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Perspective

Integrating Arid Areas in the Global Bioeconomy: Opportunities and Challenges toward Sustainable Biomass Generation and Management

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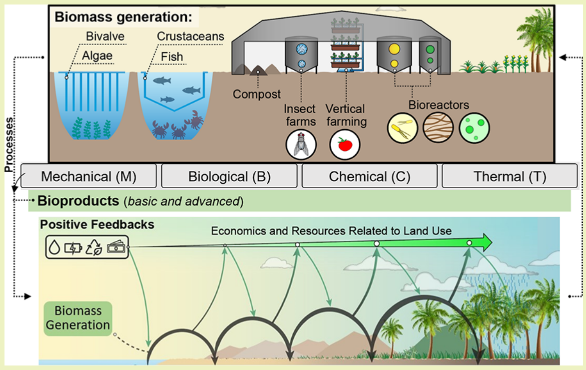

ABSTRACT: Biosystems and bioprocesses are typically not connected to arid areas, where the produced biomass and its availability are low. There is however a large potential for arid areas to become major bioeconomical actors via more localized biomass generation strategies. Indoor farming, bioengineering, and aquaculture have a great potential to be at the center of this transition. They are expected to address important challenges associated with food and (bio)materials supply and, ultimately, to climate and environment. Specifically, the utilization of the by- and coproducts deriving from these strategies could synergistically connect into a range of circular processes toward sustainable bio-products' supply and the greening of arid areas. These topics are at the center of this perspective, where emerging biomass generation and management strategies in arid areas are introduced. The potential positive feedback loops between their coproducts are then put in relation with the development of more diverse and thriving biosystems as well as the generation of a range of bioproducts. These approaches are contextualized with the current and alternative energy sectors and water treatments processes, which have well-established economical portfolios across most arid areas. The mapping of innovative bioeconomical actors in arid areas and their synergistic interactions, as put forward herein aims to intensify research efforts toward a fully integrated and global sustainable bioeconomy.

KEYWORDS: *Biorefinery, Desertification, Biomass, Biomaterials, Sustainable processes, Green engineering, Valorization, Upcycling*

1. INTRODUCTION

Arid and semiarid areas, severely lacking arable land, cover an increasingly larger fraction of the world, with current coverage approximated at 50 million km^2.[1] In Asia and Africa, where population increases are still the most significant, arid and semiarid areas represent ca. 60% of that total area.[2] Significant efforts have been made toward limiting further spread of such arid areas, principally via forestland restoration (e.g., the great green wall) and by mitigating the impact of aeolian spread of deserts, e.g., via checkerboard arrangement of straws, respectively.[3,4] Although desertified regions contribute to global nutrient cycling[5] and are auspicious to solar[6] and thermal[7] energy generation, they are mostly inhabitable and a lower economic value is generated from land-use. Desertification is currently expected to intensify significantly in the near future as a result of climate change and soil degradation.[8] Conservative estimates point to a 2.6 million km^2 increase of arid lands by the year 2100, affecting over 110 million people.[9] Therefore, it is critical to develop innovative synergies between soil remediation strategies, local economic benefits, and long-term sustainability regarding both land and individual's health.

One of the more obvious actors toward such an endeavor is the bioeconomy, where food supply, agro-industrial complexes, and associated byproducts—i.e., biobased wastes—can be efficiently processed and implemented to simultaneously increase food security and reclaim arid soils. Beyond economical valorization of both land and biowastes, there are other significant benefits from increasing localized production of biomass that include food security, cooling effects, carbon sequestration, labor demand increase, control of pollutants, or mental well-being to name a few.[10,11]

Herein, we put in perspective the main actors and their potential synergies toward the unwinding of the full potential of the bioeconomy in arid areas. A focus is put on bioprocesses and biosystems as key engines to connect the water, land, food,

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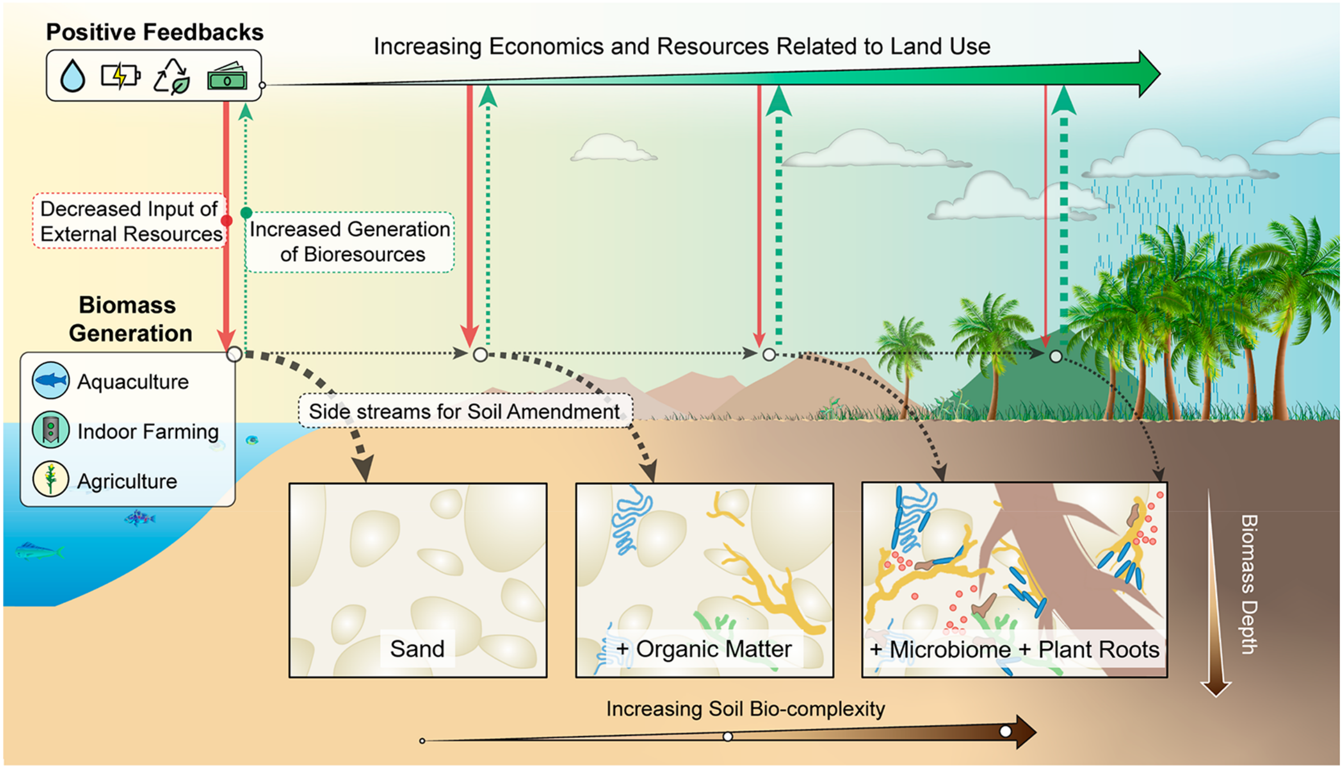

Figure 1. Top, potential for increase biomass generation illustrated through three commonly explored strategies (aquaculture, indoor farming, and outdoor cropping) and associated benefits. Center, the by-/coproducts of bioprocesses and biosystems in arid areas further generate other biobased endeavors, e.g., via a more complex and deeper biome in soil (black arrows pointing to the soil) but also by interactions between different biomass generation strategies (green dashed arrows pointing to the positive feedbacks). Bottom, example of biocomplexity as a function of the soils components and of each stage of soil's developments. When available, inland and coastal marine bodies can be considered for such improvements.

energy, and material needs of societies in these climatically challenging areas. These challenges, associated with coastal, inland, or even land-locked, arid and semiarid areas, will be discussed as associated with the range of soils—from completely desertic to biomass-rich. Thereafter, the potential synergies and positive feedback loops in terms of biomass generation and uses within the specific boundaries of the various geographic areas are put forward. The biomass generation strategies that can be efficiently implemented in arid areas and their impact are introduced as engines of these green feedback loops. These include principally aquacultures, framed within the blue-economy as a subset of the bioeconomy and indoor activities including also vertical farming and biotechnological endeavors. The impact of these endeavors to valorize unexploited resources and engage arid land toward a global bioeconomy is linked to a reflection on the critical role of sustainable energy use, water generation, and valorization. Finally, we provide an outlook on the global impact of such an emerging "arid" bioeconomy and put forward key steps toward accelerating its implementation. Accordingly, we expect that the perspectives herein provided can pave the way toward fully engaging researchers and engineers, public and private institutions, as well as policymakers toward the challenging yet pivotal endeavor of expanding the emerging bioeconomy in arid areas.

2. CONVENTIONAL BIOMASS GENERATION AND SOILS IN THE CONTEXT OF ARID AREAS

One of the most pressing challenges for inexpensive and abundant biomass generation in arid areas is associated with the poor quality of soils. A hierarchy of lands and their soils can be observed when considering their potential to be auspicious to biomass growth, to maintain sequestered carbon, and to sustain biodiversity.[12] At one end of the spectrum, hyper arid deserts present a scattered microbial diversity with no vegetation and limited animal life. On the other end, forestland represents the peak potential for a maximized soil health, high microbial density in soil, an abundant biodiversity including nearly all land-based lifeforms spanning also nematodes to large animals, and a large pool of near-permanently sequestered carbon. As some of the richest biological areas on earth, forests harbor most of the earth's terrestrial biodiversity, as they contain 80% of amphibian species, 75% of bird species, and 68% of the world's mammal species.[13] Intermediate land types such as grasslands are found between biomass-abundant forests and biomass-poor desertified areas. Altogether, these soils can be ranked from purely mineral soil (sand), to organic matter containing mineral soil typically including a sparse microbiome, followed by a fully developed microbiome, and a microbiome interacting with plants' root systems (Figure 1, Bottom).

When considering desertic areas, the sparse and scarcely populated microbiome consists principally of thermophiles, which are typically not photosynthetic.[14] Thereafter, small organic molecules present in soil can enhance the soil's properties by contributing to solubilization of metallic micronutrients and by improving the mechanics of soil.[15,16] In richer soils, having extended vegetation with a root system, rhizospheric synergies between microbiome and roots are

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ACS Sustainable Chem. Eng. 2023, 11, 12177−12193

Table 1. Summary of Processes Associated with Co-products Valorization, Basic and Advanced Bioproducts That Can Be Obtained from Biomass, and Synergies between Biomass Generating Actors[a]

Processes: * (used to yield basic or advanced products)

Physical	Biological	Chemical	Thermal
1. Comminution (crushing, shredding, sawdust, coarse milling, etc.) 2. Fibrillation (mechanical pulping, high pressure homogenizer, etc.) 3. Ball-milling 4. Membrane 5. Sorbents	1. Enzymatic 2. Solid Fermentation 3. Liquid Fermentation 4. Fungal growth	1. Pulping (e.g. Kraft cooking) 2. Acid-base depolymerization 3. Catalyst based depolymerization 4. Chemical functionalization/derivatization 5. Dissolution-regeneration 6. Solvent extraction 7. Ozonation	1. Pyrolysis 2. Gasification 3. Combustion 4. Hydrothermal (e.g. steam explosion)

Basic products: * (generated from the fractionation of the raw biomass)

Aquaculture (A)	Indoor (I)	Outdoor (O)
Pure fractions: A1. Chitin* A2. Collagen A3. Alginate A4. Carrageenan A5. Agarose A6. Hyaluronic acid A7. Minerals* A8. Lipids* **Mixed fractions (co-products):** A9. Waste water A10. Skins (collagen + fat) A11. Shells A12. Algae pulp	**Pure fractions:** I1. Proteins* I2. Chitin* I3. Lipids* I4. Lignin* I5. Hemicellulose* I6. Cellulose* I7. Carotenoids* I8. Methane I9. Minerals* I10. Tannins* **Mixed fractions (co-products):** I11. Waste water from fermentation I12. Waste water from vertical farming I13. Frass I14. Insect molts and residues • minerals, lipids, proteins, polysaccharides I15. Pulp I16. Plant parts (stalk, leaf, roots)* I17. Compost I18. Chips and sawdust*	**Pure fractions:** O1. Lignin* O2. Hemicellulose* O3. Cellulose* O4. Carotenoids* O5. Tannins* O6. Proteins* O7. Lipids* **Mixed fractions (co-products):** O8. Pulp O9. Plant parts (stalk, leaf, roots)* O10. Chips and sawdust*

Advanced products (AP): * (generated from the processing of the raw biomass or their basic products)

Carbon materials AP1. Activated carbon AP2. Biochar AP3. Graphite AP4. Graphene **Nanomaterials** AP5.Cellulosics • nanocrystals / nanofibers / regenerated AP6. Chitins	• nanocrystals / nanofibers / chitosan AP7. Catalysts AP8. Enzymes AP9. Functionalized pure fractions **Bulk materials** AP10. Textiles AP11. Films and Coatings AP12. Adhesives AP13. Delivery systems	AP14. Biomedical materials AP15. Membranes **Chemicals** AP16. Chemical precursors **Energy** AP17. Biofuels AP18. Syngas AP19. Hydrogen

Synergies: * (Products reutilization into enhancing biomass generation in arid areas, indices are referring to above products)

Aquaculture	Indoor	Outdoor
Energy = I8, **AP17-19** Animal feed = A1-12, I1-7, I14-16, O1-9 Water purification = **AP1, AP15**	Energy = I8, **AP17-19** Fertilizers = A9, A11, A12, I11-18, O8-10 Mulching materials = I15-18, O8-10 Soil amendment = A1, A9, A11, A12, I10, I15-18, O5, O8-10, **AP2, AP6** Microbial growth medium reagents = Sugars, nitrogen sources from wastewaters, etc.	Energy = I8, **AP17-19** Fertilizers = A9, A11, A12, I11-18, O8-10 Mulching materials = lignocellulosics Soil amendment = A1, A9, A11, A12, I10, I15-18, O5, O8-10, **AP2, AP6**

[a]Basic products refer to products that are readily obtained without severe treatments while advanced products indicate that multiple-steps or severe processes are required. Note that the distinction can be blurry for certain compounds. In the "Synergies" row, the bioproducts used are referenced based on the nomenclature in the corresponding basic and advanced products. A simplified heuristic is provided in Figure 2.

critical to nutrient cycling and to organic matter generation, which is further enriched in the case of woody vegetation.[12,17]

Currently, agriculture in arid areas requires increased quantities of nutritional supplements, imported soil, and processed water for irrigation purposes, which increase costs and negatively affect the environment. The amount of water available in the crop rooting zone is a primary limiting factor for crop-yield stabilization. This includes rainwater as well as freshwater pools from which to draw. The intense solar radiation, the exposure to dry air or winds, water runoff events, water deep percolation, and evapotranspiration result in a poor utilization of water resources by crops, with estimates of 30–60% water being lost in croplands and not directly used by crops to grow.[18,19] Exceptional drought events, a likely condition in arid or semiarid areas, increase the probability of crop yield losses, with possible losses exceeding 70% for soybean and maize, 68% for wheat, and 64% for rice (study limited to the 10 largest crop producing countries).[20]

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In spite of these handicaps, arid and semiarid climates have the potential benefit of shortening the total growing period of certain crops such as wheat or barley, where day length and temperature requirements are key factors. In general, crop development speeds up as temperatures increase from colder to milder temperatures. For example, average spring wheat maturity times are shorter in India (115 days) or North Africa and West Asia (168 days) in comparison with Central and Northern Europe (176 days) or Canada (195 days). As most of the cereal crops have estimated optimum growing temperatures in the 25 to 31 °C (barley at 25−31 °C, 30 °C for maize, 34 °C for millet, or 25−31 °C for oat),[21] arid and semiarid climates present a good potential for bioeconomy provided adequate irrigation systems are developed.

3. BIOECONOMY-DRIVEN POSITIVE FEEDBACK LOOPS

3.1. Overview of the Potential of an Expanded Bioeconomy in Arid Areas. When considering these challenges, beyond conventional outdoor cropping strategies, all alternative, i.e., engineered biomass producing strategies generate a significant fraction of byproducts that cannot be considered for consumption (e.g., up to 90% lignocellulosic wastes in fruits and vegetables[22] in the case of indoor farming) but can be used, circulated, and valorized across a wide range of bioeconomically driven strategies (Figure 1, Top). Herein, it is important to distinguish between organic wastes, byproducts, and coproducts. In a circular economy all, or most, "wastes" are considered as coproducts that are produced along the main product.[23] We hereafter refer holistically to these streams as coproducts, as a byproduct may eventually be converted in a coproduct with further developments. These by-/coproduct valorization strategies can also support outdoor cropping activities but also synergize with nonbiomass generating industries. A representative example is found in the steel-making industry that emits considerable amount of CO_2 into the atmosphere but also generates steel slag (∼10% of produced steel), which contains a wide range of micronutrients necessary to fermentation and soil revitalization.[24] Steel slag contains a wide range of micronutrients necessary to fermentation and soil revitalization. In particular, CaO, SiO_2, MgO, FeO, and P_2O_5 from steel slag can be used as fertilizers. These mineral oxides are key micronutrients to plants and they can also participate as carbon capture matrices by carbonation, which could also further improve the growth rate and yields of crops.[24−27] Therefore, valorization of slag toward increase biomass growth, and thus carbon capture in biomass, as well as carbon biofixation in soils represent an opportunity to synergistically close the loop and contribute to the decarbonization of the steel industry.

The main positive feedback loop for arid areas is associated with the use of generated biomass toward improving soils quality for higher yields and expansion of green lands, which itself will result in additional biomass generation (Figure 1, Center). Typically, good soil mechanics, water retention, and organic content are sought toward remediating arid soils. Indeed, the requirements to a rich microbiome in soil, necessary to a prolific vegetation, are a rich organic matter content that also promotes hygroscopicity of the soil. For example, several approaches have been proposed to amend soil with poor mechanics, i.e., where soil particles do not show cohesive behavior. The high propensity of desertic sand to form aerosol and its low hygroscopicity leads to further desertification. As a side note, desert dust is also regarded as a risk factor for inflammatory and allergic lung diseases, enhancing the toxicity of such aerosols in urban environments.[28] Such low soil cohesiveness can be efficiently remediated by organic amendments such as natural lignocellulosic polymers that concomitantly introduce nutrients to promote microbiome growth, which in turn fosters grass and forestland development.[29,30] Adequate soil and vegetation management is thereafter key to develop and sustain a high biodiversity.[31] As an important feedback loop, nutrient cycling between the biomass generation strategies is also of pivotal relevance, alongside their potential to generate various bioproducts (Table 1).

3.2. Biomass Management: Upcycling via Sustainable Chemistry and Engineering. There are several opportunities for biobased coproducts valorization in arid areas. These include staple and advanced materials (i.e., bioproducts), organic amendments that include nutrient-valorization streams and energy (Table 1). For each, the biomass available can be processed using combinations of a wide range of established routes that include physical, chemical, biological (e.g., enzymatic or microbial), and thermal processes (Table 1, Processes). This results in a wide range of established, emerging, and currently explored streams to obtain macroscaled, colloidal, polymeric, or molecular compounds (Table 1, Basic and Advanced Products). Ideally, valorization strategies should aim to exploit each scale in sequence. Through the cascade cycling approach, where less process intense streams result in compounds that are later on (re)valorized through more process intense strategies. The wood industry can provide a good example of this: round wood is first used, then its chips (e.g., particle board), then pulp, its polymeric compounds (e.g., cellulosic polymers that can be used toward textiles and other materials), and finally energy (e.g., hydrogen, biodiesel, bioethanol, methane, pyrolysis oil, etc.), biochar, and chemical precursors that can be obtained at the very end of the cycle—after all valorization streams have been exploited. For each of the steps delineated above, a wider range of compounds can be obtained than those used as examples above, including for example nanomaterials and lignin derivatives.[32] A wide range of sustainable engineers and scientists with expertise in these disciplines is required to optimally use those streams in arid areas using appropriate sustainability considerations.

Organic amendments, which are self-synergistic aspects of a bioeconomy, have been thoroughly explored using pulp and paper mill effluents and wastes,[33] peat,[16] and composting coproducts.[29,34] Other organic amendments have been explored.[30,31,35] For instance, lignocellulosics and small molecules such as humic substances enable a better cohesion to soil as well as a high water retention.[16,36] Mulching materials obtained from coproducts are another example of synergies between the different biomass generation sectors.[22] Other more commonly known examples include fertilizers from coproducts and their use as nutrients for microbial growth. The examples described above are not all relevant to arid areas, but may serve as a blueprint for the connection between biomass generation, valorization, and its use toward soil enrichment. Thereafter, it is also important to use locally produced biomass as environmental and financial costs of transportation will remain an important aspect of the positive feedback loops highlighted, where maximizing localized

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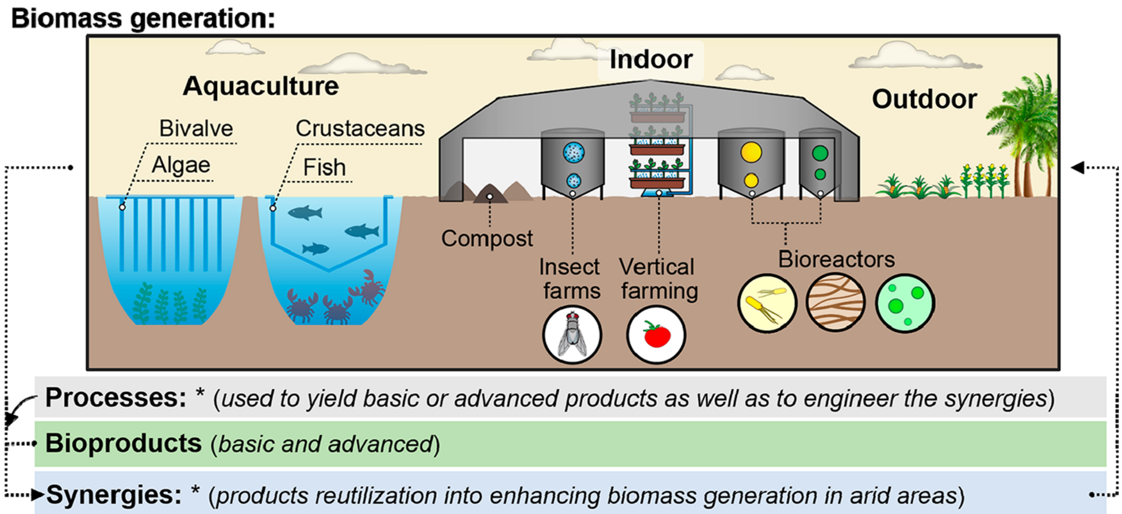

Figure 2. Top, main biomass generation strategies in challenging areas including aquaculture in ponds or open sea, indoor activities, and outdoor farming. Bottom, the relationship between these actors and what is presented in Table 1 is heuristically described.

exchanges between the different actors generating and using biomass will be key.

One of the better known streams is associated with lignocellulosics coproducts that present a tremendous potential to form advanced materials. In the past, such bioeconomical endeavors have comprised: (i) pulping efforts[37,38] toward new classes of pulp materials that include composites,[39] (ii) regeneration of dissolved cellulose, which has seen tremendous progresses recently, for example toward sustainable textiles—some of which can directly capture up to 6.5 of CO_2 per gram of cellulose through the limestone cycle,[40−42] and (iii) new classes of advanced materials proposed from synthetic proteins and advanced lignocellulosics' use with potential to outperform many synthetic systems.[43−45] Synthetic biology has now enabled a vast range of engineered materials, which could potentially be extended to a wide variety of functional and mechanically resilient materials with tethered properties.[46] In addition, biomacromolecules obtained by mechanical and solvent-based top-down deconstruction (e.g., lignin, cellulose, chitin, pectin, etc.) are now finding use in advanced applications including flexible electronics, energy storage, medical devices, etc.[32,47,48]

A list of some of the most relevant processes, basic products readily obtained and advanced products with a high value that can be obtained by emerging biomass generation strategies are highlighted in Table 1. In addition, synergies between the biomass generating actors in arid areas are put forward in Table 1 below. These connections have been covered in a range of reviews indicated in this section. Further synergies are discussed in the following section.

4. EMERGING BIOMASS GENERATION STRATEGIES

Biomass generation strategies in arid environments comprise a significant fraction of unconventional farming practices. We classify the main strategies, schematically summarized in Figure 2, into three main categories: (1) aquaculture; (2) indoor or controlled environment approaches including vertical farming, composting, and bioreactors; and (3) land-based farming, e.g., conventional cropping. (4) A discussion on food waste as an indirect biomass generation source through imbalanced imports and exports is put forward as a potential tool to support the growth of (1−3). This classification and the number of developments highlighted in each sections are comprehensive but not exhaustive and the list is very likely to be expanded in coming years as associated with the current focus in arid areas to increase food security.

4.1. Aquaculture: Main Driver of the Blue Economy.

Aquaculture represents a rich source of biomass that can generate both food and organic matter, even in arid areas (Figure 2, Left). Since most of the desertic, arid, and semiarid areas are connected to seashores, aquaculture represents one of the most promising system toward the generation of biomass for such challenging regions. Available products include macro/microalgae, crustaceans, bivalves, and fishes.[49−51] Furthermore, establishment of aquacultural primary production (algae and plankton) in arid seawater regions would utilize the natural advantages of arid areas, namely the long hours of sunshine and long growing seasons. In addition, warmer temperatures generally maximize growth, including that of planktons, which increase the ability of carbon fixation by the sea when compared to colder waters. The use of seawater can also result in 10-fold increase in productivity in fish farming when compared to fish farms that operate on food pellets manufactured from natural fishing bycatch.[52] The sea areas surrounding arid regions, such as the Arabian peninsula, were also estimated to be highly suitable for marine seaweed production.[53] Importantly, as aquacultural biomass becomes available for use, so do opportunities and synergies for coproducts that can support the development of more advanced bioeconomical operations,[54] and land-based agriculture.[55,56]

Aquaculture is considered as the worlds fastest growing food industry.[57] Global aquatic food production reached its all-time record in 2020, with 213 million tons total production.[58] The contribution of aquaculture to the total fisheries (aquatic species caught for commercial, industrial, recreational, and subsistence purposes, excluding algae) has steadily increased over the last years to reach a share of 49.2% in 2020, compared to only 13.4% that represented in 1990.[58] According to "The State of World Fisheries and Aquaculture 2022" report,[58] the economic worth of aquaculture has steadily increased in the last 30 years, rising from the 19.7% of the total production in 1990 to the 49% of the total catches by 2020 (87.5 million tons). Location wise, aquacultural production is more

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widespread inland rather than in marine waters. In inland waters, 83% of the production comes from aquaculture, whereas this value is only 30% for marine production. However, the total marine production represents the larger share of production (63%, 112 million tons), with the rest of the production situated in inland waters (37%, 66 million tons). This division of global annual aquatic production is illustrated in Figure 3. These numbers highlight the potential

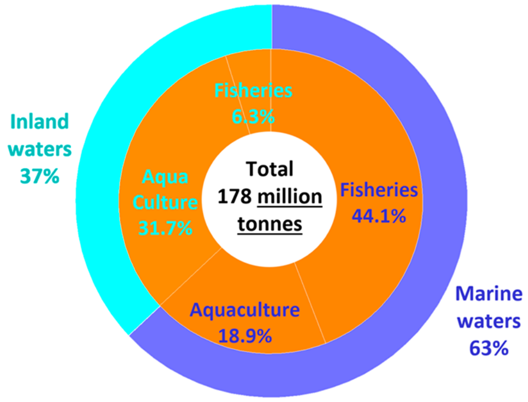

Figure 3. Total catches distribution regarding marine vs inland waters and fisheries vs aquaculture.

of aquaculture toward blue transformation, so the contribution of aquatic (marine and inland) food systems to food security, nutrition, and affordable healthy diets is secured and maximized while adhering to the Sustainable Development Goals.

Even in arid areas, upon the combination of protection against strong solar radiations and recirculation systems, productions up to 50 kg fish per m^3 of water can be achieved.[59] The exploitation of saline water sources, which are not fit for human consumption or agriculture, would allow for such arid regions to become producers of salt-tolerant organisms. Examples include the *Artemia salina* brine shrimp, the unicellular *Dunaliella salina* green algae, the Spirulina cyanobacteria, the Japanese meagre (*Argyrosomus japonicus*), the rainbow trout (*Oncorynchus mykiss*), the Asian seabass (*Lates calcarifer*), or Indian white prawn (*Penaeus indicus*).[1] Tolerance to large temperature fluctuations and fast growing species (5−8 months to reach market size) are particularly welcome to face the water limited conditions typical of arid areas. A representative example highlighting the increasing relevance of aquaculture over captures fisheries is represented by Saudi Arabia. With a continental coastline of 2640 km, the captures have been kept constant at nearly 60 000 tons from 2005 to 2020. On the contrary, as seen in Figure 4a, aquaculture production has sharply increased from 14.375 tons in 2005, to 99.906 tons in 2020 (FAO Fisheries and Aquaculture data). Similarly to the crops, the total fish and fishery product imports notably exceed the exports (Figure 4b). The same trend can be observed in the Middle East and North Africa (MENA) region, with total aquacultural production rising steadily from 422 tons in 2000 to 2.27 ktons in 2021 (FAO Fisheries and Aquaculture data), i.e., over a 5 fold increase.

Aquacultures may also be integrated with conventional agriculture for the benefit of both systems.[60] For example, microalgae are typically part of a healthy soil microbiome; thus, justifying their use for conventional agricultural practices.[61]

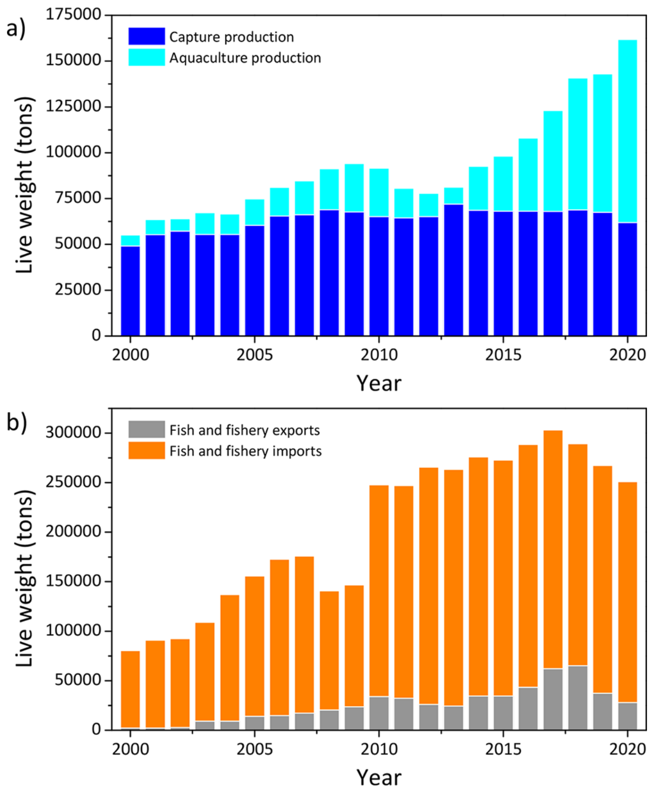

Figure 4. (a) Total capture and aquaculture production and (b) fish and fishery export and imports in Saudi Arabia during the 2000−2020 period according to "FAO Fisheries and Aquaculture data".

From an engineering perspective, this would synergistically integrate the formation of artificial and thriving ecosystems, with both economic and environmental value.

However, not all aquaculture developments are considered environmentally sustainable. Under certain scenarios aquacultural practices destroy local ecosystems such as mangrove forests to enable cultivation lands. This is particularly striking considering the critical role of mangrove forest to arid regions coastlines' biodiversity.[62] The limits of fish farming, its social and environmental impacts and the future risks should be carefully evaluated to ensure a sustainable growth of aquaculture in the mid- to long-term by involving all of the key actors.[63,64] Even in Asia, where ambitious government policies have created massive growth in aquaculture frameworks, new challenges have emerged regarding unregulated development, weak enforcement of regulation, and unsustainable intensification of aquaculture.[58] To guide the development of aquaculture toward a more sustainable direction, several concepts, such as "Ecosystem Approach to Aquaculture" (EAA) and more recently the "blue growth agenda", have been developed by the Food and Agriculture Organization (FAO) and aquaculture experts. Some success has been achieved, as the spread of these concepts within the aquaculture sector has triggered improvements in ecological sustainability within the industry. Unfortunately policymakers have shied away from the more complex institutional issues surrounding aquaculture.[65] One of the most relevant modern and sustainable practice to address these shortcomings is the integrated and multitrophic aquaculture, where a single aquacultural facility will cultivate several species of aquatic organisms. Interactions are set in a constructive manner to increase overall productivity; for example, combining fish

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cultivation, shrimp cultivation, and seaweed farming allows the seaweed to thrive from the nutrients provided by fish and shrimp waste. Furthermore, with controlled proliferation of each species, the shrimp and herbivorous fish can feed on the seaweed, while carnivorous fish can feed on either shrimps or fish.[66−68] Finally, as the seaweed cultivation absorbs excess nutrients from the facility, the volumes and toxicity of wastewaters produced by aquaculture are reduced, and nearby waters remain more habitable for wild aquatic organisms. As such, the integrated multitrophic aquaculture concept has contributed to reduce the public opposition toward intensive aquaculture.[69]

4.2. Indoor Biomass Generation. Novel solutions to increase agricultural productivity are needed to overcome the current hard limits imposed by "conventional" farming of plants as associated with intensive agriculture resulting from the "green revolution".[70] The culgrowth of biomass under controlled environmental conditions addresses some of these shortcomings. For example, indoor farming of plants is highly relevant to arid areas. The long experience in infrastructural development in terms of climate-controlled buildings can exploit these indoor farming approaches efficiently. These novel cultivation facilities are essentially modern high-tech greenhouses, referred to in modern scientific literature as indoor farms, vertical farms, vfarms, zfarms, controlled environment agriculture (CEA), and plant factories. These modern greenhouses could be seen as a solution to the limits of more conventional agriculture, as they require considerably less water, are much more effective in fertilizer utilization, can be utilized in continuous production, can be built in almost any location and offer massive increases in both plant yield and productivity.[71]

In broader terms, indoor biomass generation is mainly associated with (i) hydroponics, e.g., aeroponics and vertical indoor farming, and (ii) fermentation approaches in bioreactors that include compost generation and processing, and power-to-X approaches (transforming power to commodities, Figure 2, Center). When considering indoor farming, minimal quantities of soil may be imported and used with fertilizers. However, the use of carbon dioxide to accelerate the growth of crops represent an interesting route to utilize CO_2 emissions from other industries.[72,73] For example, stored CO_2 is a coproduct of hydrogen production, fossil fuel power plants, and other large-scaled chemical engineering endeavors that can be used for gaseous CO_2 enrichment of indoor farming activities. The use of green energy for vertical farming is critical, which further warrant its use in arid areas as solar energy is readily available. When considering the emitted CO_2 per ton of lettuce harvested, vertical farming powered by renewable energies shows a footprint of ∼170 kg CO_2, which is well below the 575 and 540 kg CO_2 emitted by conventional green house agriculture and open field agriculture, respectively.[74] Besides, vertical farming requires 8% of the standard water consumption used to irrigate field crops. Furthermore, indoor farming can be coupled with aquaculture toward aquaponics, where wastewater from fish production is remediated and used as a nutrient for plant growth.[73] However, current estimates point that the carbon footprint associated with energy consumption is ten times larger in conventional vertical farming than in open field agriculture (5744 kg CO_2). These numbers highlight the strong association between indoor farming and the energy sector. Aeroponics is a special class of indoor farming where root systems are allowed to proliferate in moist air without the need of soil.[75] For example, aeroponics farms in Jordan are growing crops using 90% less water than conventional farms.[76]

Regarding the challenges toward sustainable indoor farming, one of the major environmental hazards is associated with the high requirement for human-made fertilizers, mainly containing nitrogen, phosphate or potassium macronutrients (such as ammonium nitrate). The production of these fertilizers generate coproducts and their use increase soils' acidity and contribute to eutrophication.[77] Furthermore, when fertilizers run into waterways, algae blooms responsible of oxygen depletion from water can be generated. Other issues are the high upfront capital costs to set up indoor farms as well as their dependence on energy, which can substantially reduce their sustainability and financial viability. However, indoor farming approaches that reuse the water, minimize energy consumption, and eliminate soil as a growth medium can reduce the contribution of agriculture in destabilizing earth's biological systems at the planetary scale.[78] This can be achieved using an optimized artificial lighting (with a precise mix of beneficial red, blue, and green light) to eliminate the effects of fluctuating solar light, temperature/humidity controls, and on-demand irrigation to deliver the exact nutrient balance during plant life cycle. Modern technologies are expected to automatically optimally use algae ponds with indoor farming and aquaculture activities.[79]

An interesting approach for the indoor generation of biomass is associated with the processing of readily available bioresources. For instance, food wastes, societal biowastes such as excreta, and municipal trimmings can be efficiently composted to generate nutrient rich soil or processed by fermentation to obtain proteins, fatty acids, certain carbohydrates, and some specialty chemicals.[80] Processing food-wastes in larval farms toward, for instance, black soldier fly composting represents another approach to valorize such wastes.[81,82] Similarly, mushroom farms can also use lignocellulosic-rich waste as a growth media for the production of, e.g., food, enzymes, materials, and pharmaceutics.[83] Power-to-protein is another attractive approach for the generation of biomass by using the redox potential, e.g., of hydrogen and captured carbon as nutrients for protein-producing microbes, thus coupling electrochemistry with biotechnology.[84] Lastly, captured CO_2 from air or industrial sources can be used in emerging processes toward the generation of starch by using enzymatic complexes.[85]

All of these indoor biomass generation strategies are expected to be integrated in bioeconomical efforts in arid areas. These strategies can readily participate in nutrient cycling within the current infrastructures with minimal costs, while promoting the overall increase of regional biomass generation.[86,87]

4.3. Outdoor Crops. Conventional, outdoor crop farming is the most challenging biomass generation strategies in desertic and arid areas (Figure 2, Right) requiring the highest watering and nutrients supplementation. To alleviate these requirements, C_4 photosynthetic vegetation that conserves water as well as genetic engineering may make the crops more resilient to drought and heat.[88] For instance, corn and especially date palm trees, which are successfully farmed across near-desertic areas such as the Arabic gulf, use C_4 photosynthesis. Also, crassulacean acid metabolism, which is used for instance by pineapple or agave, is the best fit to highly arid areas, although these crops are still not widely

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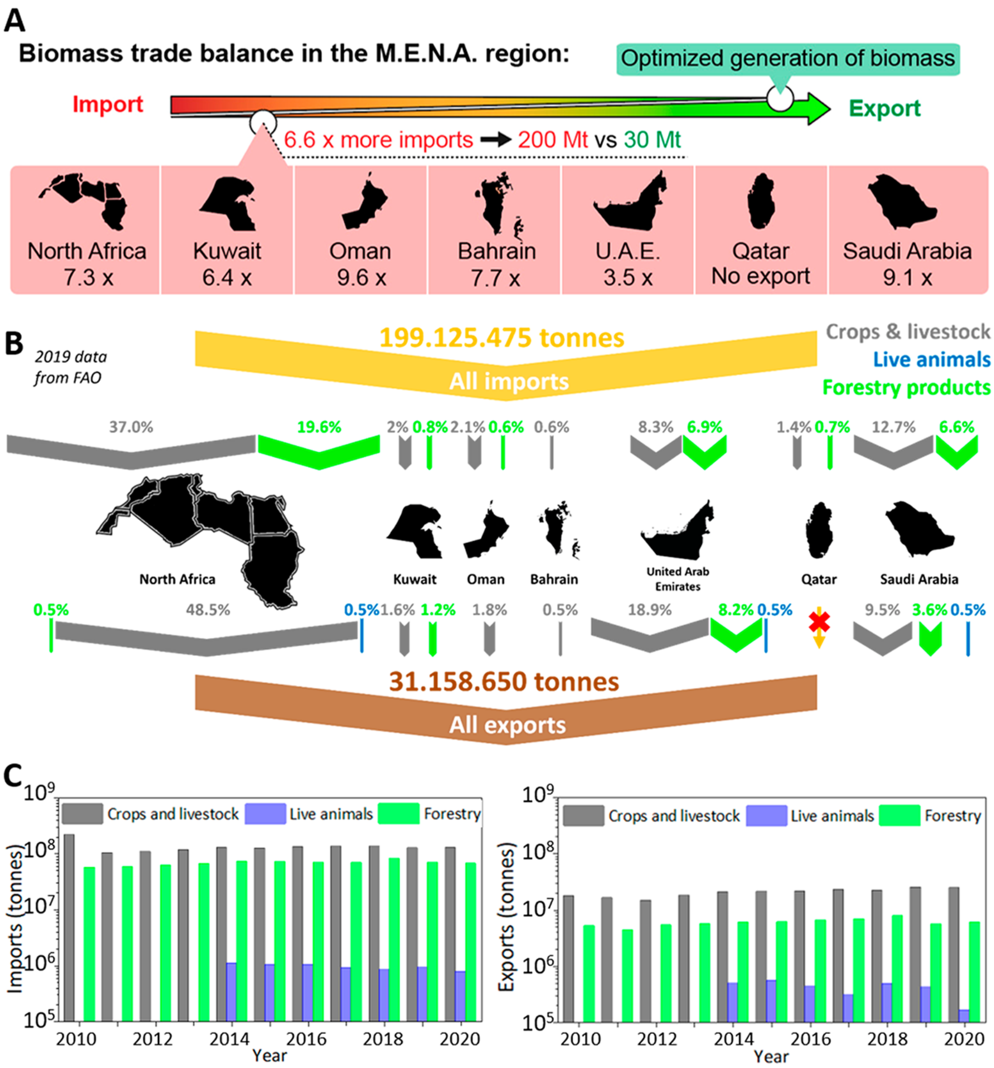

Figure 5. A, Relation between import of biomass and export in MENA countries, highlighting that developing a bioeconomy would improve the ratio and integrate these countries into the global bioeconomy. B, Total imports and exports in 2020 in the MENA region, with the contribution of each region in percentage toward the total for either import or export. For instance, 56.6% of the total imports 49.5% of the total exports were from North Africa. The red cross indicates that there were no significant exports from Qatar. The relative contribution of "Crops & livestock", "Live animals" and "Forestry products" to the total imports (top) and total exports (bottom) is indicated numerically and graphically (as a function of arrow width). C, Description of yearly imports (left) and exports (right) between 2010 and 2020 in the MENA countries. For B and C, incomplete country metadata may be a source of errors. Trade data accuracy is affected by specific characteristics such as the practice of concealing confidential information and the exemption thresholds applied by countries to reduce the burden on enterprises. The sampling error is estimated to be around 2−3%.

implemented.[89,90] In terms of biobased coproducts, it is estimated that 15 kg of trimmings can be obtained per date palm tree yearly, amounting to a total of ca. 0.5 Mton per year in the United Arab Emirates.[91] Lastly, a cropping approach that is of high interest for arid areas is the farming of halophitic crops, i.e., crops growing on saltwater. A typical example is the growth of fatty-acid rich Salicornia, which has been experimentally grown in arid areas.[92,93]

Eventually, the above-mentioned biomass generating strategies will enable integrated biorefineries that optimally exploit each biomolecules and biomacromolecules. These will be used for energy (e.g., biodiesel and bioethanol), agro-industrial (lignocellulosic amendments and soil amendments such as humic acids), or greening of urban areas. These biorefineries will take advantage of the unique biomass makeup available in each regions.[80,94]

4.4. Management of Food Waste and Losses As a Source of Biomass. Importantly, beyond the biomass produced in arid areas, a net import of biomass is generally reported in arid areas (Figure 5A, as exemplified for the MENA region) and can contribute to local biomass cycling. For instance, about 30 Mton of biomass was imported as food in 2019, of which a substantial part generally ends as nonfood coproducts. When considering the FAO database (fao.org), the total import to export ratio of biomass after grouping the categories of crops and livestock, live animals, and forestry products was ca. 6.6 (Figure 5B,C). The unfavorable biomass trade balance, related to imports exceeding exports, has remained constant over the past decade and is expected to remain constant without implementation of a food-centered bioeconomy in arid areas. The implementation of "circular" or even generative bioeconomy policies and initiatives is thus encouraged to foster sustainable natural resource uses, enable

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climate-resilient food systems and lower the emissions associated with marine transportation of goods.[95] An innovation-driven bioeconomy in MENA countries can also help to create jobs to the youth entering the job market, achieve Sustainable Development Goals (SDG), and progress toward the Agenda 2063 by the African Union. Food-associated coproducts postimport can also contribute to the rising bioeconomy and integrate the positive feedback loops suggested prior by acting as a feedstock for the emerging biomass generation strategies and toward advanced bio-products through nearly all streams highlighted in Table 1.[96−99] The valorization of food coproducts has been largely explored thus far and offers clear upcycling opportunities.[100]

5. WATER AND ENERGY TO SUSTAIN BIOECONOMICAL GOALS

In addition to biomass generation, large amounts of water and energy will be required toward the emergence of a bioeconomy in arid areas. Overall, sustainable water management, food production, and clean energy generation are the nexus at the heart of sustainable developments and are closely associated with an emerging bioeconomy (Figure 6). In particular, water cycling and reuse should be optimally explored across the biomass generation strategies to efficiently valorize organic matter and resources present in all wastewater streams, thus

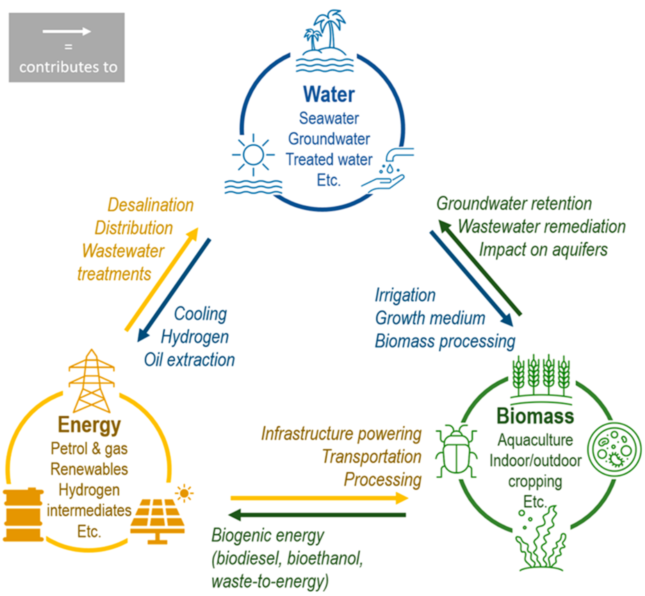

Figure 6. Interactions between the energy, water, and biomass-producing sectors in arid areas. Water, beyond water use for municipal and invidual's consumption, water is used to cool reactors, generate hydrogen, and for subterranean excavations. It is also used for irrigation, as a growth medium for bioreactors and aquaculture as well as for the treatment of biomass (e.g., pulping). Energy, the energy sector (including renewables, nonrenewables, and clean intermediats such as hydrogen) power infrastructures, distribution systems (including transportation), and electro- as well as mechanical processing of biomass or water. Biomass, biomass including all of the sources put forward in this review can contribute to the energy sector through their end of life, i.e., downcycling to biofuel or directly to energy through pyrolysis. Biomass generating activity can also enhance outdoor water retention, remediation of soils contaminants perfusing in the groundwater reservoirs. It can also use organic matter-rich wastewaters.

supporting strategic agricultural and industrial activities. Routes to manage water sources are currently diversifying within arid regions both to mitigate risks and to respond to climate change and geopolitical constraints.[101] As examples, water management strategies are typically centered around 4 main axes in the MENA and Gulf Cooperation Council (GCC) regions, including (i) desalination of sea or deep ground waters, (ii) municipal or industrial wastewaters treatment and reuse, (iii) atmospheric water generation and harvesting, and (iv) fresh or rainwater hydraulic catchments in both surface and underground configurations.[102] The Water−Energy−Food nexus is therefore more than ever relevant to sustain bioeconomical goals and strategies and will need to be strengthened to ensure sustainable growth within arid countries.

Water production by desalination, especially involving reverse osmosis membranes or multistage flash distillation are able to deliver high water quality to the industry, particularly demanding for ultrapure deionized commodity in the case of cooling and boiler systems used for power plants and petrochemical plants, as well as for farming and both textile and paper industries. The theoretical energy requirement limit, from a thermodynamic point of view, to produce freshwater from seawater is ca. 0. 86 kWh·m^{-3} (US Department of Energy, Office of Energy and Renewable Energy, 2019 Report, Chapter 7 − Desalination). However, with current technologies, this energy requirement ranges from 2.5 to 3.5 kWh·m^{-3} (WaterReuse Association Desalination Committee, Seawater Desalination Power Consumption, 2011). Energy recovery schemes implemented within reverse osmosis plants have allowed for over 30% savings in energy requirements since the early 1990s but are now reaching their thermodynamic limits.[103,104] Challenges in decreasing water production costs are therefore now related to issues of fouling and scaling, corresponding to the undesired deposition of organic or inorganic matter onto the membrane materials or heat exchangers, as well as to the presence of persistent organic pollutants.[105] Brine management is also a relevant issue to bioeconomical developments since rejects are typically at least 100% more concentrated than bare seawater, when considering good industry practices.[106] These high concentration brines affect natural ecosystems, increase local salinity and either threaten native species or lead to their migration. The development of advanced materials and integrated processes to intensify water production, particularly in terms of seawater pretreatment, brine management, and contaminants management will spearhead the development of low-cost and sustainable water production. The latter is a prerequisite to the development of an efficient and circular bioeconomy. Industrialization of separation systems and materials enabling more sustained and stable operations as well as facilitating resource extraction from brines, to reduce energy and cleaning requirements are currently desperately required.[107]

Technical changes and stronger incorporation of circular economy strategies have highlighted the need to reduce water usage and increase local water treatment capacities and thus water recovery. Current water subsidies in the Gulf Cooperation Council (GCC) region to support water-intensive industries may reach up to 70% of the water production costs in many GCC countries, and as high as 100% for strategic industries such as agriculture.[108] Public perception is a key brake to the incorporation of tap-to-tap water recycling strategies and recycled water, as although it is often of equal

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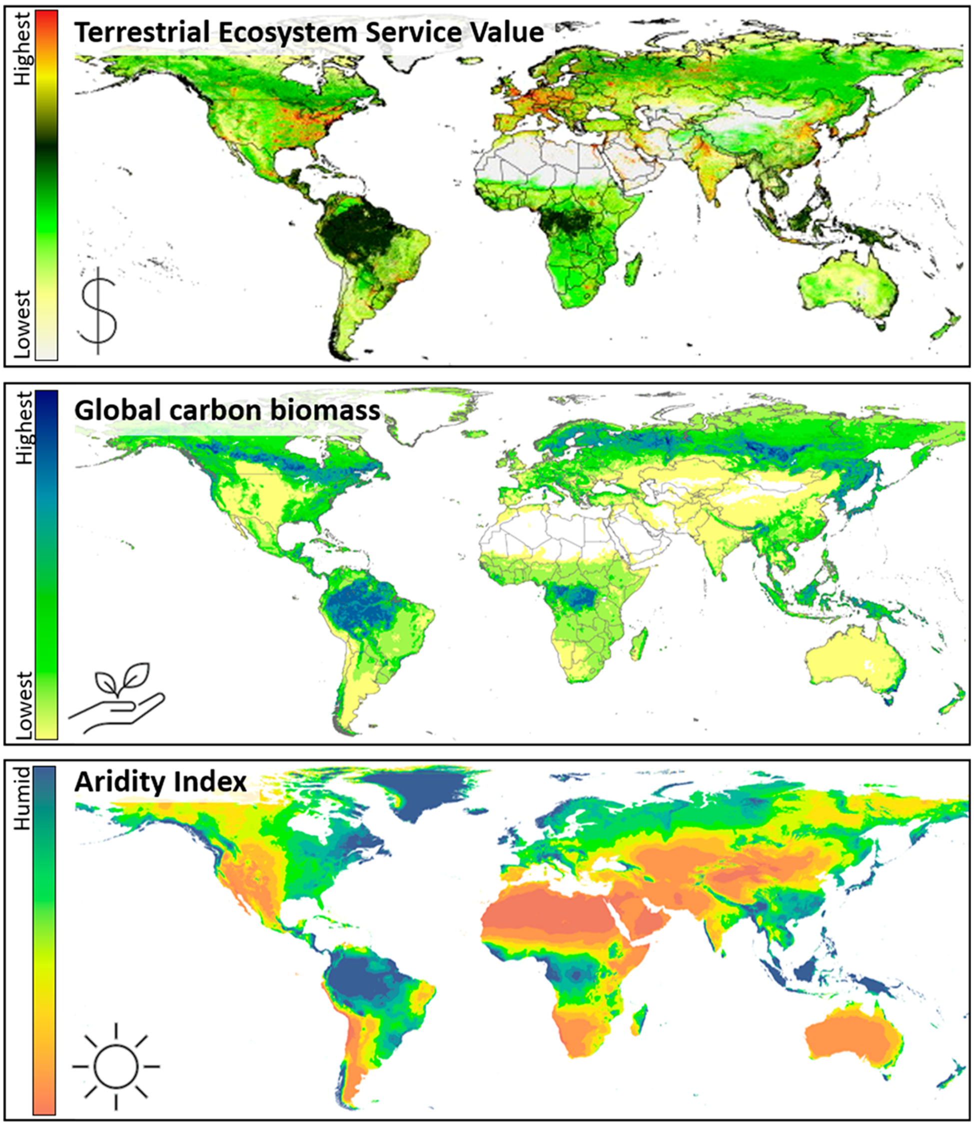

Figure 7. Top, terrestrial ecosystem service value map, associated with the wealth generated from ecosystems, namely, soil, flora and fauna. Map adapted with permission from ref 129. Copyright 2014 Elsevier. Center, corresponding carbon sink from land biomass. Map adapted with permission under a Creative Commons CC-BY 3.0 license from ref 130. Copyright 2016, the authors. Bottom, corresponding map of aridity. Map adapted with permission from ref 131. Copyright 2018, the authors.

or higher quality than that produced by other means, its use is often limited to irrigation or low-grade industrial usage.[109] Alternative routes to produce water include atmospheric water generation schemes, benefiting from the typically high ambient air humidity present across arid regions all year round.[110] Although nowadays the cost of water production by atmospheric water generation remains prohibitive, due to the intensive energy requirements, the versatility of production systems, and the ability to power them with low grade energy or renewables have made them promising supplements to existing desalination and wastewater treatment systems. Current systems offer up to 10 m^3 per day of water production for the footprint of a 20 feet container requiring up to 750–5000 $kWh \cdot m^{-3}$.[111] The emergence of diversified water production capacities and strategies is required to ensure water security agendas and support the development of remote farming, military, or industrial operations, completely disconnected from the main water network. The impact of these systems on the overall atmospheric water available is also largely negligible since it is estimated that only 0.001% of the total atmospheric water is currently tapped into annually, making the feed for these systems entirely replenishable through the natural water cycle.

Natural solutions, involving wetlands, mangroves, and other salt resistant species that can metabolize salts and contaminants present in these streams appear as highly relevant solutions to water cycling, which are considered for further expansion in the MENA and GCC.[112] Another important consideration is that although an established bioeconomy will help maintaining water in soils, its emergence will compete for water as a resource with other main water consumers in the MENA and GCC countries as well as with sustainable energy production, such as hydrogen produced from water. Thus, optimization of (re)cycling strategies for used waters and alternative water purification strategies, i.e., (ii–iv) as stated above, will be critical in addition to a balanced local water governance to maximize cycling of water across the different sectors equitably.

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ACS Sustainable Chem. Eng. 2023, 11, 12177–12193

The energy penalties to treat and store water are also an important issue. Surface storage systems not only suffer from evaporative losses over a 7−9 month period, in the driest and hottest season, but also from contamination.[113] Underground water storage is a promising option in a number of areas but is often limited on coastal areas due to the presence of high salinity aquifers at low depth, or to the natural concentration of salts present across depleted water reservoirs in potentially tight and nonconnected networks. Water production shall therefore be "just-in-time" oriented with limited water storage, increasing risks during emergency response and to cater for population growth as well as industry development.[114]

Resources recovery in wastewater represent a smart route to valorize waste and incorporate valuable organics into the development of a sustainable bioeconomy.[115] Existing wastewater treatment strategies generate large volumes of organics-rich sludges,[116] which may however contain persistent organic pollutants and higher than desired salts and metal concentrations. Solutions to pretreatment include integration of catalytic, ion exchange, or adsorption processes upstream to the sludge generation to either extract selectively or mineralize toxicants.[117]

Regarding the energy sector, another emerging industrial area requiring large amount of water, relates to the hydrogen production sector. This includes, for example, green hydrogen produced using renewable energy and water for power generation and hard to abate sectors.[118] The feasibility of the amount of water for hydrogen generation should be considered, taking into account that based on the reaction stoichiometry, every kg of hydrogen produced consumes 9 kg of water.[119] MENA and GCC countries have been historically net energy and petrochemicals producers through natural gas and oil production, and thus green hydrogen currently represents a small fraction of the water demand. However, these unions have developed ambitious hydrogen and clean energy roadmaps, which will rely largely on green hydrogen production. This requirement for water will be in direct competition with bioeconomical policies and strategies and will require adjustment in the water production capacities and distribution.[120] It is needed for water governance bodies to be balanced across these different imperatives to ensure safe and reasonable water distribution schemes as well as increased water production capacity.[121−123] In addition, down-cycling of a fraction of specific biomass can also sustainably contribute to the energy sector through biogas or biofuel generation, e.g., from fermentation or composting efforts and high energy biomass such as cooking oil waste, vegetal oil, or tallow oil.[124,125] Typically, lignocellulosics will benefit more from being used toward the valorization of other biomass generating endeavors rather than energy generation but during initial development stages a fraction may also contribute to the energy sector, including also combustion or through bioethanol production.[91,126,127]

6. OUTLOOK AND CONCLUSIONS

6.1. Critical Areas toward an Emerging Bioeconomy. Currently, bioeconomical endeavors are emerging in hyper-arid and arid areas as associated with improvements in aquaculture practices and in bioengineering, among others. For many countries currently having a low potential for economical profits via agriculture, linking food security, green areas expansion, and overall economical value of the land should be a high priority. This includes North Africa, the Middle East, China, and Oceania. In these areas, a strong overlap between low ecosystem value, high aridity index, and low carbon sink is present (Figure 7). In such arid areas, the bioeconomy is nearly nonexistent and currently offers scarce economical profits (Figure 7, top).[128] Therefore, developing an economy around biomass generation in these regions would not only improve the food security, it would largely improve biodiversity, carbon sequestration (Figure 7, middle), and consequently help mitigate the effects of climate change.

6.2. Global Engagement with Multifaceted Benefits. Globally, a vast range of efforts are currently undertaken to preserve and increase biodiversity, farmlands, and environmental friendliness of the systems and processes required to a functioning society. This is in line with the Intergovernmental Panel on Climate Change report highlighting the pivotal role of sustainably sourced biomass and bioenergy to reach net zero emissions by 2050.[132] Many of these efforts are focalized in areas that have a long-history of developments and strong know-how in bioprocesses and biosystems, such as most of North America, Europe, China, Japan, or Brazil. These countries are rich in biomass and are at the current forefront of the development of a bioeconomy. However, the overall benefits to biodiversity, restoration of the carbon balance, and sustainability are rather limited because these countries have already been topping these metrics for most of the last century. The most impactful changes to improve the biosphere's resilience will be those undertaken in desertic and arid areas. Through a diversified combination of biomass generating strategies, a developing bioeconomy in these areas would increase carbon capture in soil, decrease carbon emissions due to shorter transportation steps required for food import, improve water retention and availability, and overall reduce wastes that are difficult to sort and process, for example packaging associated with a delocalized supply chain. These benefits may have major global implications in the current climate emergency context considering that food transport emissions totaled 3 Gt CO_2 equiv. in 2017, an amount exceeding the transport emissions resulting from mining and manufacturing.[133] After several decades of supply chain changes being dictated principally by cost-efficiency, the current trade routes involve an extreme delocalization between food production and consumption sites.[134] A continuous chain of exchanges of bioresources would be favored globally if every area can be integrated into the bioeconomy efficiently, thus reducing this delocalization conundrum. Other positive aspects include localized cooling from green areas and the associated improved physical and mental well-being.

Alternative biomass generation strategies designed for arid and semiarid regions combined with robust yet cost-, and environmentally sustainable energy generation and water processing sectors can kickstart and accelerate the establishment of a bioeconomy in arid areas. Furthermore, beyond inducing an improved food-security in arid areas, the generated biobased coproducts can contribute to positive feedback loops by improving the fertility of the local soils, further expanding the potential more diverse and thriving biosystems. The highest priority to kickstart the bioeconomy in arid areas would be engaging in management of organic/biobased wastes. This involves developing the complex logistics of localized biomass wastes collection, establishing processing infrastructures, and potential sorting outlets (e.g., water-soluble vs solid waste fractions). This requires an important upfront cost that needs to be supported by governmental entities, citizens

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ACS Sustainable Chem. Eng. 2023, 11, 12177−12193

awareness, and engage companies producing biowastes at large scale. The recently achieved breakthrough agreement at The United Nations Climate Change Conference COP27 on the establishment of a new "Loss and Damage" fund for vulnerable countries hit hard by climate disasters represents a good example to consider. Second, a mapping of the commercial potential of the processing and valorization of the different biowastes by the different actors would become more evident and should then become the highest priority. For instance, this can include fermentation and insect farming endeavors that would prioritize the use of specific wastes for their production line. Third, and finally, dedicated land should be associated with regeneration efforts toward increased greeneries through the unused wastes. As the bioeconomy emerges, these three high priority endeavors would reinforce each other's and enable a wider range of commercially viable opportunities. Potentially, these endeavors can be partially blueprinted from other large-scale yet less challenging efforts where the logistics and infrastructures were organized at the continental scale, for instance in the European Union or in North America.

Making the most of the opportunities associated with a bioeconomy in arid areas represents a significant prospect to shortcut global climate, environmental issues by improving global biodiversity and carbon sinks from the resulting biosystems. The benefits of focusing on such opportunities will further promote regionalization of biobased industry, a critical component to global sustainability needs, and promote localized trade of biobased commodities. A full engagement of key countries, such as those in the MENA region or central Asia, toward these challenges will eventually benefit mankind immensely through the design of innovative strategies toward management of climatically challenged areas. For this endeavor to become reality, a healthy dialogue engaging various stakeholders making up the quadruple helix of local authorities, academia, industry, and society will be critical. In particular, the role of engineers (including chemical engineers, bioengineers, etc.) and chemists will be key toward such sustainable endeavors. The current and ongoing developments that such scientists and engineers have provided in biomass rich areas will be a strong driver of the emergence of a healthy bioeconomy in arid areas.

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B.L.T.: Conceptualization, writing−original draft, analysis, writing−review and editing. L.G.G., K.M., E.L., L.F.D., L.F.V.: Analysis, writing−original draft, writing−review and editing. L.V.: Writing−review and editing. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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ACS Sustainable Chem. Eng. 2023, 11, 12177−12193

Luiz G. Greca is a Postdoctoral researcher at the Cellulose & Wood Materials laboratory at Empa (Dübendorf, Switzerland). In 2022, he received his PhD in Chemical Engineering from the department of Bioproducts and Biosystems from Aalto University, Finland. During this time, his main focus was on using controlled wetting as a tool for guiding the self-assembly of biobased colloids and living materials. His current research focuses on the valorization of biomass into multifunctional materials by using green processing routes.

Karl Mihhels is a doctoral candidate at Aalto University, Finland, in the Department of Bioproducts and Biosystems. He has a background in pulp and paper chemistry and is particularly interested in applying the techniques and unit operations developed there on more novel sources of biomass, such as algae. This interest has led him to cross-disciplinary investigations into biology, environmental sciences and agri- and aquaculture. He is currently working on his doctoral thesis, which investigates the use of algae as a feedstock for nanocrystalline cellulose.

Erlantz Lizundia is Associate Professor at the Faculty of Engineering in Bilbao, University of the Basque Country (UPV/EHU), where he teaches on Engineering Design, Eco-design, and Circular Economy. Erlantz received his PhD in advanced materials engineering in 2011 and joined the University of British Columbia (Canada) and ETH Zurich (Switzerland) in 2016 and 2018 as a visiting scientist. At the *Life Cycle Thinking Research Group*, he develops environmentally sustainable energy storage, packaging, actuators or environmental remediation technologies based on renewable polymers using green chemistry, biomimicry, and circularity approaches. Erlantz also works on the ecodesign of batteries and their recycling, polymer upcycling, or biopolymer valorization through life cycle assessment (LCA).

Dr. Ludovic (ludo) DUMEE joined Khalifa University (Abu Dhabi, UAE) as an Assistant Professor in 2020. His team is focused on the development of advanced separation materials stemming from the properties of nanoscale structures tackling environmental challenges towards desalination, resource recovery and valorisation. He investigates routes to generate efficient separation membranes and catalysts from 1D and 2D nanomaterials towards the design of isoporous membranes for ultraselective separation of cells, proteins, ions and pollutants. He is actively engaged on the development of cost-effective alternative water production strategies in the MENA region leading activities on atmospheric water generation and desalination brine valorization. He graduated his PhD in 2012 from Victoria University (Melbourne, Victoria, Australia).

Lourdes F. Vega is a Full Professor in Chemical Engineering and the Director and Founder of the Research and Innovation Center on CO_2 and Hydrogen (RICH Center) at Khalifa University in Abu Dhabi, United Arab Emirates (UAE), and a Fellow of the American Institute of Chemical Engineers (AIChE). She obtained her PhD in Physics in 1992 at the University of Sevilla in Spain and conducted postdoctoral research at the department of Chemical Engineering at Cornell University. She has developed her career between academia and industry, with positions in the U.S.A., Spain, and the U.A.E. With more than 230 publications and 5 patents under exploitation, she is

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ACS Sustainable Chem. Eng. 2023, 11, 12177−12193

internationally recognized for applying molecular thermodynamics to clean energy, and sustainability, focused on CO_2 capture and utilization, hydrogen, sustainable cooling systems, and water treatment, receiving several prestigious awards for her contributions moving fundamental science to the applied world.

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