrolysis units serving as the front end of a phased, sequenced anaerobic digestion array. Hydrolysis is achieved by bringing the water and attendant suspended solids to a temperature ideally suited to thermophilic hydrolytic bacteria appropriate to the local circumstance (biochemistry of the influent volatile solids). Where recalcitrant volatile materials are prevalent, sequencing of thermophilic and mesophilic hydrolysis with a digestion array is recommended. Clarified overflow from the hydrolysis units filters up through a second stage within the same reactor wherein it passes through a superficial chamber filled with kenaf core "carbon donor" biofilm that is populated with additional thermophilic or mesophilic bacteria. Sequential, "circular" hydrolysis is persistent when it comes to breaking down all volatile solids. Eventually, minerals and non-volatile materials aggregate as "heavier" mineralized grit, which allows their isolation and continuous removal by an array of fine hydrocyclones through which the heaviest particles of a swirl-induced solids gradient are passed (STLTBCC, 2021).

Upwelled, clarified discharge from the hydrolysis biofilm chamber is adjusted for pH and temperature preparatory to passage into the upwelling recirculation flow of a carbon-donor biofilm-filled acidogenesis, fatty acid hydrolysis reactor. Clarified overflow from the acidogenesis reactor is similarly adjusted for pH and temperature preparatory to passage into the upwelling recirculation flow of a kenaf core biofilm-filled acetogenesis, fatty acid bioreactor (STLTBCC, 2021).

Discharge from the acetogenesis reactor is clarified, adjusted for pH and temperature preparatory to passage into the upwelling recirculation flow of a carbon-donor biofilm-filled methanogenesis reactor. Biogas produced within the methanogenesis reactor is captured and bottom-diffused, along with measured amounts of locally produced (PEM electrolysis) hydrogen gas into a carbon-donor biofilm-filled methanation reactor. High concentration methane gas produced by the methanation reactor is cleaned and dehumidified, then passed to a CNG (compressed natural gas) unit where it is prepared for delivery to the local CHP (combined heat and power)- and hydrogen-configured gas turbine array where it is combusted to produce firmed, 100% renewable, on-demand electric power, recovered heat and high CO_2 exhaust. The exhaust is piped to duckweed production greenhouses and enclosed aquaponics facilities to enhance photosynthetic activity in the production of duckweed crops and select vegetables, herbs and vine fruit (STLTBCC, 2021).

As noted above, the screen-clarified wastewater is dispatched to arrays of soluble BOD reactors designed to perform efficient hydrolysis of soluble protein molecules. Depending on circumstance and need, the soluble BOD reactors can be operated in aerobic, anoxic and anaerobic modes and phrased sequentially – allowing the possibility of different dwell times in each mode to optimize their performance. Final discharge from this reactor array assumes that soluble BOD will have been reduced close to zero. Discharge from these reactor arrays is then passed to a duckweed-based nutrient removal array. Where land is available, this will typically be done in CO_2-infused, temperature and light-controlled, inflated duckweed greenhouses that are configured as a plug flow. These fully automated greenhouses employ a variety of approaches to ensuring that water and air temperatures are always maintained within "close to optimal ranges." Additionally, care is taken to ensure that exposure to sunlight is always maintained within a similarly "close to optimal" level. pH can be adjusted if deemed necessary (STLTBCC, 2021).

Where land availability is problematic, duckweed-based nutrient removal is performed in vertically configured production circumstances employing aerosol hydraulics and self-cleaning, pulsed LED lighting. These can be built into existing shipping containers, constructed in shell buildings, or even built into basements or dedicated spaces within high rise residential, business or industrial structures. Passage of water from container to container, room to room or subsystem to subsystem effects a plug flow (sic: sequential, as opposed to mixed flow). pH and DO (dissolved oxygen) should also be adjusted to favor quasi-optimal duckweed growth while also minimizing volatilization of ammonia and loss of nitrates through denitrificatrion (STLTBCC, 2021).

Effectively, the sole purpose of the nutrient removal array is to render nitrogen presenting as ammonia/ammonium ($NH_{3/4}$) and nitrate (NO_3) to (close to) zero – and only through uptake by the duckweeds. Harvesting in both 2D and 3D systems is continuous during daylight hours in the former, and "when lit" in the latter, and it is performed in such a manner as to ensure optimal growth of the duckweed crop and minimize any plant necrosis (STLTBCC, 2021).

Duckweed harvested from the nutrient removal array has high protein, relatively high starch, some cellulose, excellent minerals, vitamin and antioxidant contents and little in the way of ash. Most of these nutritious plants are committed to desiccation and further processing, with some channeled to a downstream "pushed-polishing" array for removal of trace organics, heavy metals and other toxin vectors – as well as starch enrichment (STLTBCC, 2021).

Pushed-polishing is performed in discrete, straight and narrow, high length-to-width structures (20x) wherein nutritious, high-protein plants harvested from the nutrient-removal systems are pushed in the front end and "grow out" the rear end of the structure. These systems are configured as a plug flow, and may be operated in both parallel and sequential modes – as necessitated. Excepting for harvesting and crop density, lighting, CO_2 infusion (air and water) and temperature controls mimic those of upstream nutrient removal arrays (STLTBCC, 2021).

As noted above, the partially treated wastewater entering a pushed-polishing array has already been stripped of available nitrogen. This results in duckweed plants commencing to process vast amounts of water as they search for non-existent nitrogen. Growth rates drop but vigorous photosynthetic activity continues while plants reproduce as daughter fronds cannibalizing their mother frond's protein. Relative starch content of plants "pushed out the other end" rises, cellulose increases, at the margin, protein levels drop precipitously, and ash content rises, sometimes to above 20%. This "ash" comprises salts, minerals, heavy metals, trace organic compounds (TOrCs) and whatever other toxin vectors the plants imbibe as they seek nitrogen (STLTBCC, 2021). The two harvested duckweed streams are very different: one serves as a nutritious feedstuff and contains little in the way of anti-nutritionals or toxins; while the other, with high starch, relatively higher cellulose and relatively high ash content serves better as a feedstuff for fermentation and production of biochemicals – even bioplastics. We recommend committing to high value-added systems that maximize financial returns and job creation while minimizing any impact on the surrounding environment. Pushed-polishing can also be performed on mining and industrial waste streams that lack any nutrient content, whatsoever – with balanced fertilizer-fed duckweeds grown up front as a commercial, value-added crop and with some of that crop also submitted to the pushed-polishing array wherein mining and industrial wastes are extracted (STLTBCC, 2021).

Water discharged from a duckweed-based pushed-polishing array can be profitably brought to an advanced quaternary, virtually potable condition – the most advanced condition of any non-membrane system, worldwide. We recommend always to ensure that this treated water is taken to the next level: ultrafiltration treatment followed by sequential ozone and ultra-violet (UV) disinfection. Ultrafiltration costs are lowered by pretreating with pulsed radio frequency (RF). This has the effect of temporarily lowering the single electron-circumscribed aggregation of H_2O molecules and reducing surface tension (STLTBCC, 2021).

This significant stream of what is now potable quality water can be produced at the immediate perimeter of a village, town or city that is typically experiencing rapid, even explosive growth, and seeking additional supplies of potable water. While aversion to using treated sewage as drinking water will likely exist, care should be taken to minimize this perception among the consuming public. This is most easily and effectively done by injecting the treated water into a shallow aquifer upstream of the village, town or city's water supply tube wells. Where willingness to pay for this pure, potable water does not manifest, the enterprise producing the treated water should be willing to monetize it internally. This can be done with water intensive agribusiness, industry or real estate development (STLTBCC, 2021).

Duckweed Monetization and Value-Added Usage

Duckweed that is a product of treating sewage and MSW cannot be directly introduced as a human food. Use of such duckweed, providing it meets feed grade standards (i.e., disinfected and having no heavy metals, TOrCs or toxin vectors that exceed feed-grade limits), can be employed in production of optimized feeds and feedstuff for CAFO, pets and aquaculture systems. Of these, aquaculture and aquaponics, in particular, are superior on a value produced per footprint basis, while also affording value-added use of the treated water. Duckweeds also offer final advanced polishing of recirculating aquaculture and aquaponics growth media (STLTBCC, 2021).

While hundreds of recirculating aquaculture and aquaponics systems have been successfully demonstrated worldwide, recommendation is made to employ a system incorporating final duckweed-based polishing of the recirculating media – even in concert with an advanced aquaponics system. Duckweeds grown on nutrient removal systems (see above) can constitute between 40% and 50% of optimized aquaculture diets that also include corn, sorghum or millet meal for starch, some animal or fish lipids and also lysine and methionine supplements. Alternatively, the latter can be supplied by incorporating in-house aquatic vermiculture into the recirculating aquaculture or aquaponics model being implemented (STLTBCC, 2021).

As noted above, duckweeds grown within a pushed-polishing system are preferably used in the production of biochemicals. Bioethanol is produced using enzymatic saccharification, followed by fermentation. At a more sophisticated level, the residual product, comprising ash, proteins and a variety of other extractable compounds can also be processed to produce a wide range of industrial products. One notably profitable approach is to saccharify the duckweed starch and cellulose and ferment the combined product to produce lactic acid, which is then polymerized to produce polylactic acid, a common bioplastic. The balance, which is rich in protein can also be polymerized by adding glycerol (2 parts glycerol to 3 parts powdered duckweed), a byproduct of biodiesel production. This is done by using high-shear mixing in a Banbury mixer. These two bioplastics can be combined to produce a copolymer having favorable properties and then blended with natural bast fibers such as jute, hemp or kenaf to produce a 100% natural fiber-reinforced bioplastic that can compete in the marketplace on a cost/performance basis with glass-reinforced polypropylene and polyethylene (STLTBCC, 2021).

Some Numbers

It is instructive to apply some rule-of-thumb numbers to the systems we have discussed above. An advanced mechanical wastewater treatment plant will cost between $5 and $15 million per MGD (million gallons per day), depending on location and circumstance, and cost between one million and two million dollars per MGD per year to operate. Again, depending on location and circumstance, a comprehensive duckweed-based circular economy system will cost around half as much to construct and commission, and half as much to operate. The mechanical plant will perform to some arbitrary standard, while the duckweed circular economy system will produce only completely potable water and then, also make a significant net profit (STLTBCC, 2021).

The reference 1-MGD duckweed-based circular economy system will require around 12 hectares of land – effectively twice as much as a typical 1-MGD mechanical plant, but it will also shrink the requirement for a sanitary landfill. The fundamental difference between the two systems, however, is that the duckweed-based system will recover its half million dollar operating costs, amortize its capital costs and then make a net "in the pocket" annual profit of between $2 million and $3 million. Figure 1. shows a flow diagram of system flows prepared for the town of Koota in the Fayoum Governorate in Egypt (Skillicorn Technologies Egypt et al., 2021).

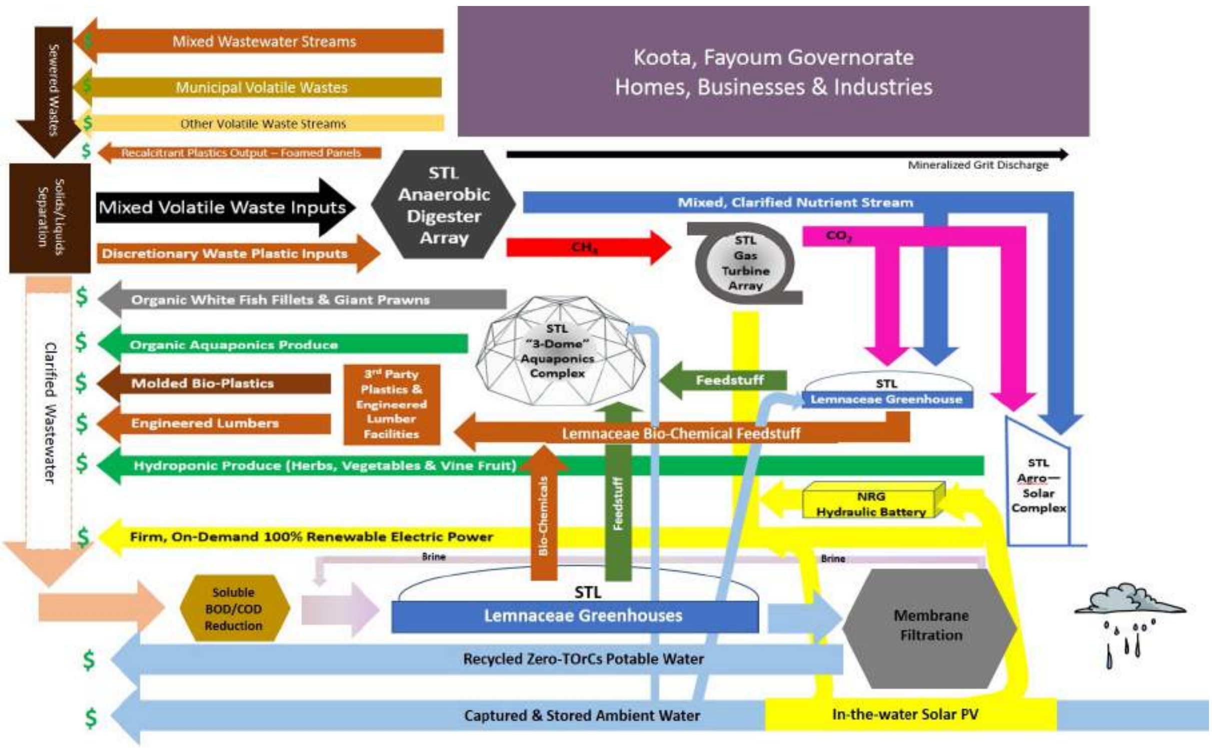

Figure 1 The New Circular Economy - (Skillicorn Technologies Egypt et al. 2021).

The Skillicorn Technologies Egypt Koota project is a JV between Skillicorn Technologies, HCWW (Holding Company for Water and Wastewater – a Government of Egypt parastatal company holding national rights and responsibilities for water, wastewater and municipal solid wastes) and The Governorate of Fayoum. The project holds an open-ended concession for treating all the wastewater produced by the Town of Koota and neighborhoods which also fall within the Koota Concession (Skillicorn Technologies Egypt et al. 2021).

For a small town of around 20,000 people[1], having wastewater and MSW dealt with and then sharing a profit of $3 million with an investment group and a company that provides and manages the service(s) is a massive step up from the alternative of spending a million dollars while providing an inferior service to constituents. That $2 million per year difference can transform the town: better parks; better EMS; better police services; better schools; better libraries; a better town hall – and the list goes on (STLTBCC, 2021).

Conclusions

"The Circular Economy" as discussed in the academic literature, often amounts to little more than aspirational semantics – and what tangible expressions do exist are too narrow to be truly meaningful (sic: recycling some paper, metals and plastics) and typically do not involve recovery and leveraged recycling of nutrients. Based on over forty years of experience developing duckweed in a wide variety of contexts and circumstances, we present here a model for The New Circular Economy that is fueled, at its core, by duckweed-based extraction of nutrients contained in wastewater and the volatile fractions of municipal solid wastes. Because the inertia of nutrient-wasting, wastewater and MSW treatment technologies historically subscribed to by the advanced economies of the EU, East Asia, Oceania, North and South America is so great, today's popular circular economy models (academic, government and media arenas) tend to ignore the greatest potential contributors to system value through nutrient recovery and carbon recycling. The Skillicorn Technologies model presented here solves that problem.

We conclude that achieving a genuine "new" circular economy is feasible and immediately possible. We caution, however, that acceptance in more advanced, industrialized societies is contingent on successfully overcoming the powerful resistance posed by the entrenched engineering and regulatory fraternity and an existing water, wastewater and municipal solid wastes infrastructure base amounting to tens of trillions of dollars. It is becoming increasingly apparent that the circumstances prevalent in many nations of the Global South, especially in Africa and rural South Asia, offers the best opportunity for pioneering this New Circular Economy.

We also acknowledge that our experience in designing, constructing, recruiting partners, training personnel, and commissioning and managing diverse New Circular Economy circumstances is limited. We also recognize that a successful New Circular Economy must attend, with high sensitivity and within the constraints imposed by each local circumstance, to always delicate issues involving politics, religion, equity, gender and diversity. This is particularly important because the model we prescribe brings into a partnership of equals: local smallholder farmers, landless laborers, local community committees and local formal government institutions as well as area, regional, state and national governments and their agencies, laboratories, institutes, colleges and universities. We also favor selection of women as our partners over their male counterparts. We do so considering the rationale that fewer women have paid jobs – certainly good jobs – that they are more bereft; they have greater responsibilities as nurturers of children; they are more willing to accept new jobs that deal with volatile and human wastes; and they are, in our experience, more diligent.

1 A town of 20,000 people would be expected to have daily wastewater flows averaging approximately 1 MGD to 3.8 MLD (million liters per day). This assumes daily consumption of 150 liters per capita per day, and some industrial and institutional production of wastewater

Finally, we have shown, in very practical terms, how The New Circular Economy can be configured, and what is required for it to take off as a vehicle for genuinely sustainable development – notably in Africa, as it moves through the 21st century.

References

Alaerts, G. J., Mahbubar, R., & Kelderman, P. (1996). Performance Analysis of a Full-Scale Duckweed-Covered Sewage Lagoon. *Water Research*, 30(4), 843–852.
Alleman, J. E., & Prakasam, T. B. S. (1983). Reflections on seven decades of activatedsludge history. *Journal (Water Pollution Control Federation),* 436-443.
Angelakis, A. N., & Snyder, S. A. (2015). Wastewater treatment and reuse: Past, present, and future.
Anyaoku, C. C., & Baroutian, S. (2018). Decentralized anaerobic digestion systems for increased utilization of biogas from municipal solid waste. *Renewable and sustainable Energy reviews*, 90, 982-991.
Asif, M. B., & Zhang, Z. (2021). Ceramic membrane technology for water and wastewater treatment: a critical review of performance, full-scale applications, membrane fouling and prospects. *Chemical Engineering Journal*, 129481.
Awal, R., Hassan, A. E., Abbas, F., Fares, A., Bayabil, H. K., Ray, R. L., & Woldesenbet, S. (2021). Patterns of Nutrient Dynamics within and below the Rootzone of Collard Greens Grown under Different Organic Amendment Types and Rates. *Sustainability*, 13(12), 6857.
Ayres, R.U., 1999. The second law, the fourth law, recycling and limits to growth. *Ecol. Econ*. 29 (3), 473-483.
Ball-Blakely, C. (2018). CAFOs: Plaguing North Carolina Communities of Color. *Sustainable Development Law & Policy*, 18(1), 3.
Banerjee, A., Bhaskar, T., & Ghosh, D. (2020). A biorefinery approach for sewage sludge. In *Waste Biorefinery* (pp. 393-421). Elsevier.
Bates, Todd, (2019) *Could Duckweed Feed the World?* https://phys.org/news/2019-08-duckweed-world.html
Bell, R. (2003). *The Application of a Duckweed Wastewater Treatment System at the Harrington Sewerage Treatment Works* (pp. 1–6).
Bell, R. E. (1998). *A potential high protein feed source for domestic animals and fish* (p. 31).
Benyus, J.M., 2002. Biomimicry: Innovation Inspired by Nature, *Perennial.*
Blomsma, F., Brennan, G., 2017. The emergence of circular economy: a new framing around prolonging resource productivity. *J. Ind. Ecol*. 21 (3), 603-614.
Bougnom, B. P., Thiele-Bruhn, S., Ricci, V., Zongo, C., & Piddock, L. J. V. (2019). High-throughput sequencing data and antibiotic resistance mechanisms of soil microbial communities in non-irrigated and irrigated soils with raw sewage in African cities. *Data in brief,* 27, 104638.
Boulding, K.E., 1966. The economics of the coming spaceship earth. In: Jarrett, H. (Ed.), *Environmental Quality Issues in a Growing Economy.* Johns Hopkins University Press, Baltimore, MD.
Burlakovs, J., Kriipsalu, M., Porshnov, D., Jani, Y., Ozols, V., Pehme, K. M., ... & Klavins, M. (2019). Gateway of landfilled plastic waste towards circular economy in Europe. *Separations*, 6(2), 25.
Calhoun, W. R., & Cecala, K. K. (2021). At the Expense of the Environment: Economic and Regulatory Factors Impacting the Location and Management of Concentrated Animal Feeding Operations (CAFOs) in North Carolina. *Case Studies in the Environment*, 5(1), 1428433.
Cammack, R. M. (2019). *From Toilet to Tap: The Evolving Discourse of Recycled Drinking Water* (Doctoral dissertation, San Diego State University).
Chin, D. A. (2012). *Water-quality engineering in natural systems: fate and transport processes in the water environment*. John Wiley & Sons.
Clapp, J. (1994). The toxic waste trade with less-industrialized countries: Economic linkages and political alliances. *Third World Quarterly,* 15(3), 505-518.
Culley, D. D., Epps, E. A., & Epps, A. (1973). Use of duckweed feed for waste treatment and animal feed. *Journal (Water Pollution Control Federation),* 45(2), 337–347.
Culley, D. D., Rejmánková, E., Květ, J., & Frye, J. B. (1981). Production, chemical quality and use of duckweeds (Lemnaceae) in aquaculture, waste management, and animal feeds. *Journal of the world mariculture society,* 12(2), 27-49.
Daly, H.E., 1996. *Beyond growth: the economics of sustainable development*. Beacon Press, Boston.
Deksissa, T., Trobman, H., Zendehdel, K., & Azam, H. (2021). Integrating Urban Agriculture and Stormwater Management in a Circular Economy to Enhance Ecosystem Services: Connecting the Dots. *Sustainability,* 13(15), 8293.
Donovan Bennett (2020), *Steel Recycling: Processes, Benefits, and Business Solutions,* https://www.rubicon.com/blog/steel-recycling/.
Drechsel, P. (2012). *AGRIQUATICS , MIRZAPUR , BANGLADESH BUSINESS CASE* (pp. 1–6).
Drechsel, P. (2012). *TERRAQUA , BARRANCA BUSINESS CASE DESCRIPTION* (pp. 1–6).
Durham, N. C., & Karan, A. (2011). Pigs, Profit, Planet: North Carolina Farmers' *Perspectives on Waste Lagoon Conversion*
Ellen MacArthur Foundation (2010). https://ellenmacarthurfoundation.org/
El-Shafai, S. a, El-Gohary, F. a, Verreth, J. a J., Schrama, J. W., & Gijzen, H. J. (2004). Apparent digestibility coefficient of duckweed (Lemna minor), fresh and dry for Nile tilapia (Oreochromis niloticus L.). *Aquaculture Research*, 35(6), 574–586.
Faraca, G., & Astrup, T. (2019). Plastic waste from recycling centres: Characterisation and evaluation of plastic recyclability. *Waste Management*, 95, 388-398.

Faraca, G., Martinez-Sanchez, V., & Astrup, T. F. (2019). Environmental life cycle cost assessment: Recycling of hard plastic waste collected at Danish recycling centres. *Resources, Conservation and Recycling*, 143, 299-309.
Frosch, D., Gallopoulos, N., 1989. Strategies for manufacturing. *Sci. Am.* 261 (3), 94-102.
Furuseth, O. J. (2001). Hog farming in eastern North Carolina. *Southeastern Geographer*, 41(1), 53-64.
Gadi, C., Bala, K. L., & Kumar, A. (2013). Study of Hygienic practices of street food vendors in Allahabad city, India and Determination of Critical control points for safe street food. *The Allahabad Farmer*, 68(2), 1-10.
Georgescu-Roegen, N., 1971. *The Entropy Law and the Economic Process*. Harvard University Press, Cambridge, MA.
Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* 114, 11-32.
Gijzen, H. J. (2001). Low Cost Wastewater Treatment and Potentials for Re-use: A Cleaner Production Approach to Wastewater Management. In International Symposium on Low-Cost Wastewater Treatment and Re-use, *NVA-WUR-EU-IHE,* February 3-4, 2001, Cairo, Egypt (p. 16).
Gijzen, H. J., & Veenstra, S. I. E. M. E. N. (2000). Duckweed based wastewater treatment for rational resource recovery and reuse. *Environmental biotechnology and clean bioprocesses*. Taylor and Francis, London, 83-100.
Graedel, T.E., 1996. On the concept of industrial ecology. *Annu. Rev. Energy Environ*. 21, 69-98.
Gross, A., & Park, E. (2018). Water and wastewater treatment worldwide: the industry and the market for equipment and chemicals. *Business Economics*, 53(1), 37-47.
Guerra-Rodríguez, S., Oulego, P., Rodríguez, E., Singh, D. N., & Rodríguez-Chueca, J. (2020). Towards the implementation of circular economy in the wastewater sector: Challenges and opportunities. *Water,* 12(5), 1431.
Gündoğdu, S., & Walker, T. R. (2021). Why Turkey should not import plastic waste pollution from developed countries? *Marine Pollution Bulletin*, 171, 112772.
Gupta, R. K., Thakur, V. K., & Matharu, A. S. (2018). Editorial overview: *From linear to circular economies: The importance and application of recycling and reuse*.
Handan-Nader, C., Ho, D. E., & Liu, L. Y. (2021). Deep learning with satellite imagery to enhance environmental enforcement. In *Data Science Applied to Sustainability Analysis* (pp. 205-228). Elsevier.
Harrison, E. E. (2020). Odor in the Court! And It Smells like Environmental Racism: How Big Pork Is Legally Abusing Poor Communities of Color in Eastern North Carolina. *Wake Forest JL & Pol'y,* 11, 433.
Hassouna, M. E., Goher, M. E., El-Sayed, S. M., & Hassan, R. A. (2019). Integrated approach to quality indices and health risk assessment of water in the Bahr Yusuf Canal, Fayoum, Egypt. *Oceanological and Hydrobiological Studies,* 48(4), 337-354.
Haustein, A. T. Gilman, R. H., Skillicorn, P. W., Vergara, V., Guevara, V., & Gastanaduy, A. (1990). Duckweed, A useful strategy for feeding chickens: performance of layers fed with sewage-grown Lemnacea species. *Poultry Science*, 69(11), 1835-1844.
Haustein, A. T., Gilman, R. H., Skillicorn, P. W., Guevara, V., Diaz, F., Vergara, V., … Gilman, J. B. (1992). Compensatory Growth in Broiler Chicks Fed on Lemna-Gibba. *British Journal of Nutrition,* 68, 329–335.
Haustein, A. T., Gilman, R. H., Skillicorn, P. W., Hannan, H., Díaz, F., Guevara, V., … Gilman, J. B. (2009). Performance of broiler chickens fed diets containing duckweed (*Lemna gibba*). *The Journal of Agricultural Science,* 122(02), 285.
Haustein, A. T., Gilman, R. H., Skillicorn, P. W., Hannan, H., Diaz, F., Guevara, V., ... & Gastanaduy, (1994), Sustainable Animal Agriculture for Developing Countries (*Lemna gibba*). *J. Agri. Sci. Camb*, 122, 285-289.
Haustein, A. T., Gilman, R. H., Skillicorn, (1994) Performance of broiler chickens fed diets containing duckweed (*Lemna gibbae*), In *P. Wilson Jr., ed., Cell wall characteristics in relation to forage digestion by ruminants* 173.
Hobbs, J. (1970). *Tertiary Treatment of Wastewater by Lemna Minor (Duckweed)* (pp. 1–47).
Hogan, B. C. (1985). U.S. Patent No. 4,536,988. Washington, DC: U.S. Patent and Trademark Office.
Honma, S., & Hu, J. L. (2021). Cost efficiency of recycling and waste disposal in Japan. *Journal of Cleaner Production*, 284, 125274.
Huang, Q., Chen, G., Wang, Y., Chen, S., Xu, L., & Wang, R. (2020). Modelling the global impact of China's ban on plastic waste imports. *Resources, Conservation and Recycling*, 154, 104607.
Icke, O., van Es, D. M., de Koning, M. F., Wuister, J. J. G., Ng, J., Phua, K. M., ... & Tao, G. (2020). Performance improvement of wastewater treatment processes by application of machine learning. *Water Science and Technology*, 82(12), 2671-2680.
Infrastructure Report Card. (2021). https://infrastructurereportcard.org/wp-content/uploads/2020/12/Wastewater-2021.pdf
Iqbal, S. (1999). Duckweed Aquaculture: Potentials, Possibilities and Limitations for Combined Wastewater Treatment and Animal Feed Production in Developing Countries. *Soil Science* (Vol. 157, p. 91).
Iroegbu, A. O., Sadiku, R. E., Ray, S. S., & Hamam, Y. (2020). Plastics in municipal drinking water and wastewater treatment plant effluents: challenges and opportunities for South Africa—a review. *Environmental Science and Pollution Research*, 27(12), 12953-12966.
Jena, J. K., Patro, B., Patri, P., Khuntia, C. P., Tripathy, N. K., Sinha, S., … Ayyappan, S. (2010). Biological treatment of domestic sewage through duckweed-cum-fish culture: a pilot-scale study. *Indian Journal of Fisheries*, 57(4), 45–51.
Kadish, V. H. (1928). Milorganite–A New Fertilizer Material1. *Industrial & Engineering Chemistry*, 20(1), 9-10.
Kehrein, P., Van Loosdrecht, M., Osseweijer, P., Garfí, M., Dewulf, J., & Posada, J. (2020). A critical review of resource recovery from municipal wastewater treatment plants–market supply potentials, technologies and bottlenecks. Environmental Science: *Water Research & Technology*, 6(4), 877-910.
Korhonen, J., Nuur, C., Feldmann, A., & Birkie, S. E. (2018). Circular economy as an essentially contested concept. *Journal of cleaner production*, 175, 544-552.

Krosofsky, A. (2021) What Percent of Recycling Actually Gets Recycled, Green Matters, https://www.greenmatters.com/p/what-percent-recycling-actually-gets-recycled

Kucała, M., Saładyga, M., & Kaminski, A. (2021). Phytoremediation of CYN, MC-LR and ANTX-a from Water by the Submerged Macrophyte Lemna trisulca. *Cells,* 10(3), 699.

Ladd, A. E., & Edward, B. (2002). Corporate swine and capitalist pigs: A decade of environmental injustice and protest in North Carolina. *Social Justice*, 29(3 (89), 26-46.

Landesman, L., Chang, J., Yamamoto, Y., & Goodwin, J. (2002). Nutritional value of wastewater-grown duckweed for fish and shrimp feed. *World Aquaculture*, 33(4), 39-40.

Landesman, L., Parker, N., Fedler, C., & Konikoff, M. (2005). Modeling duckweed growth in wastewater treatment systems. *Livestock Research for Rural Development*, 17(6), 1–8.

Landesman, L., Fedler, C., & Duan, R. (2011). Plant nutrient phytoremediation using duckweed. In *Eutrophication: causes, consequences and control* (pp. 341-354). Springer Netherlands.

Leman, J. (2020). Space Weed Could Keep Astronauts Healthy. *Popular Mechanics*, 7/16/2020

Leng, R. A., Stambolie, J. H., & Bell, R. (1995). Duckweed-a potential high-protein feed resource for domestic animals and fish. *Livestock Research for Rural Development*, 7(1), 36.

Leng, R. A. (1999). *Duckweed: A tiny aquatic plant with enormous potential for agriculture and environment* (p. 59). UN Food and Agriculture Organization (FAO).

Leng, R. A., Preston, T., & Rodriguez, L. (2004). *The duckweed invasion of Lake Maracaibo: An evaluation of the causes and proposals for future action*.

Lieder, M., Rashid, A., 2016. Towards circular economy implementation: a comprehensive review in context of manufacturing industry. *J. Clean. Prod*. 115, 36-51.

Lifset, R., Graedel, T.E., 2001. Industrial ecology: goals and definitions. In: Ayres, R.U.,Ayres, L. (Eds.), *Handbook for Industrial Ecology. Edward Elgar, Brookfield*.

Lin, L., Xu, F., Ge, X., & Li, Y. (2018). Improving the sustainability of organic waste management practices in the food-energy-water nexus: A comparative review of anaerobic digestion and composting. *Renewable and Sustainable Energy Reviews*, 89, 151-167.

Liu, M., Tan, S., Zhang, M., He, G., Chen, Z., Fu, Z., & Luan, C. (2020). Waste paper recycling decision system based on material flow analysis and life cycle assessment: a case study of waste paper recycling from China. *Journal of environmental management,* 255, 109859.

Liu, Y., Xu, H., Yu, C., & Zhou, G. (2021). Multifaceted roles of duckweed in aquatic phytoremediation and bioproducts synthesis. *GCB Bioenergy*, 13(1), 70-82.

Louyer, A., Gallissot, M., & Van-Nguyen, N. (2013). Controlling mycotoxins in pangasius. *Aquafeed*, 5(1).

MacMullan, C. N. (2007). Dairy CAFOs in California's San Joaquin Valley.

Mathewson, P. D., Evans, S., Byrnes, T., Joos, A., & Naidenko, O. V. (2020). Health and economic impact of nitrate pollution in drinking water: a Wisconsin case study. *Environmental Monitoring and Assessment*, 192(11), 1-18.

Mavhungu, A., Masindi, V., Foteinis, S., Mbaya, R., Tekere, M., Kortidis, I., & Chatzisymeon, E. (2020). Advocating circular economy in wastewater treatment: Struvite formation and drinking water reclamation from real municipal effluents. *Journal of Environmental Chemical Engineering*, 8(4), 103957.

Mayanglambam, B., & Neelam, S. S. (2020). Geochemistry and pollution status of surface sediments of Loktak Lake, Manipur, India. SN *Applied Sciences*, 2(12), 1-16.

Meilinger, V., & Monstadt, (2021) J. FROM THE SANITARY CITY TO THE CIRCULAR CITY? Technopolitics of Wastewater Restructuring in Los Angeles, California. *International Journal of Urban and Regional Research*.

McCarty, P. L., Bae, J., & Kim, J. (2011). Domestic wastewater treatment as a net energy producer–can this be achieved? 7100-7106

Mizuta, K., & Shimada, M. (2010). Benchmarking energy consumption in municipal wastewater treatment plants in Japan. *Water Science and Technology*, 62(10), 2256-2262.

Murtaza, G., Ghafoor, A., Qadir, M., Owens, G., Aziz, M. A., & Zia, M. H. (2010). Disposal and use of sewage on agricultural lands in Pakistan: A review. *Pedosphere*, 20(1), 23-34.

Nelles, M., Gruenes, J., & Morscheck, G. (2016). Waste management in Germany–development to a sustainable circular economy? *Procedia Environmental Sciences*, 35, 6-14.

Nicole, W. (2013). CAFOs and environmental justice: The case of North Carolina.

Orhon, D. (2015). Evolution of the activated sludge process: the first 50 years. *Journal of Chemical Technology & Biotechnology*, 90(4), 608-640.

Oron, G. (1990). Economic-Considerations in Waste-Water Treatment with Duckweed for Effluent and Nitrogen Renovation. *Research Journal of the Water Pollution Control Federation,* 62, 692–696.

Oron, G. (1994). Duckweed culture for wastewater renovation and biomass production. *Agricultural Water Management*, 26(1-2), 27–40.

Oron, G., Wildschut, L. R., & Porath, D. (1985). Wastewater recycling by duckweed for protein production and effluent renovation. *Water Science & Technology*, 17(4-5), 803-817.

Oron, G., Porath, D., & Wildschut, L. R. (1986). Wastewater treatment and renovation by different duckweed species. *Journal of Environmental Engineering*, 112(2), 247-263.

Oron, G., & Porath, D. (1987). Use of duckweed for wastewater treatment and recycling. In *Aquatic Plants for Water Treatment and Resource Recovery* (edited by K. R. Reddy and W. H. Smith). Magnolia Publishing Inc., Orlando, Fla. pp. 471-478. 1987.

Oron, G., Porath, D., & Jansen, H. (1987). Performance of the duckweed species *Lemna gibba* on municipal wastewater for effluent renovation and protein production. *Biotechnology and Bioengineering*, 29, 258–268.

Oron, G., Devegt, A., & Porath, D. (1988). Nitrogen removal and conversion by duckweed grown on wastewater. *Water Research*, 22(2), 179–184.
Owen, D. L. (2020). The Costs Involved. In Global Water Funding (pp. 145-187). Palgrave Macmillan, Cham.
Pagotto, M., & Halog, A. (2016). Towards a circular economy in Australian agri-food industry: an application of input-output oriented approaches for analyzing resource efficiency and competitiveness potential. *Journal of Industrial Ecology,* 20(5), 1176-1186.
Parts, C. (2019). Waste not want not: Chinese recyclable waste restrictions, their global impact, and potential US responses. *Chi. J. Int'l L.*, 20, 291.
Pescod, M. B., & Arar, A. (Eds.). (2013). Treatment and Use of Sewage Effluent for Irrigation: *Proceedings of the FAO Regional Seminar on the Treatment and Use of Sewage Effluent for Irrigation Held in Nicosia, Cyprus*, 7–9 October, 1985. Elsevier.
Phuong, N., Son, V., Bui, T., Tuan, N., & Wilder, M. (2003). Research, development and economics of giant freshwater prawn (*Macrobrachium rosenbergii*) culture in the Mekong river delta of Vietnam: a review of. *JIRCAS Working Report* (pp. 1–12).
Rahman, M. O., Hussain, A., & Basri, H. (2014). A critical review on wastepaper sorting techniques. *International journal of environmental science and technology*, 11(2), 551-564.
Rajeshkumar, S., Liu, Y., Zhang, X., Ravikumar, B., Bai, G., & Li, X. (2018). Studies on seasonal pollution of heavy metals in water, sediment, fish and oyster from the Meiliang Bay of Taihu Lake in China. *Chemosphere,* 191, 626-638.
Rejmánková, E. (1973). Seasonal changes in the growth rate of duckweed community *(Lemnetum gibbae). Folia Geobotanica et Phytotaxonomica*, 8(1), 1-13.
Rejmánková, E. (1979). The function of duckweeds in fish pond ecosystem.
Rejmankova, E. (1989). Aquatic Plant Control Research Program: Review of Senescence as an Important Factor Determining the Relationship Among Aquatic Plants, Their Epiphytes, and Pathogens. CALIFORNIA UNIV DAVIS DEPT OF BOTANY
Rejmankova, E., Blackwell, M., & Culley, D. D. (1986). Dynamics of fungal infection in duckweeds (Lemnaceae). *Veroff. Geobot. Inst. ETH, Stiftung Rubel, Zurich,* 87, 178-189.
Ring, I., 1997. Evolutionary strategies in environmental policy. *Ecol. Econ.* 23 (3), 237-250.
Robinson, D., & Singh, D. N. (2001). Alternative protein sources for laying hens. *A report for the Rural Industries Research and Development Corporation publication*, 144(1).
Rusoff, L. (1980). Duckweeds (Lemnaceae family): a potential source of protein and amino acids. *Journal of Agricultural and Food Chemistry*, 28, 848–850.
Rusoff, L. L., Gantt, D. T., Williams, D. M., & Gholson, J. H. (1977, January). Duckweed-Potential Feedstuff for Cattle. In *Journal of Dairy Science* (Vol. 60, pp. 161-161). 309 W CLARK ST, CHAMPAIGN, IL 61820: AMER DAIRY SCIENCE ASSOC.
Rusoff, L. L., Zeringue, S. P., Achacoso, A. S., & Culley, D. D. (1978, January). Feeding value of duckweed (an aquatic plant, family Lemnaceae) for ruminants. In *Journal of Dairy Science* (Vol. 61, pp. 186-186). 309 W CLARK ST, CHAMPAIGN, IL 61820: AMER DAIRY SCIENCE ASSOC.
Sharma, H. B., Vanapalli, K. R., Cheela, V. S., Ranjan, V. P., Jaglan, A. K., Dubey, B., ... & Bhattacharya, J. (2020). Challenges, opportunities, and innovations for effective solid waste management during and post COVID-19 pandemic. *Resources, Conservation and Recycling,* 162, 105052.
Shelef, G., Juanico, M., & Vikinsky, M. (1987). Reuse of stabilization pond effluent for agricultural irrigation in Israel. *Water science and technology*, 19(12), 299-305.
Sherman, L., Cantor, A., Milman, A., & Kiparsky, M. (2020). Examining the complex relationship between innovation and regulation through a survey of wastewater utility managers. *Journal of environmental management*, 260, 110025.
Shishir, T. A., Mahbub, N., & Kamal, N. E. (2019). Review on bioremediation: a tool to resurrect the polluted rivers. *Pollution,* 5(3), 555-568.
Shivayogimath, C. B., Kalburgi, P. B., Deshannavar, U. B., & Virupakshaiah, D. B. M. (2012). Water quality evaluation of river Ghataprabha, India. *Research Journal of Environment Sciences,* 1(1), 12-18.
Skillicorn, P., & Gilman R., (1985). *The Safety and Efficacy of Sewage Grown Duckweed as feed for broilers, layers and chicks;* A Report to the US Agency for International Development.
Skillicorn, P., Spira, W., & Journey, W. (1993). Duckweed Aquaculture: A new aquatic farming system for developing countries (p. 92). The World Bank
Skillicorn, P., and Torres, R.M. (2000) Kenaf: A new farmer-driven solution to Eastern Carolina's agricultural crisis. *The North Carolina Geographer*, 8, 67-74.
Skillicorn, P., & Torres, R.M. (2001). Hookerton, North Carolina: A mall community rescued by duckweed? *The North Carolina Geographer*, 9, 71-83.
Skillicorn Technologies Egypt, Holding Company for Water and Wastewater, Fayoum Governorate (2021). Koota Project MOU, Bilingual
Smith, A. L., Stadler, L. B., Cao, L., Love, N. G., Raskin, L., & Skerlos, S. J. (2014). Navigating wastewater energy recovery strategies: a life cycle comparison of anaerobic membrane bioreactor and conventional treatment systems with anaerobic digestion. *Environmental science & technology*, 48(10), 5972-5981.
Smol, M., Adam, C., & Preisner, M. (2020). Circular economy model framework in the European water and wastewater sector. *Journal of Material Cycles and Waste Management*, 1-16.
Stahel, W.R., 2010. *The Performance Economy*. Palgrave Macmillan.
Stensel, H. D., & Makinia, J. (2014). Activated sludge process development. *Activated sludge–100 years and counting*. Jenkins, D. and Wanner, J.(eds.). London: IWA Publishing, 33-47.

Stevenson, R., Evans, J.W., 2004. Editorial to: cutting across interests: cleaner production, the unified force of sustainable development. *J. Clean. Prod.* 12, 185-187.
STLTBCC, 2021. *STLTBCC C Form* submitted to the US Securities and Exchange Commission.
Su, B., Heshmati, A., Geng, Y., & Yu, X. (2013). A review of the circular economy in China: moving from rhetoric to implementation. *Journal of cleaner production,* 42, 215-227.
Tanimu, M. I., Ghazi, T. I. M., Harun, R. M., & Idris, A. (2014). Effect of carbon to nitrogen ratio of food waste on biogas methane production in a batch mesophilic anaerobic digester. *International journal of innovation, management and technology*, 5(2), 116.
Tchobanoglous, G., Burton, F. L., & Stensel, H. D. (1991). Wastewater engineering. *Management*, 7, 1-4.
The Prism Group (1996) *The Prism Group, Annual Report – 1996*.
Themelis, N. J., Castaldi, M. J., Bhatti, J., & Arsova, L. (2011). Energy and economic value of nonrecycled plastics (NRP) and municipal solid wastes (MSW) that are currently landfilled in the fifty states. *Earth Engineering Center, Columbia University, New York.*
Torres, R. M., Popke, E. J., & Hapke, H. M. (2006). The South's silent bargain: Rural restructuring, Latino labor and the ambiguities of migrant experience. Latinos in the New South: Transformations of place, 37-67.
Torres, R. M., Skillicorn, P., & Nelson, V. (2011). Community corporate joint ventures: An alternative model for pro-poor tourism development. *Tourism Planning & Development*, 8(3), 297-316.
Trica, C. L., Banacu, C. S., & Busu, M. (2019). Environmental factors and sustainability of the circular economy model at the European Union level. *Sustainability*, 11(4), 1114.
van der Schans, M. L., Harter, T., Leijnse, A., Mathews, M. C., & Meyer, R. D. (2009). Characterizing sources of nitrate leaching from an irrigated dairy farm in Merced County, California. *Journal of contaminant hydrology*, 110(1-2), 9-21.
Veenstra, S., van der Steen, P., & Gijzen, H. (2001). Natural wastewater treatment to stimulate the local economy. *Waterlines,* 20(1), 11-14.
UN Environment Programme (2019). *Could fast-growing lemna replace soy in animal feed?.* https://www.unep.org/news-and-stories/story/could-fast-growing-lemna-replace-soy-animal-feed
USEPA (2002) *Wastewater Technology Fact Sheet Sewers, Pressure.* https://www.epa.gov/sites/default/files/2015-06/documents/presewer.pdf
USEPA (2018) *Advancing Sustainable Materials Management: 2017 Fact Sheet*, https://www.epa.gov/sites/default/files/2019-11/documents/2017_facts_and_figures_fact_sheet_final.pdf
USEPA (2021) *National Overview: Facts and Figures on Materials, Wastes and Recycling,* https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials
Vollmer, I., Jenks, M. J., Roelands, M. C., White, R. J., van Harmelen, T., de Wild, P., ... & Weckhuysen, B. M. (2020). Beyond mechanical recycling: Giving new life to plastic waste. *Angewandte Chemie International Edition*, 59(36), 15402-15423.
Voulvoulis, N. (2018). Water reuse from a circular economy perspective and potential risks from an unregulated approach. *Current Opinion in Environmental Science & Health*, 2, 32-45.
Wang, X., Yang, G., Feng, Y., Ren, G., & Han, X. (2012). Optimizing feeding composition and carbon–nitrogen ratios for improved methane yield during anaerobic co-digestion of dairy, chicken manure and wheat straw. *Bioresource technology*, 120, 78-83.
Wang, Q., Jiang, G., Ye, L., & Yuan, Z. (2014). Enhancing methane production from waste activated sludge using combined free nitrous acid and heat pre-treatment. *Water research,* 63, 71-80.
Wang, H., Park, J. D., & Ren, Z. J. (2015). Practical energy harvesting for microbial fuel cells: a review. *Environmental science & technology*, 49(6), 3267-3277.
Wen, Z., Xie, Y., Chen, M., & Dinga, C. D. (2021). China's plastic import ban increases prospects of environmental impact mitigation of plastic waste trade flow worldwide. *Nature communications*, 12(1), 1-9.
Wildschut, L. R. (1984). *Introductory study on the performance of Lemnaceae on fresh municipal wastewater with emphasis on the growth of the Lemnaceae, the ammonium-removal from the wastewater*. LH.
Willett, D. (2005). Duckweed-based wastewater treatment systems: Design aspects and integrated reuse options for Queensland conditions. *Queensland Department of Primary Industries and Fisheries project report no. QI05019.*
Wolverton, B. C., McDonald, R. C., & Gordon, J. (1976). Water hyacinths and alligator weeds for final filtration of sewage. *NASA Technical Memorandum TM-X72724*, Washington DC.
Wong, S. C., & Law-Flood, A. (2011). *Tapping the energy potential of municipal wastewater treatment: anaerobic digestion and combined heat and power in Massachusetts*. Massachusetts Department of Environmental Protection.
Yadav, A., Yadav, P. K., & Shukla, D. N. (2013). Investigation of heavy metal status in soil and vegetables grown in urban area of Allahabad, Uttar Pradesh, India. *International Journal of Scientific and Research Publications*, 3(9), 1-7.
Yen, H. W., & Brune, D. E. (2007). Anaerobic co-digestion of algal sludge and waste paper to produce methane. *Bioresource technology*, 98(1), 130-134.
Yohannes, H., & Elias, E. (2017). Contamination of rivers and water reservoirs in and around Addis Ababa City and actions to combat it. *Environ Pollut Climate Change*, 1(116), 8.
Zessner, M., Lampert, C., Kroiss, H., & Lindtner, S. (2010). Cost comparison of wastewater treatment in Danubian countries. *Water Science and Technology,* 62(2), 223-230.
Zhang, X., & Liu, Y. (2021). Circular economy-driven ammonium recovery from municipal wastewater: State of the art, challenges and solutions forward. *Bioresource Technology*, 125231.
Zhang, X., & Liu, Y. (2022). Circular economy is game-changing municipal wastewater treatment technology towards energy and carbon neutrality. *Chemical Engineering Journal*, 429, 132114.

Instructions to Contributors for the Duckweed Forum

The Duckweed Forum (DF) is an electronic publication that is dedicated to serve the Duckweed Research and Applications community by disseminating pertinent information related to community standards, current and future events, as well as other commentaries that could benefit this field. As such, involvement of the community is essential and the DF can provide a convenient platform for members in the field to exchange ideas and observations. While we would invite everyone to contribute, we do have to establish clear guidelines for interested contributors to follow in order to standardize the workflow for their review and publication by the Duckweed Steering Committee members.

Contributions to DF must be written in English, although they may be submitted by authors from any country. Authors who are not native English speakers may appreciate assistance with grammar, vocabulary, and style when submitting papers to the DF.
DF is currently arranged in sections, which may be chosen by a prospective author(s) to contribute to: Main text, Opinion paper, Discussion corner, Useful methods, Student experiments, Student spotlight, Science meets art, and Cover photo(s). 1,000 words are suggested as the upper limit for each contribution, but can be extended on request to the Steering Committee if the reason for the waiver request is warranted.

Presubmissions

In addition to invitees by a Duckweed Steering Committee member, if you are considering submitting a contribution to DF but are unsure about the fit of your idea, please feel free to contact one of the members in the Duckweed Steering Committee in order to obtain feedback as to the appropriateness of the subject for DF. Please include a few sentences describing the overall topic that you are interested to present on, and why you think it is of interest to the general duckweed community. If you have the abstract or draft text prepared, please include it. The Duckweed Steering Committee will discuss the material in one of its meetings and the decision to formally invite submission will be given shortly afterwards.

Copyright and co-author consent

All listed authors must concur in the submission and the final version must be seen and approved by all authors of the contribution. As a public forum, we do not carry out any Copyright application. If you need to copyright your material, please do so beforehand.

Formatting requirements:

- A commonly used word processing program, such as Word, is highly recommended.

- Formatting requirements: 8.5-by-11-inch (or 22 cm-by-28 cm) paper size (standard US letter).
- Single-spaced text throughout.
- One-inch (or 2.5 cm) left and right, as well as top and bottom margins.
- 11-point Times New Roman font.
- Number all pages, including those with figures on the bottom and center of each page.

Title:

- Should be intelligible to DF readers who are not specialists in the field and should convey your essential points clearly.
- Should be short (no more than 150 characters including spaces) and informative.
- Should avoid acronyms or abbreviations aside from the most common biochemical abbreviations (e.g., ATP). Other acronyms or abbreviations should either:
    - be introduced in their full form (e.g., Visualization of Polarized Membrane Type 1 Matrix Metalloproteinase (MT1-MMP) Activity in Live Cells by Fluorescence Resonance Energy Transfer (FRET) Imaging); or
    - be clarified by use as a modifier of the appropriate noun (e.g., FOX1 transcription factor, ACC dopamine receptor).

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Image resolution and submission:

It is extremely important that figures be prepared with the proper resolution for publication in order to avoid inaccurate presentation of the data. The minimum acceptable resolution for all figures is 300 dpi. Excessive file compression can distort images, so files should be carefully checked after compression. Note that figures that contain both line art (such as graphs) and RGB/grayscale areas (such as photographs) are best prepared as EPS (vector) files with embedded TIFF images for the RGB/grayscale portions. The resolution of those embedded TIFF images should be at least 300 dpi. Original images should be submitted as a separate file to the text file. It would be helpful to insert the intended into the Word file as well, if desired, to indicate the location for it. The legend to the image/figure should be added at the end of the text file and labeled as "Legend to Figures".

Links for Further Reading

http://www.ruduckweed.org/ Rutgers Duckweed Stock Cooperative, New Brunswick, New Jersey State University. Prof. Dr. Eric Lam

http://www.InternationalLemnaAssociation.org/ Working to develop commercial applications for duckweed globally, Exec. Director, Tamra Fakhoorian

http://thecharmsofduckweed.org Comprehensive site on all things duckweed-related, By Dr. John Cross, maintained by Paul Fourounjian.

http://plants.ifas.ufl.edu/ University of Florida's Center for Aquatic & Invasive Plants.

Community Resources - Updated Table for Duckweed Collections in the Community

For information related to the location, collection size and contact email for duckweed collections in our community, please access the website of the RDSC (Rutgers Duckweed Stock Cooperative) under the heading "List of Worldwide Duckweed Collections". This Table will be updated as new entries for duckweed collections are being supplied to members of the International Steering Committee for Duckweed Research and Applications (ISCDRA). We also plan to publish the updated table in the first issue of each Duckweed Forum newsletter volume starting in 2021.

Note to the Reader

Know of someone who would like to receive their own copy of this newsletter? Would you like to offer ideas for future articles or have comments about this newsletter? Need to be added or removed from our contact list?

Please let us know via email to the Chair of ISCDRA, Prof. Eric Lam: ericL89@hotmail.com