LandLessFood

Designing sustainable and circular agricultural systems for the year 2100

November 14-16, 2019

Workshop in Marrakesh, Morocco

Programme and Papers

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Workshop

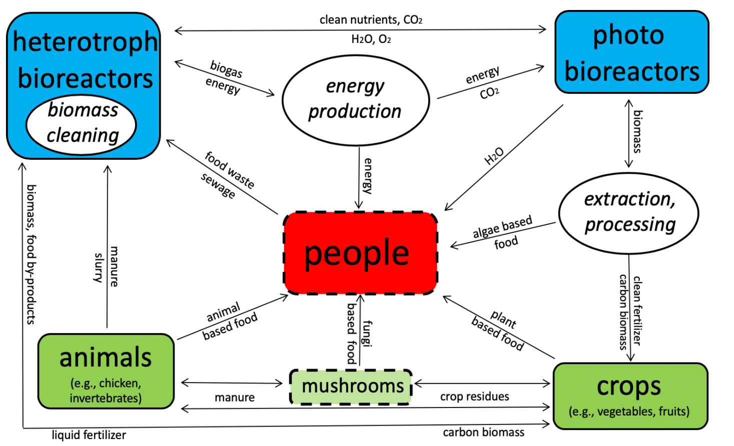
Combining land-based organic and landless food production: concept for a sustainable solution for Africa in 2100

November 14-16, 2019 in Marrakesh, Morocco

The background
Even optimistic assumptions about population growth, agricultural productivity and potentially available cropland, produce a grim image for the **future food security and sovereignty**, in particular for sub-Saharan Africa and parts of Asia. The challenge is to have enough, healthy and affordable food for everyone on the earth in 2100. Rahmann et al. (2019) propose a "ten actions plan" for sustainable, circular, climate smart and accepted food systems to feed a global population between **13.2 and 16.6 billion people** and to allow **food sovereignty** for every country **in 2100**.

The workshop
The workshop will focus on ***"Action Number 10: landless food systems in combination with land-based food production, using modern "organic agriculture tricks"***.
Reactor based food production can play an important role to meet the food challenges in 2100, additionally to **land and water based food production**.
The **target of the workshop** is to find possible mistakes of the concept and to design a research agenda which can meet the food challenges 2100, particularly for sub-Saharan Africa and parts of Asia. We want to **discuss the concept** with 15-20 open minded, innovative and solution-oriented experts.

LandLessFood concept: A coherent circular food chain model



Rahmann et al. (2019)

We like to have written **scientific papers of about 4 pages** in the research area of the participants, including ideas to meet the future food challenges, in advance. These papers shall be presented at the workshop and stimulate the discussion.
After the workshop the papers, the results of the discussions and a research agenda shall be **published** in a special issue of the **peer-reviewed** "Journal of Sustainable and Organic Agricultural Systems".

Programme

Venue and accommodation: Palm Plaza Hotel (www.hotelpalmplaza.com/en/)

Date	Time	Topic
Nov 14	whole day	Arrival of participants
	18:00 - 19:00	The concept of LandLessFood ***(Gerold Rahmann)***
	19:30 - 22:00	*Discussion while Dinner at Hotel, seating order along forum main themes of the workshop:* *1. Plants (Jessica, Andrew, Khalid, Victor, Daniel N),* *2. Waste-resources (Li, Mia, Jan-Willem, Anne-Kristin),* *3. Algae (Jörg, Irena, Anja, Wahyudi),* *4. Animals and Fungi (Arnold, Wan, Daniel G, Mahesh, Saliou)*
Nov 15	09:00 - 09:15	Africa 2100: how to feed Nigeria in 2100 with 800 million inhabitants? ***(Victor Olowe)***
	09:15 - 09:30	Landless food versus crop intensification in Africa - where do the substrates for food synthesis come from? ***(Daniel Neuhoff)***
	09:30 - 09:45	Decreasing Reactive Nitrogen Losses in Organic Systems ***(Jessica Shade)***
	09:45 - 10:00	Is Organic the Interface Between Smart Agriculture and Ecological Intensification? (***Andrew Hammermeister***)
	10:00 - 10:15	Insect pest control ***(Saliou Niassy)***
	10:15 - 11:00	*Discussion with coffee, tea and biscuits*
	11:00 - 11:15	*Recycling of organic wastes as fertilizers: perspectives for China and the city of Suzhou* ***(Li Ji)***
	11:15 - 11:30	Circular Netherlands – real sustainable nutrient cycles and permanent food cultures (***Jan Willem Erisman***)
	11:30 - 11:45	Small-scale biogas facilities to enhance nutrient flows in rural Africa - relevance, acceptance, and implementation challenges in Ethiopia (***Mia Schoeber***)
	11:45 – 12:00	Feeding the reactors: potentials in re-cycled organic fertilisers (***Anne-Kristin Løes***)
	12:00 - 13:30	*Lunch, discussion and break*
	13:30 - 13:45	Versatility of algae - Exploring the potential of algae for nutrient circulation (***Anja Kuenz***)
	13:45 - 14:00	The potential role of algae in a circular & green economy and for a sustainable food production (***Jörg Ulmann***)
	14:00 – 14:15	Algae as a means of converting waste carbon dioxide into food with a high nutritional value. (***Irena Brányiková***)
	14:15 – 14:30	What we understand about food (***Wahyudi David***)
	14:30 - 15:30	*Discussion with coffee, tea and biscuits*
	15:30 - 15:45	Landless Animal and poultry production prospects: an overview on feeding, keeping and sustainability (***Mahesh Chander***)
	15:45 - 16:00	Edible Insects (***Arnold van Huis***)
	16:00 - 16:15	Fungal solutions for circular food chains (***Daniel Grimm***)
	16:15 – 16:30	Effect of Bioreactor-grown biomass from the mycelium of Ganoderma lucidum on Red Hybrid Tilapia for sustainable aquaculture (***Wan Mohtar***)
	16:30 – 18:00	*Discussion*
	19:00 - 22:00	Dinner at La Trattoria (http://latrattoriamarrakech.com)
Nov 16	09:00 - 09:15	Changing food habits and ethics: experience from the past to design the future (***Raffaele Zanoli***)
	09:15 - 09:30	Solid phosphate sludge composting: a way to produce phosphorus enriched organic amendment for African soil fertilization and carbon sequestration (***Khalid Azim***)
	9:30 – 12:00	*Final discussion with coffee, tea and biscuits*
	12:00 - 13:00	Lunch
	13:00 – 17:00	Excursion to the OCP phosphate mines (www.ocpgroup.ma/en/home)

List of Participants

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19. Prof. Dr. Raffaele Zanoli, Università Politecnica delle Marche, Italy (web: www.univpm.it; email: zanoli@agrecon.univpm.it)
20. Dr. Azim Khalid, Institut National pour la Recherche Agronomique (INRA), Morocco (web: www.inra.org.ma**;** email: azim.khalid@yahoo.fr)

Content

458 m2: Model calculation for a sustainable, circular and local land-based and landless food production system

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Introduction

458 m2, this is the available cropland per person throughout Africa, if the population will increase 4 to 5 times towards 5.8 billion people in 2100, the maximum estimation of the UN 2019 (95% confidence interval). This space is not enough for food sovereignty, if the low African yields remain. Even with the global average yields, which are more than twice as high as in Africa for most staple crops, and even with much slower population growth, it will be extremely hard to achieve food sovereignty in Africa. Hunger, wars, diseases and mass migration could be the consequence already long before 2100. In future, intensification (yields) and/or expansion (grassland, forest: LULUCF) of agriculture will not be able to produce enough nutritious and affordable food for everyone. But clever combining of land-based and landless food production can be a solution. Maize and soybeans are best for WFP minimum diets and have the best yields. Using mushrooms, insects and earthworms as protein source could deliver enough protein and micronutrients, and local photoreactors can produce oil /and/or starch for food energy. This “out-of-the-box” system approach needs research and development. Every good research needs good questions and a concept with some simple calculations to assess the strengths, weaknesses, opportunities and threats. Socio-economic aspects are often not considered enough in technical focused and far ahead R&D.

The food production and consumption problem

Food security is a global challenge and responsibility, rather than a problem which only the most critical countries and communities have to deal with. The forcasts for 2100, are alarming for nearly all countries in Africa and some countries in Asia (e.g. India, China, Indonesia, Bangladesh) (*Table 1*).

Table 1. Global and continental population, land availability and space per person in 2100

	World	Africa	Americas	Asia	Europe	Oceania
Population (mio people):						
- 2015	7,349	1,186	992	4,393	738	39
- 2050 **	10,875	4,280	1,171	4,720	630	75
- 2100 (medium est.) *	9,735	2,489	1,188	5,290	710	57
- 2100 (maximum est.) **	15,600	5,878	1,696	7,027	896	102
Land use 2015 (mio hectare):						
- country area ***	13,467	3,032	4,075	3,198	2,306	856
- agricultural area	4,869	1,133	1,225	1,664	467	379
- grassland ****	3,275	861	826	1,082	176	331
- arable land	1,426	235	371	496	276	47
- permanent crops	165	34	28	86	15	2
- agricultural area/total land (%)	36%	37%	30%	52%	20%	44%
Available space per person 2015 (m2/p):						
- country area	18,324	25,564	41,080	7,279	31,244	219,524
- grassland*****	4,457	7,260	8,326	2,464	2,379	84,757
- cropland*****	2,165	2,269	4,024	1,325	3,951	12,512

Available space per person 2100 (m2/p):						
Medium est.: *						
- country area	12,383	7,084	34,804	6,775	36,625	114,280
- grassland*****	3,012	2,012	7,054	2,293	2,789	44,123
- cropland*****	1,463	629	3,409	1,233	4,632	6,514
Maximum est.: **						
- country area	8,632	5,158	24,025	4,550	25,720	83,852
- grassland*****	2,100	1,465	4,870	1,540	1,959	32,375
- cropland*****	1.020	458	2,353	828	3,253	4,779

* medium population est. 2050 and 2100 (UN 2019)
** maximum population est. 2050 and 2100 (UN 2019 medium est. +0.95 confidence)
*** including deserts, high mountains, ice covered areas
**** mainly low productive savannas, pampa etc. (usually not suitable for cropping yet)
***** Cropland is sum of arable land plus permanent crops. Sum of grassland and cropland is agricultural area.
Source: Rahmann et al. 2019

Increasing food production will be necessary to feed every human on the earth with enough, nutritional, healthy and affordable food. In this paper, we assume that the SDG No. 2 (no hunger) will not be achieved and regional food insecurity will become worse after 2030, at least in Africa and in some densely populated and low developed countries in Asia. Significant and much more ambitious increase of food production with efficient food chains and sustainable consumption has to be developed and scaled-up as soon as possible.

Food requirements

Food is one of the core requirements and needs of us: the homo sapiens (humans). In principle, we are very adaptive in diets and food sources. As omnivores, we can digest a wide range of plants, fungi, animals and others, at least after processing and/or cooking (Gibbons 2007). Despite or because of this fact it is difficult to find a “typical ration” for a “typical human” in kilogram of food per day. The need is defined on the basis of nutritional demand.

Life needs food for energy (calories, joule) and structural material for body growth and rebuilding, delivered as macro and micro-nutrients (carbohydrates, fats, fiber, minerals, proteins, vitamins), as well as water. Carbohydrates and protein deliver about 17 kJ (4 kcal) and fat 37 kJ (9 kcal) of energy per gram DM. Vitamins, minerals, fiber and water do not deliver significant amounts of energy, but are required as structural material, health components and to help digestion. All food has at least some of the nutrients mentioned above. Not all food can be digested, therefore the feces carry energy and structural material. Because it is so difficult to measure the food quantity per person per day, the energy and structural material (protein etc.) is used for calculations.
The human food energy requirement is measured in kilocalories and Joule (1 calorie is 4,184 Joule), about 1 kcal per kg liveweight and hour is needed as minimum energy without any activities (example: 70 kg man x 24 hours = 1,680 kcal x 4,184 Joule = 7,029 MJ). Adding activities, age and sex is difficult, due to individual conditions, but roughly about 2,500 kcal (10,460 MJ Metabolizable Energy ME) for men and 2,000 kcal (8,368 MJ ME) for women can be assumed as average daily need (FAO 2001).
Energy and ingredients density are different between all the different foods. Due to availability, the food baskets and food cultures are very different throughout the world. Despite the high variability, it can be assumed, that about 2 kg food as fresh matter (0.75 kg dry matter) are the daily need for an “adult average human” (30 years, normal activity, healthy, temperate climate) (without losses, usually 25% extra). The stomach of such an “adult average human” has a capacity of 1 to 1.5 liters and can digest about 1 to 1.5 times filling a day (depends on digestibility of food). Therefore, the stomach can digest about 1 to 2.25 kg fresh matter food a day. Food must have a digestible nutrient density that fits with the capacity of the stomach.

Table 2. Nutrient content of maize, rice, wheat and soybeans

Food name *scientific name*	Maize *Zea mays*	Rice *Oryza sativa*	Wheat *T. aestivum*	Soybean *Glycine max*
water in FM (%)	14	14	14	14
kcal (per kg DM)	3,840	3,640	3,640	4,490
protein (g xP per kg DM)	100	80	140	440
fat (g per kg DM)	44	07	23	209

The World Food Programme (WFP 2019) offers a food basket for emergencies and refugees with 2,100 kcal (10-12% from protein and 17% from fat). A recommended WFP-standard ration is composed by wheat, maize or rice, lentils, soybeans, or other pulses, vegetable oil (fortified with vitamin A and D), sugar and iodized salt. Additionally, 1 to 1.3 g crude protein XP per person and day should be available (WHO 2019). Of course, this minimum ration is not enough for adult and hard-working man or lactating woman, but much more than a young child or an elder person needs. Nevertheless, in a society this minimum ration should be fine, if people share it in context to the individual demand (elder people, adults, children; hard or less hard working).

If we assume, that the WFP daily ration has 2,100 kcal energy and 85 g protein, the minimum annual need per person is 767,000 kcal and 24 kg protein[1]. This has to be produced on available cropland or imported, if other option like landless food production is not considered.

Food production

For 70,000 years the collection of wild plants and hunting were the basis of food security. Until 10,000 BC, a maximum of 2 people per km2 (50 ha per person) could find enough food and survive and only estimated 1 to 15 million pre-historic humans lived on the earth. With the invention of agriculture, about 12,000 years ago in Mesopotamia and adjacent areas (Bellwood 2005), humans have been able to produce more food per ha for increasing population densities (Puleston and Tuljapurkar 2008). In the year 1400, 500 mio humans used extensively 7% of the global land surface have been used for farming (1.1 billion ha crop and grassland), respectively 2.2 ha per person. The year 1804 is seen as the first time when 1 billion humans lived on the earth.

Today, 7.6 billion humans use 4.8 billion ha crop and grassland intensively (0.6 ha per person). The global population density has increased towards 57 people per km2 (USCB 2019). Most of our recent food comes from land locked plants and livestock, only 10% from fishing and aquaculture. 36% of the land surface (13.5 billion ha, excluding Antarctica) is used for crop and livestock production. Further encroachment into deserts, forests, mountains and frosty areas is difficult and/or costly.

A "good" diet is a balance between different foods to meet the demand, and there are many different staple foods and food cultures all over the world. However, in the last decades, a harmonization of food cultures took place. Today, only 3 food plants (wheat, maize, rice) contribute about 60% of human food intake, direct as plant food or indirect as meat, eggs or milk (FAO 2019b).

Compared to rice and wheat, maize is the most important food product of the world (Table 3). This crop already covers already 14% of the total global arable land. A lot of the global maize production is for animal feed. In addition to maize, soybean is best choice as pulse for a WFP minimum ration. This legume is more valuable for a WFP ration than others, due to high protein and fat content (Table

[1] Protein: 1 g per day and kg liveweight of a person is needed, and the digestion rate (biological value) of crude protein (xP) in maize and soybeans is 75%. That would mean, 1.3 g xP per person and day is necessary. An average person of 50 kg liveweight would need 23.741 g xP per year.

2). Today, 8.6% share of the global arable land is cultivated with soybeans, like maize mainly for livestock feed.

Table 3. Production and yields per ha of maize, rice, wheat and soybeans (2017)

Food name	Maize	Rice	Wheat	Soybean
Global hectare land (mio ha)	197	167	218	123
Production (mio tons)	1,135	770	772	353
Global average yields(tons/ha)	5.755	4.601	3.531	2.854
Lowest yields (continent average) (tons/ha)	Africa 2.073	Africa 2.444	Africa 2.604	Asia/Africa 1.371
Highest yields (continent average) (tons/ha)	Americas 8.069	Oceania 9.379	Europe 4.360	Americas 3.245

Maize and soybeans have not only high nutritional and production yields advantages. These two plants grow in a wide climatic/weather range and high performance varieties for most of the earth are available. This does include GMO seeds, which are pest or herbicide resistant, and in the future probably with higher water efficiency and salinity tolerance and last but not least high nutritional values (vitamins, amino acids, etc.). Because GMO are under ethical discussion (private business, patents, ecological and health risks), not invented for poor farmers but as expensive commodity, and the production costs with GMO are high (high input - high output systems) and therefore difficult for poor and remote small scale farmers, the ecological and socio-economic assessments of GM maize and soybeans have not been finalized yet.

Food insecurity can increase

Future food security is a global challenge, as for example defined the United Nations Sustainable Development Goal SDG No. 2 (Zero Hunger) until 2030. Today, 800 million people are facing hunger, nearly 2 billion malnutrition and 1.5 billion obesity (BMI>25). It should not be forgotten, that there have never been more people fed sufficiently on the earth (more than 6.5 billion), and that obesity is a contradictory problem of hunger issues. Fair distribution of food is still not happening, althoug enough food would be available for everyone.

But the real challenge will appear after 2030. Most predictably, Africa South of the Sahara and some countries in Asia (e.g. India, Pakistan, Bangladesh) will have severe food security problems. It is already observable today, that the conditions for sufficient food production will become worse in these regions (climate change, population growth, ecological degradation, socio-economic difficulties), despite all efforts and developments of farming systems and food chains.

Table 4. Needed and available cropland in Africa under different scenarios

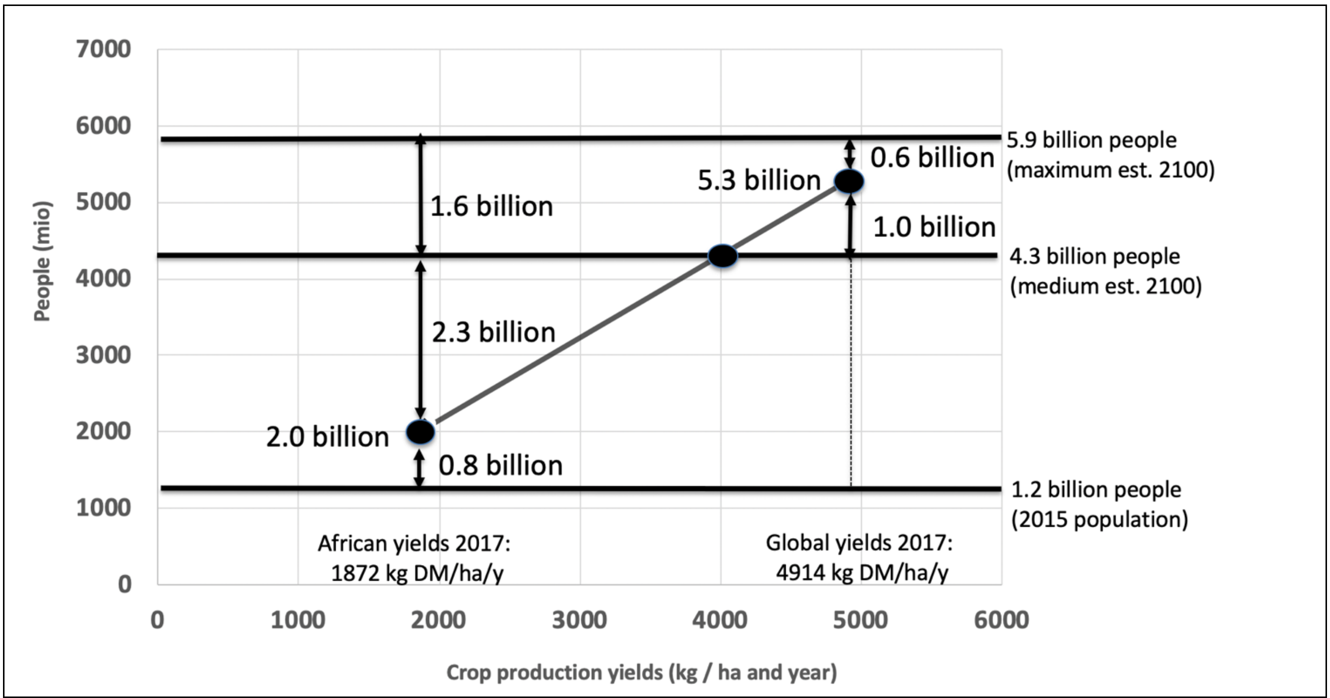
Cropland needed for WFP minimum ration: (m2 per person):		Cropland available per person: (m2 per person):	
Global production yields*	489	4.3 billion people**	629
African production yields*	1,216	5.9 billion people**	458

* Average production yields 2017: Global: maize 5.8, soybean 2.8 t/ha/y. Africa: maize 2.1, soybean 1.4 t/ha/y (FAOstat 2019). ** Population estimations (UN 2019)

The main change and challenge will appear after 2050, particularly in densely populated and less developed areas of the world (e.g. in Africa will be only 458 m2 arable land, there will be not enough space left over for food sovereignty in Africa). Increasing yields (very low) is difficult due to lack of knowledge and markets (farm inputs and outputs) (*Table 4*). Encroaching cropping on grassland and nature areas is limited and difficult due to lack of water, infrastructure, capital and land rights. Food import is also limited due to lack of money and/or competitive products for the world market. Food aid seems to be the only option for most of the countries.

Even though food security problems will affect countries in many other regions of the world too, the following calculation will use the African continent as an example, to extrapolate the development.

Until 2100, in 80 years, the African population will increase from currently 1.2 to 4.3 billion under medium fertility assumptions and up to 5.87 billion under high fertility assumptions. Already today, Africa is the continent of hunger and land degradation is obvious throughout the continent.



Average production yields 2017: Global: maize 5.8, soybean 2.8 = 4.9 t/ha/y, Africa: maize 2.1, soybean = 1.9 tons/ha/y (FAOstat 2019). Cropland use: 71% maize and 29% soybeans. Population estimations (UN 2019): medium est. 4.3 billion; maximum est. 5.9 billion people. Assumptions: only maize and soybeans are produced, no post-harvest losses, no LULUCF, only WFP ration (2,100 kcal/p/d): 190 kg maize and 60 kg soybeans per person and year.

Figure 1. Number of people in African, which can be fed with a WFP minimum diet if global or African production yields are achieved

Food sovereignty for Africa is only possible if a) the population will not increase above 5.3 billion (Figure 1), b) no more than the WFP ration is consumed, c) no post-harvest losses occur, d) the global crop production yields are achieved and e) only maize and soybeans are produced on all 269 mio ha African cropland. If the production yields will remain low like today, only 2 billion people can be fed – 0.8 billion more people than live in Africa today. If this can be achieved is uncertain, because already today 240 mio (20%) of the people face hunger and Africa is a net-importer of food and agricultural goods. In 2016, the continent imported about 20 million tons of maize for 4.1 billion USD (205 USD/ton) and 2 mio tons of soybeans for 812 million USD (406 USD/ton) (FAOstat 2019).

It is doubtful whether an increase of 280% for maize and 200% for soybeans towards global average yields throughout Africa and no losses in the food chain are possible. To increase the production from “low external input – low output” production towards “medium input – medium output” yields, the production costs for example for maize and soybeans will increase by roughly 300 USD/ha/y (100 USD for improved seeds, 150 USD for fertilizer, 150 USD for pesticides), even if the costs for labor, machines, capital and land do not increase (this would probably need 300 USD more per ha and year). If we calculate this per person to increase the production from African yields towards global yields, 14.66 USD per person would be necessary per year. This seems to be a little, but extrapolated for all 269 mio ha cropland in Africa, that would be about 80.718 billion USD per year, or 3.3% of the 2.45 trillion USD of Gross National Production of the continent (2019).

If the production yields in Africa will remain low, 53 to 66 % of the required minimum food have to be imported (Table 5). This would amount to 413 to 737 million tons of maize and 136 to 233 million tons of soybeans (Table 5). If the food is produced for example in the Americas (highest continental yields with 8 tons per ha maize and 3.2 tons per ha soybeans), between 82 and 169 mio ha arable land would be needed to produce food for export to Africa. This would be about 5% and 10% of the global arable land today (2017).

*Table 5. Annual volume and value of food import needs in Africa for 4.3 or 5.9 billion people, if production yields remain low in the continent**

	units	Maize** (71%)	Soybean** (29%)	Total (100%)
4.3 billion people (53% of food imported):				
Import need	mio tons/y	431	136	567
Import value***	billion USD/y	88	55	144
Volume/person	kg/p/y	101	32	133
Value/person	USD/p/y	20.64	12.91	33.55
5.8 billion people (66% of food imported):				
Import need	mio tons/y	737	233	970
Import value***	billion USD/y	151	95	246
Volume/person	kg/p/y	125	40	165
Value per person	USD/p/y	25.71	16.08	41.78

* African yields 2017: maize 2.1 t/ha/y, soybeans 1,4 t/ha/y.
** Standard WFP ration: 2,100 kcal/p/d, 12% from protein, 17% from fat = 71% maize and 29% soybean in cropland use.
*** Import figures Africa 2016: maize 20 mio tons for 4.1 billion USD (205 USD/ton) and 2 mio tons soybeans for 0.812 billion USD (406 USD/ton) (FAOstat 2019).

Using the prizes of 2016 (‘cost include fright’ -cif- Africa: 205 USD per ton maize and 406 USD per ton soybeans; FAOstat 2019), the value of the African minimum food import in 2100 would be between 118 and 210 billion USD every year. That would be between 28 and 36 USD per person and year for food import to Africa (Table 5). The question is: who will pay for this? If Africa will not have enough money to afford it, food aid would be necessary.

Not only the production, but also the food distribution will be a challenge. While rural people can produce their food on their own (subsistence), urban people have to buy food (market). Today, Africa is the most rural continent, with only about 43% of people living in urban areas (United Nations 2018). However, this is changing rapidly and Africa’s cities will grow very fast in the future. Today, none of the largest 10 cities in the world is in Africa but by 2100 five of them are predicted to be. If current growth trends were to continue, the situation would be as follows: Lagos (88 mio; biggest city of the world), Kinshasa (83 mio, No. 2), Dar Es Salaam (74 mio, No. 3), Khartoum and Niamey (56 mio each, No. 6 and 7) (Hoornweg and Pope, 2014). Though these estimates are likely to be high, it is certain that many meta cities (more than 20 million inhabitants) are going to emerge on the continent.

Solutions to reduce food insecurity

In the context of the worst-case scenarios for Africa described above, under which not all necessary food can be produced on limited local cropland, other options are needed:

- Global: increase of global food trade (from high productivity towards high demand areas) and/or
- Local: to produce food locally in land-based (e.g., intensive gardening) and landless systems (balcony, indoor, roof, vertical, container, reactor food, aquaponics etc.).

Both options have advantages and disadvantages, and both need to be developed to solve future food challenges.

Table 5. Food security action assessment

•Actions	•Assessment	•Impact
Expansion of crop production	• Difficult due to water shortage, low soil fertility, remote, steep, rocky. • Grassland: largely only extensive grazing possible. • Protected areas (e.g. reserves) restricted for farming. • In many countries no additional cropland available.	low
Intensification of crop production	• Deficits in infrastructure, agricultural competence and capital. • Food hazards and ecological risks high. • Mainly not related to hunger reduction: difficult for small scale family farming, non-food, cash crops and/or export oriented, ...) • More impacted by soil degradation, plant diseases, climate change	middle
Imports	• Imports have to be paid (hunger is a result of poverty) • Food aid) for billion people difficult?	low
Population growths control	• „Life happens“, children are not only a result of family planning. • UN estimations fertility are optimistic with 2.1 child / wife in 2100.	low
Migration	• Urbanization is on the go. • Intra- and international und intercontinental is increasing.	high
Nutrition change (habits and food)	• Livestock products become more important (“white meat“)! • Food: post-harvest losses and misuse reduction? • Insects, mushrooms, algae, etc. for food?	low high high

Let us have a short look at the global option. Despite all the impacts and effects, the globalized food chain has brought significant problems and risks cannot be ignored. The main problems are: private and profit oriented global food chains, market difficulties (transport and processing disruptions, food demanding areas are not able to pay for imported food and aid is needed), degradation and contamination (pesticides, nutrients in water, drug resistant germs) of natural resources (soil, water, biodiversity, air, landscape). On the other side, the global land-based food is not free from risks like natural calamities (more frequent and damaging storms, droughts, floods), and last but not least political risks (e.g. wars, protection, embargos, terrorism). Therefore, global food chains have done a good job, but the impact has negative impacts as well. Several food system changes try to reduce the impacts, for example Organic Agriculture with globally already 1.6% farmland share (IFOAM 2019). But this is not scaled-up enough, probably not good enough for the real future challenges, because the production yields are not high and the ecological impacts are not low enough (Rahmann et al. 2008, 2009, 2017).

Now to the local option: Food sovereignty in very densely populated and low developed areas/regions is becoming less secure. Not only productive farmland is becoming more and more scarce, but also sufficient and clean water, necessary nutrients, productive seed varieties, renewable energy and – very important – better knowledge of all actors in improving food systems sustainable (from production to consumption). For such conditions, we proposed a combination of land-based and landless food production for a local, circular and sustainable food chain (Rahmann et al. 2019).

Space efficient food production

Maize and soybean are the most space efficient crops to produce a WFP ration. In the case of Africa, 489 m2/person would be necessary (Table 7), if global average yields can be achieved, food losses go towards zero and only maize and soybeans are produced. If the production yields will remain low like today, 1,216 m2/person crop land would be needed, and – vis-a-versa – with the highest continental yields of Americas, 22% could be saved (382 m2/person). This shows, there would be a chance to achieve food sovereignty, but only in the case of very high yields.

Table 7. Minimum food and cropland need for annual WFP ration

	Maize (71%)	Soybeans (29%)	Total
Food energy supply (kcal/p/d) *	1,491	609	2,100
Protein supply (g/p/d) **	33	54	87
Food demand (kg /p/y)	190	60	250
Cropland needed (m2/p/y): ***			
- lowest continental yields (Africa):	796	420	1,216
- global average yields (all continents):	287	202	489
- highest continental yields (Americas):	205	178	382

* 2,100 kcal/p/d, 12% of the kcal are coming from protein and 17% from fat (WFP 2019)
** 1.3 g xP per kg liveweight to achieve with 80% digestibility
*** based on average yields found in FAO databank for the year 2017 (visited 2019)

With the assumptions in Table 5 we can calculate that 28 to 36 USD per person and year are the threshold for the landless production to substitute 118 to 210 kg imported food. This would cost roughly 0.20 USD/kg (maize import -cif- Africa: 205 USD/ton) and would be very low, compared to production costs of recent photobioreactors, which produce high quality products for cosmetics and food additives for 10 to 50 USD/kg dry mater.

Of course, these model calculations of minimum diet and minimum cropland space (Table 1) do not consider all aspects. Some other crops (e.g. potatoes, white beans) do have comparable high yields and product qualities, some areas allow more than one harvest a year, maize and soybean cannot produced everywhere. On the other side, food chain losses, nutritional and food culture needs are not considered. For this paper, these factors are not considered

Local, circular and sustainable food chains

If the food supply is insecure and import and aid not possible, local food systems are crucial. A local, circular and sustainable nutrient, energy and food chain was designed in Rahmann et al. (2019). As shown in Figure 1, the "green chain" displays the traditional nutrient and food chain: from cropping to human and livestock. Because this chain is not able to produce enough food, the "blue chain" was added. Biomass from the "green chain", sewage and waste-water from households are used for energy production and become homogenizing for a reactor-based and landless food production. Both chains together have to produce enough, healthy and affordable food for people in high populated regions and low development conditions.

Let us have a look at the two chains. The crop production of the “green chain” is the core of the system. If only 458 m2 per person are available, an intensive production for a maximum of needed food has to be carried-out. Maize and soybean are the best crops to meet WFP ration demands. A cultivation scenario of these two crops, showing the potential and limitations of the “green chain” is depicted in tables 8 and 9.

Table 8. Calculated production yields of selected crops per m2 and year

		maize	soybeans
Food energy (kcal/kg DM)		3,840	4,490
Food protein (g/kg DM)		100	440
Production of food (kg DM/m2/year)	low yields*	0.18	0.12
	average yields*	0.49	0.25
	high yields*	0.69	0.28
Production of food energy (kcal/m2/y)	low yields	685	529
	average yields	1,901	1,102
	high yields	2,665	1,253
Production of protein (g xP/m2/y)	low yields	18	52
	average yields	49	108
	high yields	69	123

* Global average, lowest and highest continent production figures 2017 (FAOstat).

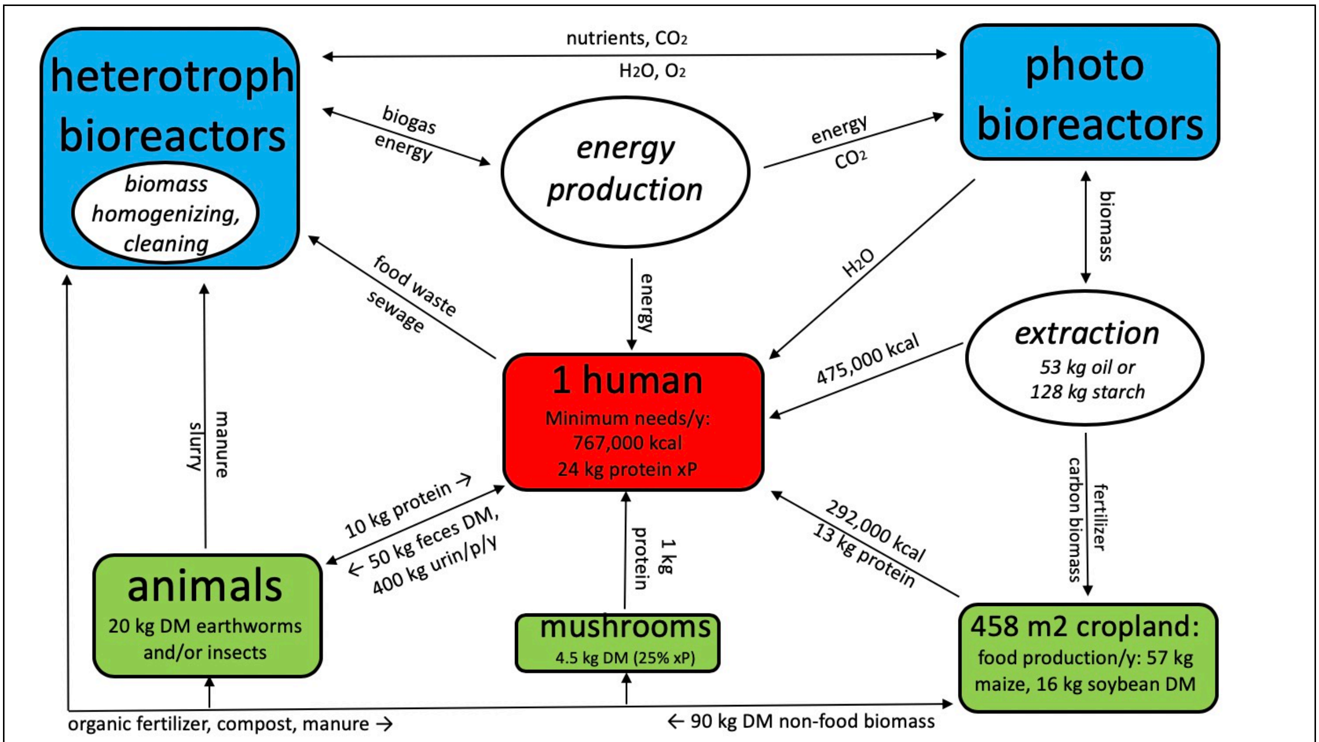
Table 9. Calculation of food energy and protein production with maize, soybean and cabbage on 458 m2 cropland plot under different yields.

		maize 320 m2	soybeans 138 m2	Total 458 m2
Total biomass** production (kg DM)	low yields*	131	33	164
	average yields*	364	68	432
	high yields*	511	77	588
Total food production* (kg DM)	low yields	57	16	73
	average yields	158	34	192
	high yields	222	39	261
Production of energy (kcal/y)	low yields	219,068	73,057	292,125
	average yields	608,170	152,082	760,252
	high yields	852,706	172,917	1,025,623
Production of protein (g xP/y)	low yields	5,705	7,159	12,864
	average yields	15,838	14,903	30,741
	high yields	22,206	16,945	39,151

* Global average, lowest and highest continent production figures 2017 (FAOstat).
** Total biomass production is food and non-food: relation for maize: 1 : 1.3 and soybean: 1 : 1.

The nutrient flow in Average African production yields 2017: maize 2.1, soybean = 1.9 tons/ha/y (FAOstat 2019). Assumptions: only maize and soybeans are produced with a land use relation of 71% maize and 29% soybeans, no post-harvest losses, no LULUCF, only WFP ration (2,100 kcal/p/d): 190 kg maize and 60 kg soybeans per person and year.

Figure 2 shows, that it is not possible to produce enough food with low African production yields. Not protein, but production of food energy (kcal) is the main deficit. Less than one third can be harvested. Protein is also a challenge, but it can be enough produced, if mushrooms are cultivated on the 70 kg non-food biomass from cropping (0.1 kg mushroom/kg biomass DM with 2.5% protein) and earthworms and insects are used for animal protein (insects with 50% and earthworms with 60% protein).



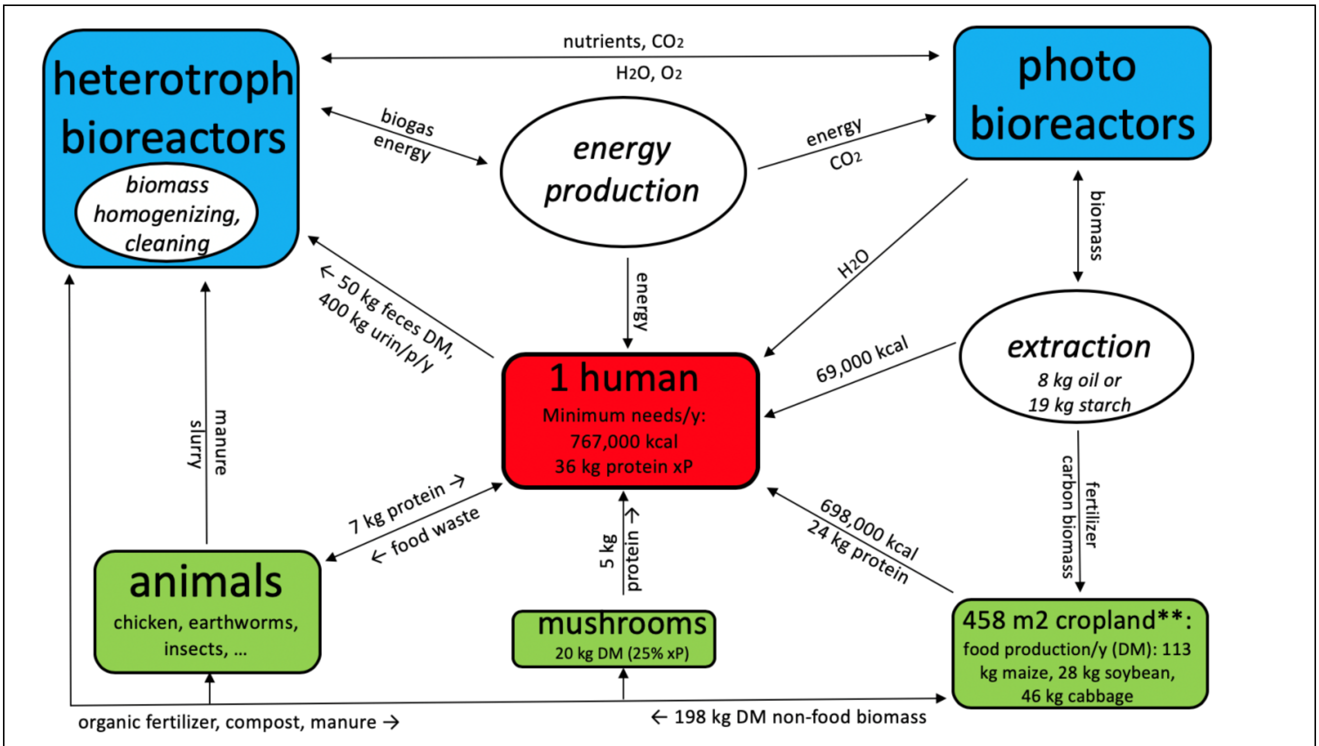
- * Lowest continental yields 2017 showed Africa: 2.1 tons maize (1.8 tons DM) and 1.4 tons soybean (1.2 tons DM) per ha and y.

Average African production yields 2017: maize 2.1, soybean = 1.9 tons/ha/y (FAOstat 2019). Assumptions: only maize and soybeans are produced with a land use relation of 71% maize and 29% soybeans, no post-harvest losses, no LULUCF, only WFP ration (2,100 kcal/p/d): 190 kg maize and 60 kg soybeans per person and year.

Figure 2: Subsistence food production for one person on 458 m2 cropland under African yields scenario

If global yields would be achieved on 458 m2 cropland, not all the space would be necessary for maize (50% of total cropland) and soybeans (25%) (Average Global production yields 2017: maize 5.8, soybean 2.8 = 4.9 tons/ha/y (FAOstat 2019). Assumptions: only maize and soybeans are produced with a land use relation of 71% maize and 29% soybeans, no post-harvest losses, no LULUCF, only WFP ration (2,100 kcal/p/d): 190 kg maize and 60 kg soybeans per person and year.

Figure 3). Up top 25% could be planted with vegetable and/or fruits. The system would be much more productive and efficient. Even chicken could be kept, fed with protein from mushrooms and crop production.



* Global average yields 2017: 5.8 tons maize (4.9 tons DM) and 2.9 tons soybean (2.5 tons DM) /ha/y.

- ** 50% maize, 25% soybeans, 25% cabbage (or other vetetables and fruits)

Average Global production yields 2017: maize 5.8, soybean 2.8 = 4.9 tons/ha/y (FAOstat 2019). Assumptions: only maize and soybeans are produced with a land use relation of 71% maize and 29% soybeans, no post-harvest losses, no LULUCF, only WFP ration (2,100 kcal/p/d): 190 kg maize and 60 kg soybeans per person and year.

Figure 3. Subsistence food production on 458 m2 for one person cropland under Global average yields scenario.

Landless food production

Landless food production is a field currently occupied only by a hand full of pioneers and inventors. Recent research is going for e.g. artificial meat (Ireland 2019), roof/vertical gardens (Southey 2019) and container hydroponics (Sustainia 2019). They are all producing with highly sophisticated technology, infrastructure, knowledge and hygiene and are capital intensive. Additionally, they are neither linked to land-and water-based food production nor the nutrient chains (e.g. human feces). Potential products target high price, rather than staple food chains. Therefore, they do not yet present a solution for food insecurity in less developed areas/regions with very high population densities. Landless food production, using “contaminated” nutrients for low/no price staple food for poor and fragile markets are an open research area. We initiated the project “LandLessFood” (https://www.thuenen.de/en/ol/by-specialist-disciplines/biodiversity/landlessfood/) as a conceptional model to cope with these defined pre-conditions and published it in Rahmann et al. (2019).

To ensure food sovereignty in Africa, photobioreactor-based food production would have to deliver 475,000 kcal/person/year, if only 458 m2 cropland per person are available and the production yields remain low like today. This could be 53 kg oil (9,000 kcal/kg) or 286 kg starch (3,700 kcal/kg), produced by algae or bacteria.

The reactor-based production costs of food energy must be low, e.g. 0.06 USD/1,000 kcal, if the food import costs (cheapest is maize, with 205 USD/ton cif Africa) is considered as an economic benchmark. If the reactor food would be more expensive, the import of maize would be the better alternative (including the protein in maize), if available and payable. The market price for one kg of oil could not exceed 0.54 USD and one kg of starch 0.22 USD, respectively. This would be 32 USD per person and year and about 188 billion USD for 5.9 billion people. Bioreactor food technology can be high-tech and industrial-like, but it would be much more suitable to have it low-tech, homebased and robust. If algae or bacteria can be produced at home by people, some of the main costs in production can be ignored: buildings and labor. Simple and cheap technology for reactor-based production of oil or starch is a R&D challenge.

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Africa 2100: How to feed Nigeria in 2100 with 800 million inhabitants?

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Abstract

Out of 54 countries in Africa, Nigeria is the most populous (>180 million) and the seventh largest in the world with an annual population growth rate of 2.7%. Unfortunately, the country drifted into the status of lower-middle-income status in 2014 and presently about 110 million Nigerians live below the poverty line with 36.4% of the population experiencing moderate-severe food insecurity. The population of the country had been predicted to reach 800 million in 2100 with the implication that there will be more demand for food to be produced on limited crop land. This paper discusses Nigeria's population dynamics, available land per person to produce food, vegetable and fruit production, and strategies to attain sustainable food and nutrition security in 2100.

Introduction

Nigeria is located in west Africa and occupies a land area of 923.768 km^2. The country is bordered by Benin Republic, Niger, Chad, Cameroun and a coast line of 853 km. Nigeria lies between latitudes 4^o and 14^{o}N, and longitudes 2^o and 15^{o}E with about 263 billion cubic meters of water and two of the largest rivers in Africa namely Rivers Niger and Benue (FEPSAN and FDD 2016). The population of Nigeria is estimated to be >180 million and the country ranks 152 out of 188 countries in Human Development Index (HDI) as at 2019 (Anon 2019a). The nation's total agricultural land comprises of 91 million ha out of which 71 million is arable, but only 40 million is being cultivated (United Nations 2017). This is against the estimated land area of 78.5 million ha of land required for farming to feed Nigeria's growing population (Anon 2019b). Presently, over 50% of Nigerians live in the rural areas and the nation's economy is highly dependent on agriculture which provides employment for about 70% of the population and contributes approximately 21% of the country's Gross Domestic Product (GDP) as reported by PwC (2019). The contribution of agriculture into the GDP has not improved markedly in the last decade partly because of internal conflicts such as terrorism and herdsmen crisis which has displaced about 1.92 million people and left over 7.7 million in need of humanitarian assistance. Consequently, an estimated 110 million Nigerians (60% of population) live below the poverty line (WFP 2019).

Furthermore, hunger is on the increase and the combination of moderate and severe hunger levels of food insecurity is estimated at 36.4% in the country with undernourishment doubling from 6.5 to 13.4% between 2014 and 2018 (FAO 2019). According to the prediction of the United Nations, a population of 793 million people will be living in Nigeria in 2100 which is currently food insecure (United Nations 2017). Therefore, there is the need to start addressing the inevitable immense challenge of feeding 800 million Nigerians in 2100.

Nigeria's population dynamics

The annual population growth rate for Nigeria is 2.7% and over 50% of the population live in the rural areas. This growth rate is influenced by birth, death and migration (Nwokoye 2009). With a fertility rate of 36.9 births per 1,000 people, Nigeria's population is bound to continue to increase indefinitely. Nigeria is projected to add about 202 million people to its current population estimate of 198 million between 2018 and 2050 to achieve a total of 398 million people (PwC 2019). Based on this statistics, the country has been identified as the second among the nine countries (India, the Democratic Republic of Congo, Pakistan, Ethiopia, Tanzania, the United States, Uganda and Indonesia) expected to account for half of the world's projected population increase by 2050 (United Nations 2017b). A study on population growth and economic development in Nigeria between 1980 and 2003 revealed that growth in population outweighed that of output and consequently hindered the capacity of successive governments to provide adequate social services to Nigerians (Onwuka 2006). According to PwC (2019), age demography in Nigeria as at 2018 stood at 42.54% (0-14 years), 19.61% (15-24 years), 34.72% (25-54 years) and 3.13% (>65 years).

A total of 62.15% of Nigerian youths (<25 years) are most likely to prefer life in the urban areas. In fact the commercial capital of Nigeria (Lagos) has been predicted to become the largest city in the world with a population of 88 million people in 2100 (Hoomweg and Pope 2017). It is now becoming increasingly difficult to produce adequate food to feed the teeming population of Nigerians. An earlier systematic study on the analysis of Nigeria food imports and bills between 1900 and 2011, noted that the country imported about USD 9.28 million worth of food per day (Vaughan et al. 2014). Today the import food bill of the country now stands at an average of $22 billion USD per annum (Thibiebi 2018). Therefore, to produce adequate food to feed Nigeria's increasing population is a very critical challenge.

Nigeria's population growth and land availability

Based on data compiled by the United Nations (2017) and FAOSTATA (2018), Nigeria's population has been projected to reach 973 million and 1082 million in 2100 under medium and worst cases, respectively. The country occupies 91 million hectares out of which 40 million hectares are utilized as cropland. At present with an estimated population of 193.5 million people, it translates to 2100 m^2 of land available per person. Under medium and high fertility assumption till 2100 with a predicted population of 793 and 1082 million people, only 504 and 370 m^2 of land will be available per person. Apparently, the country will not be able to attain self-sufficiency in food production under such limited land space. Against the backdrop that food demand is increasing globally than the population, it is expected to increase by 100 – 110% in 2050 (Tilman et al. 2011). The problem of lack of adequate food and basic facilities is further compounded by the conflict with the Boko Haram insurgent group especially in the vast north eastern states of Nigeria where an estimated 823,000 people live in areas that are not accessible to international humanitarian organisations (Anon 2019a). By 2100, Nigeria is bound to face very serious challenges in order to feed her population. At present, only 44% (40 million ha out of 91million ha) of crop land is being used for agriculture. Under best assumption, the arable land must be increased to 82% in order to feed her people and this is not humanly possible. Worst case will require 321% arable land (Rahmann 2019). The implication is that the country will require an arable land of 292.11 million ha which is a little more than three times its current size (91 million ha) to produce food for her population. This is simply humanly impossible to achieve.

Vegetable production in Nigeria

In general, vegetables (leafy and fruits) are widely cultivated in Nigeria primarily as a cheap and reliable source of protein, vitamins, zinc and iron. However, this enterprise is characterized with the use of crude implements at subsistence level, limited improved inputs such as improved varieties, bio-pesticides and soil amendments (Mofeke et al. 2003), illiteracy, emerging expensive and complicated technologies (Sabo and Zira 2009). In 2017, Nigeria produced 16.4 million tonnes of vegetables as against 2.79 million tonnes in 1968 (Fig. 1). The estimated growth rate of vegetable production is 3.83% (Anon 2019c). The common tropical vegetables produced in Nigeria include amaranth, celosia, pumpkin, roselle, okra, garden egg, species of pepper, tomatoes and sorrel. Whilst some exotic vegetable species being cultivated also include beet, lettuce, cabbage, radish, cucumber, carrot, celery and potato (Olasantan 1996; Ibeawuchi et al. 2015). The major fruits being produced in Nigeria include mango, pineapple, plantain/banana, citrus, guava, pawpaw and others (Ibeawuchi et al. 2015). These vegetables are produced mainly under rain-fed conditions and seldom during off-season (dry season) under irrigation or under lowland or valley beds. The proportion of rain-fed and irrigated vegetable production is 72% to 28% (humid region), 58% to 42% (sub-humid) and 32% to 68% (dry savanna), respectively as described by Olasantan (1996). Vegetable production is predominantly done by resource-constrained peasant farmers who do not readily have access to improved technologies. As such, their practice can best be described intensive traditional system in which they seldom use synthetic inputs. This scenario corroborates the report that average fertilizer consumption in Nigeria 12 – 15 kg/ha as against 100 kg/ha in the world (FEPAN FDD 2014). In order to boost production, an integrated approach in nutrient management will be more appropriate. According to the recommendation of the World Health Organisation (WHO), 400g of fruits and vegetables per day (excluding potatoes and other starchy tubers) can prevent heart disease, cancer, diabetes and obesity (FAO & WHO 2004). A rough calculation that if 16.4 million tonnes of vegetables were produced in 2017 in Nigeria with an estimated population of 193.5 million people and assuming that 50% of produce will get to the consumer (Rahmann et al. 2017), only 116.1 g of vegetable and fruit is available to an individual as against 400 g recommended by the WHO. Consequently, the situation will be more critical in 2100 if appropriate measures are not taken very soon.

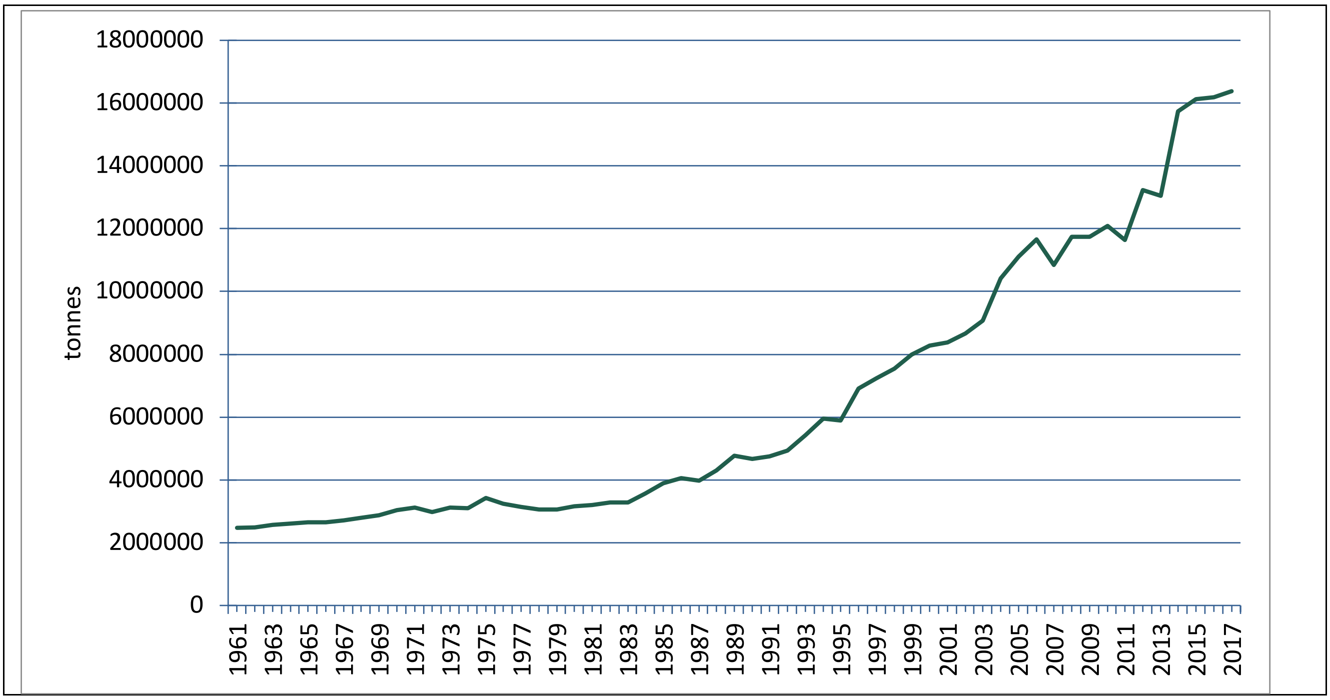

Fig 1: Vegetable production in Nigeria between 1961 and 2017

Towards achieving sustainable food security before 2100

With the apparent significant decrease in available land for farming to an individual from 2,067 m^2 in 2019 to 504 m^2 and 370 m^2 in 2100 under moderate and worst cases, respectively, if Nigeria must attain food and nutrition sufficiency in 2100, then appropriate measures must be taken to address the challenge of limited land available for food production in the country. A veritable option might be the combination of land based production system and sustainable landless food production system in Nigeria. Therefore, the following broad based strategies are recommended:

a. Need for greater investment in agriculture and food systems research and development (R&D) by Government at all levels and the private sector in order to upgrade the value chain and increase production output. Agriculture has been receiving budgetary allocation of <4.0% for several years as against 10% recommended by Maputo Declaration in 2003 (Ebi and Amaraihu 2018).

b. Sustainable intensification of the available limited production system such as practicing climate smart agriculture, precision farming, nutrition-sensitive agriculture, agroecological related approaches.
c. Encouragement of innovation platforms that provide opportunities for co-learning and collective actions that can drive agricultural productivity.
d. Upgrading of the present storage facilities and construction of new and modern facilities to arrest the huge postharvest losses of up to 40% depending on the commodity (Olayemi et al. 2012)
e. Policies to be put in place must be such that will take into consideration risk insurance scheme, help sustain household resilience to shocks.
f. Need to develop infrastructural facilities in the rural areas to facilitate the movement of agricultural produce from the primary source of production to the markets.

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Landless food versus crop intensification in Africa - where do the substrates for food synthesis come from?

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Introduction

The biophysical conditions for food production in Africa are ambivalent. Low inherent soil fertility including P deficiency generally reduce crop productivity, while climatic conditions, in particular solar radiation and temperature strongly favor crop growth, if nutrients and water are not limiting. A major reason for the low productivity of African agriculture is poor management often resulting from missing know-how and capital. Some people argue that so called reactor food is a promising option to satisfy the future food demand of a growing African population (Rahmann et al. 2019). Here we critically discuss this approach based on an analysis of the mass flows. To increase African food production, we propose a para-organic approach, which integrates classical organic management practices and reasonable use of chemical inputs.

What is reactor food?

In contrast to land-based food, reactor food is the outcome of biochemical processes in a controlled artificial environment. During the process any type of biomass may be converted into nutrients, physiologically available for humans, such as carbohydrates, fats and proteins. For example, wheat straw in theory can be converted to sugars physiologically available for humans. More sophisticated, meat could be produced with muscle cells reproduced on nutrient solutions (Orzechowski, 2015). Both processes have in common that they need substrates that can be metabolized unless using photoautotrophic bioreactors.

Which substrates can be used?

Theoretically, all types of biomass such as crop residues, organic household waste, slurry, grass, wood, algae or even sewage sludge could fuel the reactor provided that corresponding techniques for conversion are available. Reactor food should be energy dense and free of harmful compounds, e.g. heavy metals. A further important criteria for substrate suitability is local availability in sufficient amounts.

Limits of the approach

Hitherto the reactor food approach is without any relevance for current world nutrition. Potentials and constraints however need to be assessed before setting any future research agenda. Socio-economic, technical and ecological implications of the approach have to be analysed in advance.
First and foremost, reactor food will meet serious economic constraints, mainly due to the low purchasing power of the people in SSA, unless economies will make a quantum leap in this century. Missing capital is currently one of the main reasons for low productivity of African agriculture. When assuming no financial constraints, both the physical availability of substrates for the reactor, and the access to reactor food in needy areas are the key challenges.

Constraints to substrate availability mainly occur in regions, where plant biomass production is low e.g. the Sahel zone. Low rainfall and poor soils in these regions not only limit current food supply, but also potential reactor substrate supply. In regions with favorable agronomic conditions, in contrast, exploiting the unused potential of land based food production systems has to be prioritized.

Algae, in contrast could be a promising substrate for bioreactors in coastal regions, which, however, are generally less prone to food shortage.

It is also important to consider ecological aspects of substrate provision and alternative use options for biomass. Crop residues and animal manure, for example, are essential components to maintain soil fertility. Wooden biomass can be used for various other purposes such as construction, commodities and fire wood. To avoid competition for substrate use the implementation of photoautotroph systems is most promising from a theoretical point of view, provided that economic and technical constraints can be resolved. Experiments with photoautotrophic microalgae have shown that a total of 7 t ha^{-1} of starch could be produced within 150 d even under the climatic conditions of Middle Europe (Branikova et al. 2010). This is a higly productive process however only equaling a 50 t per ha potato yield with 20% dm and 70% starch in the dm. Whenever biomass production is generated by photoautotrophic processes, larger land areas will be needed that could be used for soil based cropping as well. In addition, all resources needed for plant growth have to be externally supplied including in particular P.

The main challenge for all innovations, however, remains the affordability of food for low income households in low income countries. In any case, sustainably increasing crop productivity, i.e. the area related output over time, is essential. Implementing key elements of Organic Farming in African cropping systems can help to improve productivity, if they are embedded in a free concept of ecological intensification.

Approaches to increase food production and crop productivity

Improving soil fertility and crop management

In the frame of a recent research project extensive studies on paddy rice and maize productivity were carried out from 2015 - 2018 on two sites in East Africa (https://www.wetlands-africa.uni-bonn.de/). The experiments, which were in part carried out on wetland soils during the dry season revealed both a considerable maize production potential during the dry season and yield gaps in Uganda. Intensive mineral nitrogen application (120 kg N ha^{-1}) resulted on average of three seasons in maize grain yields of 5 t ha^{-1}, while only 1.6 t ha^{-1} under farmer's practice. High application rates of organic amendments (poultry and green manure equaling 120 kg N ha^{-1}) gave yields of 4.2 t ha^{-1} (Alibu et al. 2019). Significant yield increases were also recorded for paddy rice in the Kilombero flood plain in Tanzania after mineral nitrogen or intensive green and animal manure application (Kwesiga et al. 2019). In the same experiments rice grain yield could be more than doubled compared with farmers practice (3 t ha^{-1}), just by implementing GAP combined with a reasonable urea input of 60 kg N ha^{-1} (Kwesiga et al. 2019).

However, there are several constraints for implementing ecological intensification in SSA. First and foremost, animal manure is rare and production requires mixed farming systems including stable systems. Both do currently not exist and would require a significant social shift targeted on making pastoralists farmers and *vice versa*. Do ensure legume productivity sufficient P supply is needed, a mineral often deficient in African soils. Green manure application, although a promising approach to increase crop productivity is still in the cradle stage. Interestingly, knowledge on using green manure is available since decades (e.g. http://www.tropicalforages.info/), but the adoption by farmers is low. However, closing the yield gaps in a sustainable way is the first step to increase productivity of African agriculture. Given the low current input level of mineral fertilizers, in particular N and P, and the low availability of green manure seeds, approaches for ecological intensification need to consider both, a reasonable amount of mineral fertilizer input and the site adapted use of organic amendments.
For a proper assessment of the agricultural conditions in SSA it is important to give a fair assessment on mineral nitrogen fertilizers. The negative implications of its use, in particular substantial fossil energy consumption, release of reactive nitrogen in the atmosphere, eutrophication and food quality

impairment, have to be counterbalanced with the evident yield increasing effect. For African agriculture, the strict non-use of mineral nitrogen fertilizers, a compulsory rule in Organic Farming, is not a viable option. The historical argumentation that the use of nitrogen fertilizers is the starting point of a general intensification including also other chemicals, e.g. for crop protection, is not necessarily true for the African context. The use of mineral nitrogen fertilizers should be limited as much as possible for reasons of resource conservation. For that purpose a diversification of the cropping systems is urgently needed. In the Arsi region in Ethiopia for example close to 80% of the arable land is used for wheat production, making these systems prone to calamities. Under these conditions, crop diversification and the use of animal and green manure including legumes, i.e. para-organic, could help to stabilize the systems if economically viable. A key constraint for crop diversification is the lower short term income generation. Currently, for farmers in the Arsi region no crop is as profitable as wheat and farm sizes are small (1-2 ha).

To ensure a sustainable development, in a medium term, it will be decisive that global mineral N fertilizer production will be fuelled with renewable energy sources, for both ecological and economic reasons.

Agroforesty and polyculture

In some regions of Africa, the optimal use of natural resources could be achieved by sophisticated systems of agroforestry or polyculture. These systems can be very productive and are best adapted to climatic hazards. The implementation of fertilizer tree systems in Southern Africa, for example, turned out to be an inexpensive technology that significantly raised crop yields, reduced food insecurity providing environmental services (Ayai et al. 2011). However, developing and establishing productive systems, is both research and knowledge intensive and needs to be adopted by farmers.
3. Water harvesting and irrigation

According to the IAASTD global report 2009 water harvesting and irrigation have a great potential to increase crop productivity in African regions with sufficient rainfall, but an unfavorable rainfall pattern. Including a second growing season, e.g. in some regions of Tanzania, could help to increase the production, in particular of horticultural products. Likewise, rain fed production could be upgraded with supplemental irrigation to increase yield stability. Establishing irrigation facilities is the paradigm for ecological intensification if based on sustainable water harvesting. Missing technical skills and capital, however, currently limit the adoption of this approach. Similar to other innovations the profitability of this approach might be critical since it mainly depends of the producer prices. Higher prices probably resulting from raising global food demand, may help to boost investment in irrigation also in low income countries.

Reducing PHL

According to the African Post Harvest Losses Information System (https://www.aphlis.net/en/) loss of food can be considerable, counteracting any effort of improving crop productivity. On average of over 30 African countries, dry weight losses of maize averaged 18% in 2018. The main reasons for losses are unsuitable storage facilities favoring pests such as the large grain borer (*Prostephanus truncatus*), which can damage important staple crops such as maize. Future strategies need to focus on both large-scale professional storage and small scale solutions using metal clips with reduced oxygen content (Tefera et al. 2011). Improved storage systems require both technical know-how and capital.

Extending arable land size

According to the FAO there are still considerable land reserves in Africa for conversion to arable land. A recent reassessment of the potential crop area in Africa has shown a wide range of 80 to 247 $*10^6$ ha, when not considering forest conversion (Chamberlin et al. 2014). Important criteria causing variation included the suitability and profitability of cropland conversion as well as the status of land-use prior to conversion. Suitable agricultural cropland without forest amounted $247*10^6$ ha, but only $80*10^6$, if current profitability was factored in. Currently mainly economic constraints hinder cropland expansion in Africa, but the approach remains an ace up the sleeve of African agriculture.

6: Nourishing not only feeding the people

According to a recent study, calorie supply *per capita* in Ethiopia has increased during the last decade, while food diversity has decreased, resulting in hidden hunger and malnutrition (Baye et al 2019). Therefore, a diversification of crop production including more vegetables and fruits, but also more dairy products, has to be targeted in future African agriculture. Again, only increased purchasing power of the African consumer can boost this development.

Conclusion

Many of the approaches mentioned here are not new, but have already been discussed for more than a decade (Tilman et al. 2002, Foley et al. 2011, van Ittersum 2016). The implementation needs to be predominantly pursued by the countries concerned. A promising future for African agriculture will mainly depend of the overall economic development, in particular with respect to infrastructure and purchasing power of the people. Political and societal changes targeted on capacity building and on strengthening the performance awareness of the people can help to boost the development.

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Feeding the reactors: potentials in re-cycled organic fertilisers

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Abstract

There is a large and growing interest in producing proteins, oils and other important commodities in bioreactors. Mineral fertilisers, especially nitrogen (N) and phosphorus (P), are used to supply the living organisms with nutrients, and for growing of fungi and other heterotroph microorganisms, carbon is usually applied from sugar or starch products. This input-for-output approach does not contribute to cycling of nutrients and organic matter in the society. Organic*[2] agriculture has a strong interest in recycled fertilisers and best utilisation of organic materials, and such products should be developed not only for use in agricultural fields but also for other purposes, such as hydroponics, aquaponics and bioreactors. Animal bones, and precipitated struvite from waste water, are examples of materials which may be applicable in bioreactors. Containing easily available N and P, recent studies have shown that these materials are valuable for amendment of soil fertility and crop productivity in land-based agriculture. Studies should be initiated to design bioreactors utilising locally available sources of nutrients and organic matter, to make the bioreactors more sustainable and develop organic* farming systems in a context of landless farming.

Introduction

Human populations grow, and undisturbed environments decline. Urbanisation, salinization, desertification, rising sea levels, floods and erosion pose significant threats to the global capital of cultivated land. Options are sought, and required, to produce food and feed with other methods than traditional cultivation of agricultural land, and natural collection. *Landless food systems* are called for, e.g. in a paper aiming at securing the availability of food in Africa in 2100 by more circular and sustainable food chains (Rahmann et al. 2019). The authors propose a combination of landless and land-based food production as the last, and most important, out of totally 10 actions towards this important aim. The main idea is to establish a system of bioreactors to circulate nutrients and produce calories (food ingredients) for food and feed. Microalgae and fungi, especially yeast, are the most relevant organisms to be grown in bioreactors. Growing yeast in closed systems is a well-established industry. Fungi are dependent on supply of a source of fixated carbon (e.g. sugar), whereas microalgae fixate carbon from the air with light as energy source. Both groups of organisms are dependent on supply of some elements like nitrogen (N) and phosphorus (P).

Strains of yeast have been cultivated since about 1900, and strains may be traditionally bred, or genetically modified, for different purpose. For instance, it is possible to produce “animal-free milk” from a strain designed for this purpose, by inserting genes for milk production into the yeast cell, multiplying the strain, adding nutrients and sugar required for fermentation, and filtering off the requested product (Kowitt 2017). Research on enzymes being able to degrade complex types of organic matter such as lignin to sugars is vigorous, and proteins for feeding fish are planned to be produced from wood (Øverland & Skrede 2017). Some yeast species produce filaments which may be useful for extracting food and feed-like materials from the fermentation broths. A product called mycoprotein is grown in bioreactors from a filamentous type of fungi originally isolated from soil, *Fusarium venenatum*. The output is a material comparable to minced meat. Mixed with a binding

[2] To distinguish between the term “organic” as in certified organic farming, and “organic” as in soil organic matter, the first notion will be indicated with an asterix, *

agent from eggs or potatoes, the commercial product “Quorn” is increasingly popular, but also questioned for being far from natural (Blythman 2018). Growing single animal cells in bioreactors is another approach (e.g. JUST meat).

Microalgae have been harvested from natural environments for human consumption e.g. in pills and cookies, commercially cultivated for human consumption and aquaculture, and broadly studied for technical applications (biofuel) and/or application as food ingredients (protein, lipids, polysaccharides, prebiotics) (Caporgno & Mathys 2018). For this group of organisms, research has so far rather concentrated on utilising various naturally occurring species, than breeding new strains. Species may be harvested for further cultivation both from sea water and fresh water. The sea water species *Spirulina platensis*, being very high in proteins, has received a special interest (e.g. Lupatini et al. 2017). There is a possibility for utilising waste-water (Lundquist et al. 2010), or salinized drainage water in cultivation systems for microalgae (Bosschaert 2001).

Whereas the interest in producing alternatives to meat, and transforming less valuable organic materials to biofuels, is massive, the interest for combining such approaches with recycling of nutrients from organic waste instead of purified mineral fertilisers is low. The authors of the landless food concept are ambitious: One hectare of cropland should be replaced by not more than one square meter of bioreactor space (Rahmann et al. 2019). Released cropland should be used for production of high-quality, fresh and edible food items. The food system should be able to produce enough, healthy and affordable food 11-16 billion people by 2100. To be a part of a complete organic* food systems, these reactors should be fed by recycled fertilisers and poorly utilised sources of organic matter, being locally available and integrated in a circular economy. Hydroponic and aquaponic growing systems, and raising of snails, larvae and other nutritious organisms are other examples of food and feed production which may occur in landless food production, where recycled fertilisers and organic waste may be utilised and upgraded. Such production methods are out of the scope of this paper.

Landless approaches to food production challenge the concept of naturalness, emphasised by many environmentally concerned consumers and developed e.g. in certified organic* food production. As discussed by Blythman (2018), a lot of processing and food additives are required between the reactor and the final consumer. On the other side, a better recycling of nutrients, and increasing food security for all, are challenges where organic* food production needs better solutions to design a complete food system which can contribute significantly to sustainable development.

In the present paper, basic requirements for fertilisation of organisms produced in bioreactors will be presented, focussing on microalgae and yeasts. Based on results and experiences with various recycled fertiliser materials and using animal bones and struvite from sewage as examples, I will then discuss how we may design landless food-reactors adapted to such sources of nutrients, rather than conventional mineral fertilisers. The aim of the paper is to present relevant research findings and discuss how they may contribute to realise a system of food and feed producing bioreactors required in a landless food system.

Conditions for growing microalgae and yeast fungi in bioreactors

Required elements

Terrestrial crop plants acquire carbon (C, as carbon dioxide, CO_2) and oxygen (O_2) from the air. They acquire hydrogen from water (H_2O) and essential macro-minerals nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) from the soil. Legume plants can also assimilate N_2 from the air. Additionally, a range of microminerals (boron (B), chloride (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni) and zink (Zn)) are required.

For microalgae, the nutrient demand is somewhat different. The basic mineral requirements are equal for all species of microalgae, and comprise N, P and carbon (C) (Khan et al. 2018). Some marine microalgae species also require silicon (Si) as a macronutrient. Microalgae demand B, cobalt (Co), Fe, potassium (K), Mg, Mo, Mn and Zn in trace amounts for successful growth. Microalgae absorb O_2 and H_2 from water. The concentrations of available N in the culture substrate has a strong effect on algal growth. N limitation may reduce algal growth and biomass productivity but may increase the production of carbohydrates and lipids. The source of carbon can be organic forms, such as glycerol or acetates, or CO_2, which may allow for a concurrent carbon sequestration if the gas is well utilised by the algae. However, in practice this may be difficult to achieve (Slade & Bauen 2013).

For the growing of single cell protein or other compounds from yeast, N, P, S, Fe, Cu, Zn and Mn are essential elements required, in addition to carbon, oxygen and hydrogen. Sugars are most often used as the C source, but with the right enzymes available, also much less readily degradable materials such as cellulose and even lignin may be used as raw materials (Bekatorou et al. 2006).

Other conditions

Microalgae are dependent on a source of energy, either from the sun or artificial light. Commercial production of microalgae occurs in two principally different systems; the raceway pond system, which occurs outdoor in a flat area with good access to sunlight, and the photo-bioreactor system where the algae are cultivated in transparent tubes or containers in a controlled environment (Slade & Bauen 2013). In both systems, the broth of algae and nutrients must be circulated to avoid sedimentation or clogging. In regions of the world with good access to sunlight, fresh water is commonly a scarce resource and marine species of algae may be a better option. Since the cultivation of microalgae in a controlled environment is quite expensive, a two-step system where the initial phase of cultivation occurs indoors, and the final growth phase in a cheaper raceway pond, may be relevant. Cheap access to CO_2 and fertilisers (N, P) is crucial for economic viability, and plants may well be combined with cleaning of exhaust and waste water to benefit from cleaning gate fees (Lundquist et al. 2010). Most microalgae prefer a temperature range of 15 to 30 °C, and the pH in the growing media should be 7-9 (Esbroek 2018).

For the production of biomass by yeast cells, no light is required, but the process demands a continuous aeration. While yeasts can grow in a range of temperatures from 0 to 47 °C, the optimum temperature for growth is 20–30 °C. Yeasts favour acidic conditions and grow well at pH 4.0–4.5 (Battock & Azam-Ali 1998).

Recycled fertilisers applicable for fertilisation of bioreactors

One of the characteristics of residual and waste materials of organic origin is that all elements are integrated in tissues which are often easily degradable, and large molecules with characteristics quite different from the soluble salts in mineral fertilisers, or the dissolved nutrients in liquid fertilisers. A "final" treatment of organic waste materials occurs in waste treatment plants, which may be very different across the globe dependent on local conditions and scale. Mixing with soil, composting, anaerobic digestion (fermentation), dumping (in landfills, rivers or the sea) and incineration are some major pathways of treatment for solid waste, whereas liquid waste and sludges are commonly treated in water-treatment plants or applied to soil. Huge amounts of nutrients and organic matter (carbon) are currently poorly utilised in both small-scale and large-scale treatment systems of organic waste, and there is a conflict between the aims of producing high-quality food with low concentrations of unwanted elements and compounds such as pesticide residues and heavy metals, and the need to maintain soil fertility and avoid polluting the environment with excess nutrients e.g. by eutrophication (Løes & Adler 2019).

Producing more food and feed nearby the sites where large amounts of organic waste materials are produced, may open new possibilities for better utilisation of valuable nutrients and organic matter. However, since organic materials are susceptible to degradation and hence commonly the place of living for a range of organisms, they may be challenging to utilise in a simplistic system where only one type of organism is expected to survive, such as in a bioreactor. Procedures to sanitise the materials before applying them to the reactors may be required.

For utilisation in a food and feed-grade bioreactor, one option is to apply fertiliser inputs which are also food grade, e.g. derived from food industry. This applies to large volumes e.g. of bone-rich residues, which have proven to be highly efficient fertilisers for crop plants, being rich in N, P, Ca and other minerals. The challenge would then be to maintain food-grade quality throughout the production chain, e.g. during storage and distribution of the fertilisers.

Another option could be to precipitate minerals such as struvite (magnesium-ammonium phosphate) from waste water, and thereby remove both N and P and reduce the environmental load to natural waterbodies. By this chemical processing, very pure minerals are achieved, reducing the risk of contamination e.g. with bacteria or heavy metals.

Recycled organic fertilisers: Sediments from oil and protein extraction

After removal of the commercially available meat parts, cartilage and muscle fibres rich in N are still present on animal bones, which are also in themselves rich in N, in addition to P and Ca. Such residues may be ground and hydrolysed, and food or feed grade oils may be produced, along with food or feed grade soluble proteins. Until now, less use has been made of the remaining sediments, which still contain significant amounts of N in proteins not dissolved by hydrolysis, plus Ca and P.

Studies of sediments from ground bones of laying hens, and white fish (cod, saithe) at NORSØK have shown that plants grow vigorously with such materials applied as fertilisers (Løes 2017; Ahuja & Løes 2019). The growth effect is much more rapid than for calcium nitrate, which is considered as a rapidly available N fertiliser. This may be due to the concurrent availability of P. However, it may also be that the N in the animal residues is not necessarily being mineralised into ammonium and/or nitrate but taken up directly by the plants. This is not easy to study in practice, but research has shown that plants may assimilate small organic molecules and not only dissolved ions (Dion et al. 2018).
The potential use of such sediments in a bioreactor needs to be studied. The rapid availability of nutrients in experiments with crop plants indicate that nutrients may become available also in a circulating solution. Microalgae are rich in protein and demand high N concentrations. The concentration of N and P can vary quite substantially, from 5 to 10% of dry matter for N and 0.3-1.2% for P (Lundquist et al. 2010), and the utilisation efficiency of N (which may be susceptible to gaseous losses) on average may be assumed to be about 50% (ibid.).

One option to avoid that bioreactors are filled up with solid particles could be to keep materials like this in nylon bags which the water circulates through. However, this will increase the energy consumption for water circulation.

Recycled mineral fertilisers

Phosphorus is a scarce resource, but can be circulated in the soil-plant-food-soil continuum with a clever design of farming systems. A significant proportion of the total amount of P available for such cycling is found in wastewater (sewage; Möller et al. 2018). In some countries, biosolids from sewage are used for soil amendment, but in other countries such material is incinerated. In biosolids, the P is often bound by chemicals, making the P less available for uptake in plants or other organisms. Even with such binding of P, treated wastewater may still contain significant concentrations of P.

Hence, there are many reasons to improve the removal of P from wastewater. N may be emitted as gas, which reduces the risk of eutrophication. A better option could be to also remove the N in solid form. Precipitation of struvite implies removal of both N and P. This mineral is easily solubilised in soil, even if it is not water soluble. Applying this mineral to organically managed soil could be an efficient way to increase P cycling (Rittl et al. 2019), since P is often depleted by long-term organic* management (Cooper et al. 2018).

If conditions for dissolving the salt can be established, struvite may be a very relevant fertiliser to apply in bioreactors. Another option is to combine bioreactors with wastewater treatment, to utilise the capacity of the living organisms to take up N and P.

Discussion

Two types of waste materials have been presented here. These materials were selected because they have shown promising effects in recent studies with crop plants, and the author has an up-to-date, hands-on experience with these fertilisers. However, several other materials are available in addition which may be useful for applying elements (N, P, K, S, Ca, Mg, micronutrients) and/or organic matter as a source of C. Liquid anaerobic digestate, or liquid animal manure, may be applicable since these materials are easy to mix into a fermentation broth or liquid media for microalgae. Digestate from facilities for treating food waste often comes in a sanitised state, but this status is challenging to maintain since the content of mineral N and other nutrients is high and there is still much organic material ready for decomposition. Liquid animal manure is far from sterile, but in a system where the growing medium is exposed to solar radiation (such as in a raceway system for microalgae), these organisms may die off rapidly.

As for other innovations, the question of scale is crucial. Organic waste is produced on a small-scale level with individuals and families, on a medium-scale level from catering services, and on a large-scale level for food and feed industry. Bioreactors with yeast or microalgae are likely less robust than e.g. crop plants towards infectious diseases or suboptimal growing conditions. With their generally short life span, the natural behaviour of these organisms will be to spread vigorously and utilise events of satisfactory conditions for a very rapid growth (e.g. leading to algal blooms), leading to a wave of repeated/further spreading. Crop plants may demand more care and infrastructure (e.g. weed-free soil, water, sunlight, fertilisers), but when established they have some resistance e.g. towards diseases and pest attacks, and ability to recover from temporary unfavourable conditions. Hence, bioreactors call for substrates which are easier to handle than e.g. source-separated household waste which is a very diverse mixture of materials and better suited for a more robust treatment such as anaerobic digestion. The digestate however, may be suitable for application, and the same is valid for compost tea.

The high concentrations of both N and P in animal bones (including fish bones) and struvite precipitated from wastewater match the demand for these elements in both yeast and microalgae. This is interesting, since both of these types of recycled fertilisers are poorly balanced with respect to the needs of crop plants (Ahuja & Løes 2019; Rittl et al. 2019), and hence need to be applied only in special cases e.g. of P depletion or mixed with other materials. Possibly, bioreactors can be a growing system where these fertilisers fit especially well to the demands of the organisms being grown. However, this needs to be studied in detail.

Until now, staple food produced in bioreactors is still quite rare, but research efforts are extensive. As shown by Lundquist et al. (2010), the infrastructure for bioreactors is costly, and variable costs such as costs for growing substrates (sugar), nutrients and light are significant. Hence, combining such reactors with other purposes, such as cleaning of wastewater, may be beneficial. Since bioreactors demand relatively much P, but less of other macronutrients, the potential of such growing systems to contribute to increase the proportion of P which enters a cycling instead of an "input-output-lost for cycling" approach is also of high interest.

All in all, it deserves a further consideration, and well-planned studies, to combine ideas from organic* agriculture such as utilising locally available sources of organic matter and nutrients, with technologically advanced growing systems like bioreactors. The author of this paper has never worked with a bioreactor and hence is very much aware that the arguments presented here may be heavily challenged by scientists with other background and perspectives. Possibly, discussions in the upcoming workshop, "Combining land-based organic and landless food production: concept for a sustainable solution for Africa in 2100" in Marrakech, November 14-16, 2019, may contribute to a further development of this very preliminary paper.

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Versatility of algae -Exploring the potential of algae for nutrient circulation

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Abstract

For feeding the world in 2100, the global agriculture, the entire food chain, as well as the behavior of all consumers must be change fundamentally. Essential resources needed to intensify agriculture and use barren land, such as phosphorus, water and fossil fuels, are becoming increasingly scarce and expensive. An ecological form of agriculture that uses these resources more responsibly requires more land for the same yields. Therefore, new concepts for food and feed production have to be developed, in which nutrients are recycled beyond these areas. A possible starting point could be bioreactors, since these are enormously efficient and enable resource-efficient land use. Wastewater treatment as a means of nutrient recycling will be one of the most important tasks in the future. Hereby, not only the heterotrophic bioreactors currently used for this purpose but also autotrophic photobioreactors show great potential, especially if these two reactor types would be combined. Because of the ability to use inorganic nitrogen and phosphorous for their growth as well as the ability to produce a wide range of metabolites microalgae offer an integrated approach. This review provides an overview of the potential of microalgae as components of a sustainable, circular agricultural system for feed and food production.

Introduction

Today agriculture is based on the primary production of terrestrial plants. With the notable exception of most fish (etc.), almost every calorie a human consumes was produced in the leaf of a relatively large, soil-based vascular plant. In water, living organisms which operate photosynthesis are called algae. The number of species can only be estimated but they are the major contributors of biodiversity and present in salt-, brackish- or freshwater (Graham et al. 2009; Metting 1996). On the basis of their size, a distinction is made between microalgae and macroalgae. Microalgae are single-celled organism and they can be found individually, in chains or groups with a size ranging from a few micrometers to a few hundred micrometers. Responsible for roughly 70% of the oxygen in the atmosphere, these single celled algae and cyanobacteria (together referred to as microalgae) dominate in aquatic ecosystems. These organisms have long been viewed by scientists as having great potential for the agricultural system, especially with regards to biofuel but also for food, feed and fertilizer production. The main reasons for this optimism are very high photosynthetic efficiency of microalgae and the possibility of using waste water for their cultivation, as well as flue gases, which can be fed into photobioreactors to increase productivity and mitigate CO_2. However, the “hype” (Posten 2009; Walker et al. 2005) around the potential of microalgae cultivation has not yet been accompanied by large-scale success of photobioreactors.

The individual algae classes (divisions), Fig. 1, are distinguished primarily by the composition of their photosynthetic pigments and products. The microalgae diatoms (Bacillariophyceae) can be found in the oceans, fresh water, brackish water and soils of the world. The green algae (Chlorophyceae) are abundant, especially in freshwater and have the same photosynthetic pigments (chlorophyll a and b), the same set of carotenoids (alpha, beta and gamma carotene, lutein, zeaxanthin, violaxanthin, etc.), the same reserve substance (starch) and the same framework substance of the cell wall (Cellulose) as green plants. Euglenophyta (Euglenophyceae) are predominating in fresh water, especially in eutrophic waters. Their frequent occurrence can cause a water bloom. The golden algae (Chrysophyceae) are a large group of algae, found mostly in freshwater. The dinoflagellates (Pyrrhophyta) belong to the class of Dinophyceae with more than 1000 species, many of which live parasitic. Dinoflagellates occur in salt and fresh water. In the sea they are the second most important group of phytoplankton after diatoms. In warm waters biodiversity is high with low numbers of individuals. In cold climates, few species with high numbers of individuals predominate. At regular intervals mass developments of certain species occur in which the water turns red or orange (red tide) because of the large amount of carotenoids formed. (Algen 1996-2004). The red algae (Rhodophyta, Rhodophyceae) are a division of algae, which are colored red by the phycobilin that is involved in photosynthesis. Beside Glaucophyta and Chloroplastida, the red algae form one of the three groups of Archaeplastida. Red algae occur in the majority in the littoral zone of the sea, some species also in fresh water and in moist soil.

The brown algae (Phaeophyceae) are a large group of multicellular algae mostly living in marine environments, and they are important for food and as habitat. The blue green algae (Cyanophyceae; Cyanobacteria, prokaryotes) are an excellent source of biologically active natural products including vitamin, protein, fine chemicals, and renewable fuel. They are largely unexplored and offer a great opportunity to discover new compounds, among others, biologically active compounds like antibacterial, antiviral, antifungal, algaecide, therapeutic agents and cytotoxic activities (El Abed et al. 2008; van den Hoek C 1995).

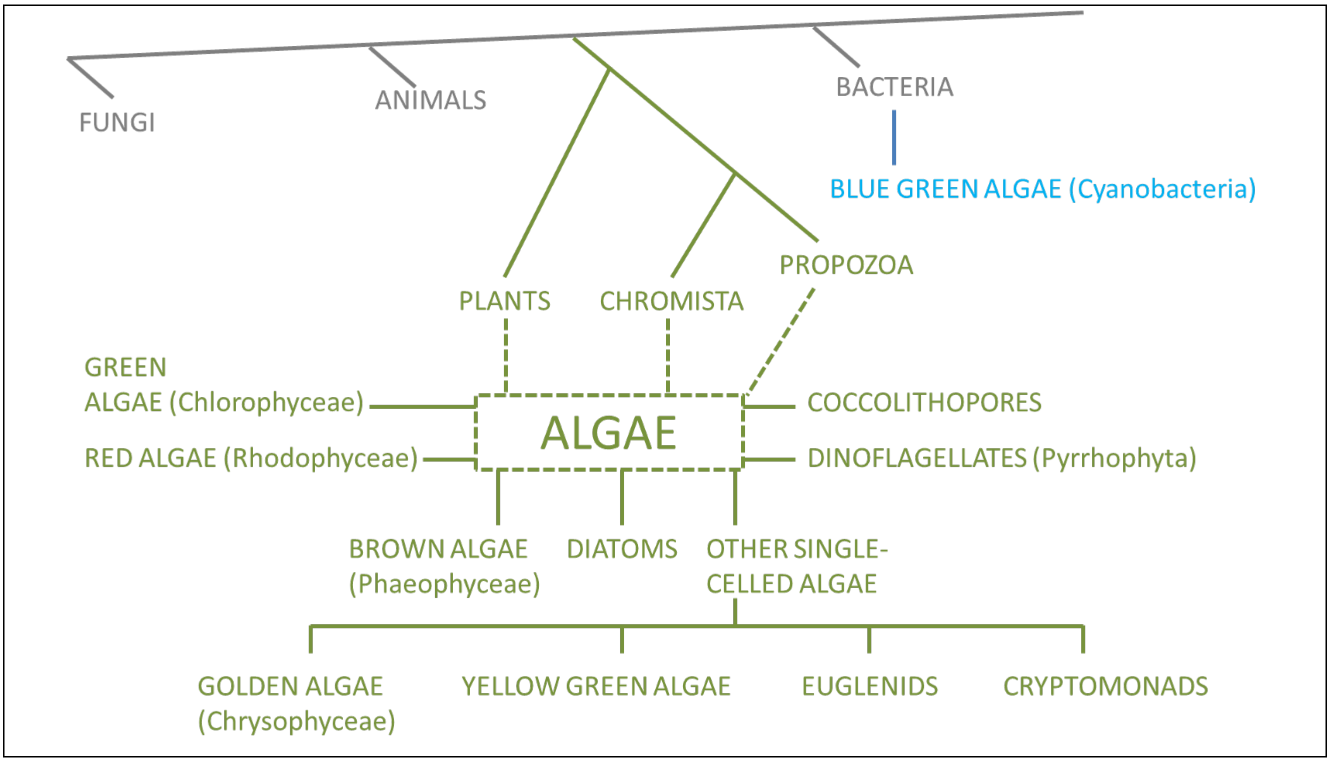

Figure 1: Simplified taxonomy of single-celled algae and cyanobacteria, modified after (Enamala et al. 2018; Fondriest Environmental 2014); dashed line: classification under debate.

Microalgae are a large, unexplored group of organisms and only a few of the 30,000 known species are currently of commercial significance (Tab. 1). Even though they can be used to produce a wide range of metabolites like proteins, lipids, carbohydrates, carotenoids and vitamins for health, food and feed additives, cosmetics and for energy production. Microalgae can enhance the nutritional value of food and feed and play a crucial role in aquaculture (polyunsaturated fatty acids - PUFA). Three key points of microalgae can be converted into technical and commercial advantages:

- genetically very diverse with a wide range of physiological and biochemical characteristics,
- cost-effectively incorporate the stable isotopes ^{13}C, ^{15}N and ^{2}H into their biomass,
- a large, unexplored group of organisms which offer an untapped source for products (Chew et al. 2017; Priyadarshani and Rath 2012; Vanthoor-Koopmans et al. 2013b).

Table 6: Major microalgae commercialized for human nutrition, adapted from (Priyadarshani and Rath 2012)

Major Producers	Microalgae	Products
Hainan Simai Pharmacy Co. (China); Earthrise Nutritionals (California, USA); Cyanotech Corp. (Hawaii, USA); Myanmar Spirulina factory (Myanmar)	*Spirulina (Arthrosphira)*	powders, extracts tablets, beverages, chips, pasta and liquid extract
Taiwan Chlorella Manufacturing Co. (Taiwan); Roquette Klötze GmbH & Co. KG (Germany)	*Chlorella*	tablets, nectar, noodles, powders
Cognis Nutrition and Health (Australia)	*Dunaliella salina*	powders, b-carotene
Blue Green Foods (USA) Vision (USA)	*Aphanizomenon flos-aquae*	capsules, crystals, powder

Nevertheless, the positive aspects of using microalgae also have downsides - or rather challenges. High yields can only be achieved by high energy expenditure. Light energy is an important factor, therefore either artificial lighting costs have to be borne or the strong dependence of sunlight has to be accepted. Currently, the use of algae as an alternative to fuels is not competitive (Hannon et al. 2010; Lehr and Posten 2009; Razzak et al. 2013; Richardson et al. 2012).

Technological improvements and economic changes, as well as a gradual cost reduction when photobioreactors become more established could lead to more large-scale operations in the coming years. However, it is not clear yet how microalgae cultivation can best be integrated into the agricultural system as a whole. Here we analyze the potential of microalgae cultivation with regard to photosynthetic and areal efficiency, as well as resource-use and nutrient circulation.

Photosynthetic efficiency

Photosynthetic efficiency (PE), sometimes also referred to as photon conversion efficiency, is the conversion rate from solar energy (photons) to chemical energy (biomass), usually given as a percentage in relation to the light that hits a certain surface area. The basis of photosynthesis is the quantum-mechanical process of light absorption, which takes place at the thylakoid membranes in chloroplasts. In this process energy is transferred from photons to pigments, which are part of large protein-pigment complexes. These either form antenna, meant exclusively for light harvesting, or reaction centers, which also absorb light but are most important for passing on the energy, to power the chemical reactions which ultimately cumulate in the production of glucose from CO_2 and H_2O. These pigments can only absorb light in a certain band-width. Most higher plants use light in the range from 400 – 700 nm, which means that 51.3% of solar energy is unavailable to them (Zhu et al. 2008). Chlorophylls are the most important pigments for photosynthesis. Different types of chlorophylls have different absorption characteristics, but in general they absorb light in the red and blue range, leaving a “green gap” between roughly 500 and 600 nm. Microalgae and cyanobacteria have different types of chlorophyll, which enable them to absorb light above 700 nm and below 400 nm (Zhu et al. 2010). To fill the green gap, different pigments, such as the bacterial phycobillins are used (Zhu et al. 2010). The use of a wider range of pigments is one of the reasons why microalgae usually have higher PE than vascular plants. However, too much light can be harmful and lead to photosynthetic stress and the creation of toxic reactive oxygen species (ROS). To react to this, plants and microalgae can change the interactions between pigments through conformational changes of the proteins, or they can use pigments such as carotenoids, xanthophyll and zeaxanthin as protection. These pigments emit the energy from light absorption as heat rather than passing it on to the reaction centers (Zhu et al. 2010).

Photosynthesis also depends on a light-independent chain of reactions: the Calvin cycle. Here, one of the main factors affecting PE is the functioning of the enzyme RuBisCO. This enzyme is responsible for fixating CO_2 but also has an affinity to O_2. When O_2 concentrations are high, usually due to oxygen production in the light-dependent reaction of photosynthesis, electrons will be transferred to O_2 more frequently, which leads to energy loss. Many higher plants solve this problem by separating the light-dependent and independent reactions in space, by letting them take place in different compartments (C4-plants), or by separating them in time, letting the light-independent reaction take place at night (CAM-plants). Microalgae cannot use these strategies and are thus dependent on protection from light stress through the use of protective pigments and antioxidants. However, while higher plants will regularly experience high oxygen concentrations in their leaves when closing the stomata, the level of photorespiration in microalgae is mostly dependent on the oxygen concentration in the surrounding substrate. While this might mean that microalgae are experiencing less photorespiration than higher plants in most natural environments, in photobioreactors it represents one of the central problems and challenges, since it means that the cultivation process is only effective when oxygen concentrations are sufficiently low and CO_2 concentrations sufficiently high. In most reactor types this requires constant gas exchange. An advantage of this circumstance is however, that the productivity (and thus PE) can be increased through feeding excess CO_2 from industrial or agricultural activities (e.g. biogas plants) into the photobioreactors. This has the added benefit of CO_2 mitigation.

PE is not only affected by molecular differences, such as described above, but also by morphological traits. Microalgae for example have a lower surface to volume ratio, which is beneficial. Also, microalgae do not have to grow and support non-photosynthetic tissues. While a tree has to form roots, stems, fruits etc. and keep up nutrient and water flow between these different body parts to complete its life cycle, microalgae will simply duplicate once their single cell has reached sufficient size and accumulated enough energy. It is important to note for microalgae cultivation that electric energy is needed to fulfill many of the functions that a higher plant takes care of itself: gas exchange, nutrient and water flow, as well as temperature control (Sayre 2010). To determine the PE of a photobioreactor, it is necessary to take these energy inputs into account. Sometimes it is not clear whether this was done when researchers give PE values for photobioreactors.

Estimations of the PE of different organisms vary widely but the general consensus is that microalgae have much higher PE than higher plants. It is however difficult to pinpoint the magnitude of this difference from literature. Sometimes PE is given as a theoretical maximum, sometimes as a “realistic estimate” and very occasionally as a value that has actually been measured. Another difficulty is that some estimates of PE refer to the whole spectrum of sunlight, while others refer only to the spectrum of light available to plants.

The theoretical maximum of PE is generally higher for C4 plants than for C3 plants, with 6% compared to 4.6% (Zhu et al. 20010). In the “real world” however, PE of higher plants is typically below 1% in temperate and tropical climates (Blankenship et al. 2011). Microalgae are said to have theoretical maximum PE of more than 20% (Janssen et al. 2003), based on photosynthetically available light, which would amount to about 10% PE and thus roughly twice as much a higher plants.

In reality, the PE of photobioreactors is also way below the theoretical maximum. A PE of above 5% can however be seen as realistic according to most sources (Schenk et al. 2008; Janssen et al. 2003; Wijffels and Barbosa 2010). All in all, the energy yield of photobioreactors is lower than that of photovoltaic solar panels (Blankenship et al. 2011) but very high compared to crops. Solar panels take advantage of a larger spectrum of light, by stacking different light-absorbing layers above each other (Blankenship et al. 2011). It would be possible to do the same with photobioreactors, for example by positioning two flat-panel bioreactors with two different species that make use of different wavelengths of light, in front of each other. Researchers are also looking at ways of improving energy yield of photosynthesis by genetically altering organisms and for example making RuBisCO less prone to photorespiration or modifying the pigment-protein complexes (Zhu et al. 2010).

Algae for nutrient circulation

Microalgae mainly consist of proteins, carbohydrates and lipids with varying composition depending on the microalgae species. The carbohydrate fraction (starch, sugars, glucose and other polysaccharides) is found to be up to 64% in microalgae biomass, the protein fraction up to 71% and the lipid fraction up to 22% of cell dry weight (Becker 2007; Razzak et al. 2013). The content is highly specific to species and depending on growth conditions (Weyer et al. 2009). Under stress conditions like low nitrogen content or in the presence of supplemental reductants like sugar or glycerol, some species, e.g. *Nannochloropsis* sp. F&M-M24, accumulate energy-dense storage compounds such as lipids. Up to 60% of neutral lipids per gram of dry weight (Rodolfi et al. 2009; Sayre 2010). Of course, to build up biomass, microalgae need a carbon source, water, temperature control and light, but also minerals like nitrogen, phosphorus and other essential nutrients like sulfur, iron, magnesium, etc. (Graham et al. 2009). Therefore algae are well suited to grow on wastewater that naturally includes high amounts of nutrients (Arashiro et al. 2019; Razzak et al. 2013).

Carbon source

Microalgae are capable of using carbon in form of carbon dioxide from the atmosphere as well as emission from industrial power plants, inorganic carbon like $NaHCO_3$ and Na_2CO_3 and organic carbon in form of sodium acetate, glucose, and glycerol. Since the beginning of the industrialization, the well-balanced ecosystem, including carbon capture from photosynthesis, carbon deposition in soil and oceans, and carbon release from biological and geological sources, is out of balance. The atmospheric CO_2 concentration increased from 295 ppm to 380 ppm over the last century, which is one of the main driving factors of global warming and climate change (Sayre 2010). According to Razzak et al. (2013), producing 100 t of algal biomass fixes about 183 t of CO_2. The nongaseous form of CO_2, which occurres in water at concentration over 50% at pH values between 6.4 and 10.3, is bicarbonate which can be transported and concentrated in algae. Inside the cell, the bicarbonate is reconverted to CO_2 and can be fixed to RuBisCO. After several reactions these molecules are substrates for starch and oil production (Huertas et al. 2001; Sayre 2010). According to literature, flue gas can be used as a carbon source for the production of microalgae (Demirbas 2011; Doucha et al. 2005; Holdmann and Schmid-Staiger 2016; Kadam 2002). Doucha et al. provided a combined biotechnological process scheme where agricultural wastes are anaerobically digested, the produced biogas is combusted in a boiler and, following this, the flue gases are decarbonized by microalgae (Doucha et al. 2005). In addition to autotrphic microalgae, which mainly use CO_2 as a carbon source, there are several mixotrophic and heterotrophi species which can access carbon from a range of different substrates. In the cultivation of these species, light energy is not an absolutely limiting factor (Kong et al. 2013). According to Cheng et al. the algae *Chlorella protothecoides* achieved an oil content of 53% by cell dry weight during a heterotrophic cultivation in a media containing sugar cane juice as an alternative carbon source (Cheng et al. 2009). This strain is also able to use glycerol, crude glycerol and a glucose/glycerol mixture as carbon sources (Kamjunke et al. 2008; O'Grady and Morgan 2011).

Nitrogen and phosphorus

Nitrogen and phosphorus are essential to all organisms. Therefore, not only the environmental burdens resulting from excessive use should be considered, but also the overuse of a finite resource. Nitrogen is the essential element of proteins and DNA and therefore also the building block of all enzymes that control plant, animal and human metabolism. Nitrogen and hydrogen can be taken from the ambient air to synthesize ammonia (Haber-Bosch process). Among other things, ammonia is used to produce urea, ammonium nitrate, ammonium sulphate and ammonium phosphates, which are used as fertilizers and contribute to the nutrition of a large part of the world's population. Also compounds of phosphorus are essential for all living organisms and involved in the structure and function of organisms in key areas, such as DNA and the cellular energy supply (ADP/ATP). Phosphorus is naturally present in minerals, most commonly apatite. These minerals are mined in places with high phosphate content and, after appropriate treatment, used as mineral fertilizer, thus entering the phosphate cycle. Phosphorus, with increasing annual degradation, is about to reach the peak, where production reaches its maximum. It is estimated that the world's reserves will cover the need for about 100 years (BMEL 2011), and other sources calculate shorter periods of time out (White and Cordell 2008).

Through traditional technologies for wastewater treatment nitrogen, phosphorus, carbon and other nutrients are not completely utilized and recycled (Abdel-Raouf et al. 2012; Han et al. 2019). In order to guarantee an environmentally friendly supply of these essential nutrients, continued work on economic recovery and recycling of these resources is necessary.

Microalgae offer the opportunity for the treatment of wastewater due to their ability to use inorganic nitrogen and phosphorus to build up biomass (Abdel-Raouf et al. 2012; Zhao et al. 2019). Sources of nitrogen are inorganic nitrogen sources like nitrate, nitrite, ammonia and urea (Li et al. 2008; Xiong et al. 2008) and for some algae species also organic nitrogen sources like glycine and yeast extract (Xiong et al. 2008). Algae take up nitrate and ammonium ions directly from the surrounding water, with ammonium being preferred to build up cellular nitrogen compounds. Using the enzyme nitrate reductase, algae are able to convert nitrate to ammonium (Graham et al. 2009).

Phosphorus in form of orthophosphate (PO_4^{3-}) is the preferred uptake form of algae.

After aerobic or anaerobic biological degradation of wastewater, the content of inorganic components like nitrate, ammonium and phosphate ions is sufficient for eutrophication of water environment. Microalgae show high capacity to take up these components and use inorganic nitrogen and phosphorous for their growth (Abdel-Raouf et al. 2012; Zhao et al. 2019).

Other nutrients

Elements like sulfur, iron, magnesium and others are required as trace elements. Indeed, iron acts as a cofactor for several enzymes like ferredoxin, catalase, cytrocomes, glutamate synthetase, nitrogenase, nitrate and nitrite reductase (Graham et al. 2009). Sulfur is usually taken up and assimilated as sulfate and is essential for the incorporation into a variety of sulfur-containing compounds critical for protein, lipid and polysaccharide synthesis, as well as signaling molecules (Giordano M. et al. 2008; Shibagaki N. and A. 2008). Magnesium also serves as a cofactor of several enzymes and is required for the biosynthesis of chlorophyll (Brzezowski et al. 2015; Graham et al. 2009). Beside the requirement of trace elements, algae are also known for their ability to absorb and accumulate heavy metals and compounds like organochlorides. Additionally the secretion of extracellular esterase, which degrades Deltamethrin (insecticide) and the ability to degrade a range of hydrocarbons (found in oily wastes) are known for some species of microalgae (Abdel-Raouf et al. 2012; Arunakumara and Zhang 2008; Worms et al. 2010).

Potential of microalgae

Due to the biodiversity, the composition of the biomass depending on the nutrient availability, use of different nutrients and the production of different substances, microalgae show great potential for a wide variety of applications (Metting 1996).

Microalgae assisted aquaculture is known for live feed for larvae, fish species and zooplankton (Brown et al. 1997), as food additive to supply basic nutrients, enhance the color of salmonids or for other biological activities (Muller-Feuga 2000), stabilization and improvement of quality of culture medium (Chuntapa et al. 2003), stimulation of immune systems (Spolaore et al. 2006) as well as probiotic effects (Irianto and Austin 2002; Han et al. 2019; Roy and Pal 2014). The most-used species are *Spirulina*, *Chlorella*, *Scenedesmus*, *Dunaliella*, *Tetraselmis*, *Isochrysis*, *Pavlova*, *Skeletonema*, *Chaetoceros*, *Phaeodactylum*, *Nitzschia*, and *Thalassiosira* (Beal et al. 2018; Brown et al. 1997; Han et al. 2019).

Next to the potential of microalgae in aquaculture, the potential is also given in the area of implementing an eco-friendly system using microalgae in form of, e.g., wastewater treatment and nitrogen removal (Abdel-Raouf et al. 2012; Arashiro et al. 2019; Di Termini et al. 2011; Ledda et al. 2015b; Razzak et al. 2013; Wang et al. 2019; Yu et al. 2019), treatment of heavily polluted meat processing wastewater as primary or secondary treatment option (Hu et al. 2019), recycling of animal wastewater and manure (Kim et al. 2007; Ledda et al. 2015a; Pizarro et al. 2002) and flue gas (Doucha et al. 2005; Nagase et al. 1997; Yoo et al. 2010).

The potential of microalgae in generating biofuels has been of major interest over the last decades (Chew et al. 2017; Hussian 2018; Vanthoor-Koopmans et al. 2013a). The usage of algae components like carbohydrates, mainly consisting of glucose, starch, cellulose as well as polysaccharides, show potential too (Chew et al. 2017). Microalgae are able to generate a wide variety of photosynthetic storage products including α-(1-4)-linked glucans (starches), β-(1-3)-glucans, fructans, low molecular weight carbohydrates, and fats and oils. Different types of starches are produced by different divisions of algae, e.g., red algae are known to synthesize floridean starch (amylopectin subunits), whereas blue-green algae synthesize myxophycean starch (amylopectin or glycogen-like subunits). Some species of green algae synthesize, a cross-linked amylose-amylopectin starch and fructosans (inulin-like fructose oligosaccharides), which are comparable to starch in land plants. Cryptophytes and dinoftagellates generate α-(1-4)-linked glucans. Chrysophytes store oils or chrysophycean starch, a water-soluble β-(1-3) glucopyranoside (Metting 1996). According to literature starch contents up to 60% of dry weight are achieved with *Chlorella vulgaris* (Branyikova et al. 2011; Dragone et al. 2011; Pruvost et al. 2011) and *Tetraselmis subcordiformis* (Yao et al. 2012), and up to 50% of dry weight with *Phaeodactylum tricornutum* (Jakob et al. 2007).

Hence, investigations (beside the usage for biofuel, or as a source of bioactive compounds and pharmaceuticals, health foods or cosmetic additives) could be of high interest maybe to yield starch (produced without the need of arable land) or fermentable monosaccharides to receive an ecological and sustainable bioresource (Chew et al. 2017; Reisky et al. 2019).

Conclusion

The versatility of algae and therefore their potential for nutrient circulation, biomitigation of carbons must be of increasing interest in the future due to existing problems including global warming, discharge of wastes, supply of nutrients (nitrogen, phosphorus) or toxic chemicals.

The possibility given through these highly diverse microalgae, capable to grow photoautotroph, heterotroph, and mixotroph on barren land and the ability of CO_2 fixation must be investigated more intensively. An ideal algae strain for tropical climates should be able to produce biomass at high solar radiance and high oxygen levels.

The challenge will be to have this ideal strain in the right place and in a perfect, yet simple combination of wastewater treatment, CO_2 biomitigation and nutrient recycling to create new concepts for food and feed production in bioreactors. The implementation must be technically simple, long-term stable and easy to handle and to care for. In order to have enough purified water, food and feed to supply the world in 2100, the integrated usage of microalgae could be an opportunity for the global agriculture.

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Algae as means of converting waste carbon dioxide into food with a high nutritional value

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Abstract

Microalgae form a wide group of photosynthetic microorganisms, which includes prokaryotic cyanobacteria (e.g. genus *Arthrospira*) as well as eukaryotic unicellular algae (e.g. genus *Chlorella*). Microalgae can be regarded as "microplants" able to convert carbon dioxide and water into organic compounds via photosynthesis. Nevertheless, comparing to higher plants (agricultural crops) the microalgae have much higher areal productivities; high content of proteins, vitamins, antioxidants, polyunsaturated fatty acids and other health-promoting components. Moreover, they can be produced in non-arable areas requiring low-cost inputs. To reach high productivities of microalgal cultures, it is necessary to supply them with sufficient illumination, carbon dioxide and minerals in culturing media. Nowadays microalgae for human and/or animal nutrition are produced in different types of photobioreactors where previously mentioned suitable conditions are ensured along with appropriate mixing and oxygen release. In order to decrease the cultivation cost of microalgae, it was proven that different kinds of flue gasses can be used as a carbon dioxide source; sunlight is the source of energy (illumination) and in some cases suitable waste water can be used as the source of mineral nutrients. Considering current state of knowledge, *Arthrospira* (spirulina, often rated among "superfoods") seems to be the most promising microalga for widespread cultivation in large scale as for its cultivation and harvesting no expensive technologies are needed.

Use of microalgal biomass and possibilities of waste water utilization

The biomass of microalgae is nowadays used as food and feed supplement (*Arthrospira, Chlorella*), in aquacultures (*Nannochloropsis, Isochrysis, Tetraselmis, Phaeodactylum*) and for β-carotene (*Dunaliella*) and astaxanthin production (*Haematococcus).* Future use can be extended to agriculture as biofertilizers/biostimulants, in this case even use of municipal waste water can be considered. For other purposes, the required microbial safety of the microalgal biomass prevents use of waste waters for cultivation without prior hygienization or specific nutrient extraction (Doušková et al. 2010). Only some specific waste waters like different food industry effluents can be recycled to form basis of cultivation media (Ghobrini et al. 2018).

Photobioreactors

Microalgal biotechnology has a history of about 60 years, over this time period many different types of photobioreactors (PBRs) were invented, but only few types are used in large scale for price-competitive production of the microalgal biomass. Generally, the PBRs can be divided into two groups: closed and open systems (some authors use the term PBRs only for closed systems). Other criterion is the source of illumination – artificial/solar, but for sustainable microalgae production we consider only solar cultivation systems. Generally, the most important requirements on PBR are to ensure:

(i) Suitable illumination (Too much light causes so called photoinhibition – loss in productivity, low light limits the growth as well. Geometry of the PBR and location define the amount of incident light including its distribution over day and over year period - cultivation season.)

(ii) Non-limiting supply of carbon dioxide (Depending on the system, concentrations from 1 to 100 % v/v of carbon dioxide is used. Content of carbon dioxide in air is too low to keep the production culture not-limited by.)

(iii) Efficient mixing which avoid settling of microalgae and ensure uniform light distribution in whole volume of algal culture.

(iv) Effective oxygen release (Oxygen emerging by photosynthesis causes decreases in photosynthetic activity of microalgae and so lower the productivity.)

(v) Suitable temperature (PBR can be easily overheated by sunlight and microalgae irreversibly damaged by high temperature. Water evaporation from open systems serves as simple and efficient temperature control. In closed systems temperature must be regulated by thermostatic water bath or spraying with water.)

(vi) Easy cleaning, sanitation and overall operation

It can be concluded, that closed systems are more expensive, more suitable for slow growing microalgae as they are less prone to microbial contamination. The utilization of carbon dioxide is usually better in closed systems but the culture often suffers from oversaturation by oxygen (Fig. 1). On the other hand, open systems (raceway ponds, Fig. 2) are less expensive, but final harvesting concentrations of biomass are very low, which increase harvesting costs. One of very promising options is floating PBR, which is using ocean waves to provide mixing energy and surrounding water to control the temperature (Huang et al. 2016; Zhu et al. 2019).

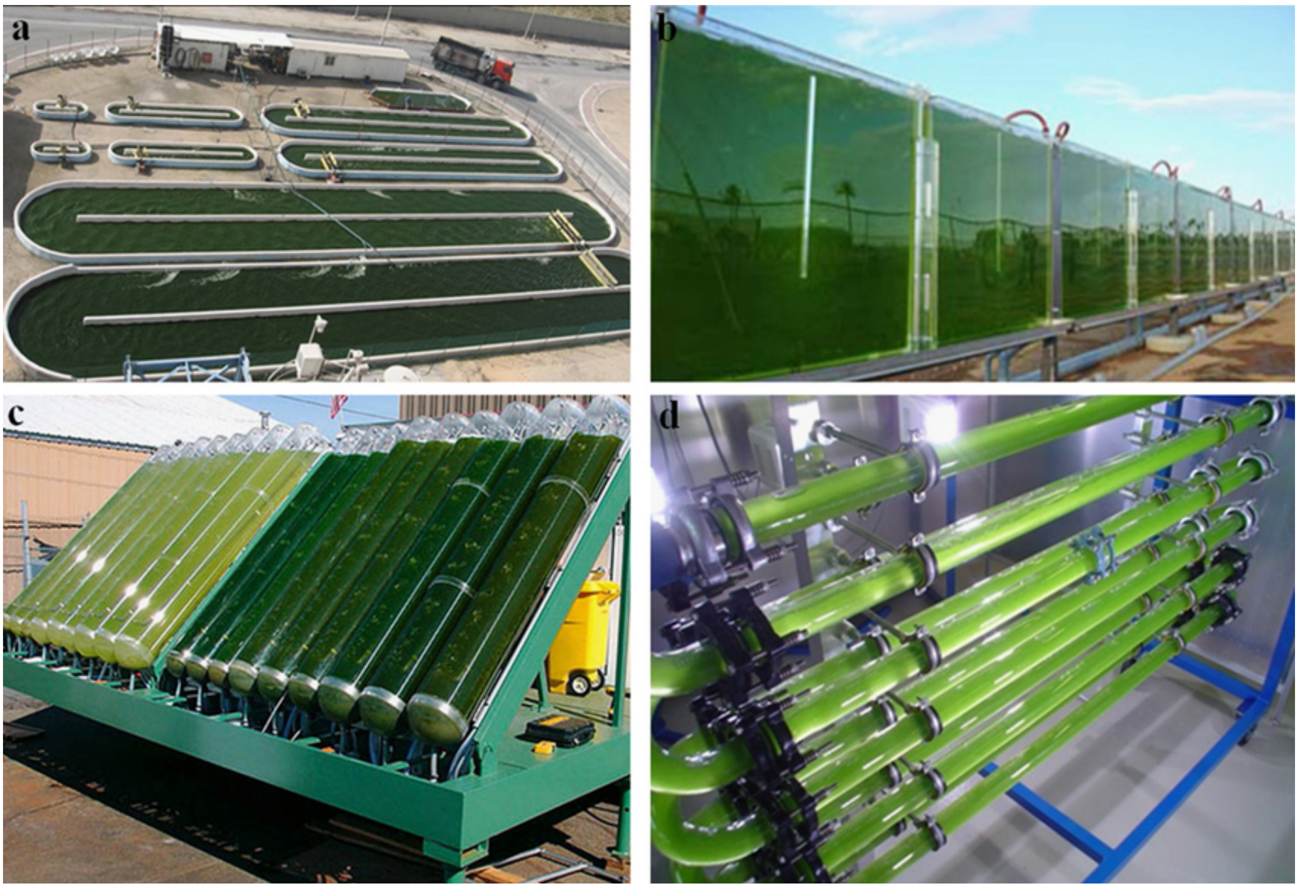

Fig. 1: Basic types of photobioreactors: a) open raceway pond, b) flat-plate photobioreactor, c) inclined tubular photobioreactor, d) horizontal tubular photobioreactor (Bitog et al. 2011).

Waste carbon dioxide

It was proven, that different kinds of waste carbon dioxide can be used for cultivation of microalgae e.g. flue gas from municipal waste incinerator, cogeneration unit or power station, biogas, fermentation gas, etc.) This approach can reduce production costs substantially but on the other hand waste sources of carbon dioxide may contain some toxic components (heavy metals, dioxins, polycyclic aromatic hydrocarbons, etc.), which can for one thing affect the growth of microalgae and for another be accumulated in the microalgal biomass. That is why the available source of waste carbon dioxide must be proven with respect to sensitivity of the given microalga and intended use of the gained biomass. An interesting example is shown in our previous work, where it was proofed that *Chlorella vulgaris* grown solely on flue gas from municipal waste incinerator fulfilled food grade criteria (Doušková et al. 2009).

Productivity of microalgae

The issue of microalgae productivity is very complex. The productivity is extremely dependent on:

(i) Microalgal strain selected
(ii) Type of photobioreactor
(iii) Climate (intensity of solar irradiance, temperature)
(iv) Appropriate settings of cultivation parameters (media composition, carbon dioxide supply, oxygen release, etc.)

Moreover, productivity must be always evaluated in context with reached harvesting density, as microalgae harvesting is often a very energy and cost demanding operation. For example one of the most often used microalga *Chlorella* sp. is usually harvested by centrifugation, which besides great investment costs spent about 2 kWh/kg dry biomass (Fasaei et al. 2018). The most common types of photobioreactors with gained microalgae biomass productivities for selected strains are in Tab. 1.

Tab. 1: Biomass productivities in common types of photobioreactors for selected microalgae strains.

Cultivation device	**Microalgal strain**	**Biomass productivity [g/L.day]**	Reference
Open thin-layer PBR	*Chlorella vulgaris*	4.30	(Doucha, 2009)
Open raceway pond	*Spirulina maxima*	0.21	(Gouveia and Oliviera, 2009)
Open raceway pond	*Chlorella vulgaris*	0.18	(Gouveia and Oliveira, 2009)
Open raceway pond	*Dunaliella tertiolecta*	0.12	(Gouveia and Oliveira, 2009)
Tubular PBR	*Chlorella sorokiniana*	0.23	(Rodolfi et al. 2009)
Tubular PBR	*Nannochloropsis*	0.17	(Rodolfi et al. 2009)
Tubular PBR	*Chlorella vulgaris*	0.10	(Rodolfi et al. 2009)

In the techno-economic analysis of cultivation of microalga *Tetraselmic suecica* in a flat-plate disposable photobioreactor was estimated that the biomass productivity in Italy could reach up 36 tons per hectare per year in price approximately 12,4 EUR/kg of dry biomass. With scale-up of this technology to from 1-ha scale to 100-ha scale the cost of the biomass would be lowered to 5,1 EUR/kg of dry biomass. If the production would be relocated to locality with more favorable climate conditions (f. e. Tunisia), the final cost of 1 kg of dry biomass would be lowered to 3,2 EUR in 100-ha production (Tredici et al. 2016).

Tab.2: Comparison of annual productivity of selected microalgal strains to crops.

Microalgal strain	**Locality**	**Cultivation device**	**Productivity [tons/ha.year]**	**Production cost [EUR/kg_{DW}]**	**Reference**
Tetraselmis suecica	Italy	Flat-plate PBR	36.0	5.10	(Tredici et al. 2016)
Tetraselmis suecica	Tunisia	Flat-plate PBR	54.0	3.20	(Tredici et al. 2016)
Nannochloropsis	Israel	Open pond	7.3	0.31	(Schenk et al. 2008)
Scenedesmus quadricauda	Czech Republic	Open thin-layer PBR	18.0	-	(Doucha et al. 2014)
Spirulina platensis	Spain	Open pond	30.0-32.0	-	(Jiménez et al. 2003)
Nannochloropsis	Israel	Flat-plate PBR	33.6-84.0	-	(Chauton et al. 2015)
Nannochloropsis	Brazil	Open pond	40.2	-	(Jorquera et al. 2010)
Type of crop	**Locality**	**Cultivaton device**	**Productivity [tons/ha.year]**	**Production cost [EUR/kg_{DW}]**	**Reference**
Soybean	Average worldwide	Arable area	3.4	0.35	OECD, 2019
Wheat	Average worldwide	Arable area	3.8	0.20	OECD, 2019
Maize	Average worldwide	Arable area	9.4	0.20	OECD, 2019

The price for microalgae biomass production is higher compared to the cost of agronomic crop production (EU Commission, 2019), but this situation can change rapidly during next few decades with introduction of innovative cultivation systems and procedures. Indisputable advantage of microalgae cultivation is significantly higher areal productivity comparing to traditional crop production (OECD, 2019). As it is shown in the Tab. 2, the productivity of selected microalgae strains is approximately 10 times higher compared to the productivity of agronomically cultivated crops as soybean or wheat.

Spirulina

Comparing to other microalgae spirulina (common name for *Arthrospira platensis* and *Arthrospira maxima*) has many advantages, due to which it is in our opinion the most promising and feasible choice. Dry spirulina is traditionally used food supplement in north-central Africa in the area of Chad lake. Spirulina growing in natural alkaline lagoons in this area is harvested by filtration through cloth or sand and dry on the sun. The dry cake called “dihé” is marketed in the same way as was documented from 9th century. Similar tradition was recorded in Aztecs and other Mesoamericans till 16th century. Since the 60s of the 20th century, spirulina is produced in industrial large-scale cultivation devices and marketed globally. Spirulina received “GRAS” (Generally Recognized As Safe) status from FDA (U.S. Food and Drug Administration) in the year 2003. Spirulina growth in alkaline pH (8,5-11), which makes the culture resistant to contamination by bacteria and other microalgae. Spirulina forms trichomes (helixes) about 0.5 mm long (Fig. 3), they are large enough to enable simple and cost effective separation from culture media by filtration. The cell wall of spirulina is thin and easy digestible for monogastric organisms (including humans), so no cell disintegration is needed. Unlike e.g. *Chlorella*, that must be centrifuged and disintegrated prior to consumption. Even FAO (Food and Agriculture Organization of the United Nations) regards spirulina as an important mean of treating malnutrition as it can be often produced *in situ* in very primitive conditions and represent concentrated complex source of valuable nutrients for human (FAO, 2008). Interestingly in south France (Europe) a phenomenon called “spiruliners” occur, some farmers change from traditional agricultural practices and starts to produce spirulina biomass. A French Federation of Spirulina producers (Fédération des Spiruliniers de France) has around 150 members (http://www.spiruliniersdefrance.fr). Similar scenario seems very feasible for many African countries as well, as they have favorable climate for spirulina cultivation. Additionally non-arable land, sea water and generally “low technologies” are sufficient for effective cultivation of spirulina.

Fig. 2: a) Arthrospira platensis SAG 85.79 microphotograph, b) filtering and drying of spirulina in primitive conditions, c) selling dihé in the market in Chad (FAO, http://www.fao.org/agriculture/crops/thematic-sitemap/theme/spi/photogallery/ar/)

Relevance of microalgae cultivation for the LandLessFood concept

Due to their ability of photosynthesis, microalgae are able to convert water and carbon dioxide into valuable organic compounds. Comparing to higher plants their areal productivities are much higher simultaneously with high content of nutritional beneficial components as proteins, polyunsaturated fatty acids, vitamins and minerals. In contrast with agricultural crops, microalgal biomass can be produced in non-arable areas. To produce algal biomass with high productivity is necessary to supply the culture with illumination as a source of energy and a sufficient amount of carbon dioxide as a source of inorganic carbon. In order to decrease the product cost, alternative sources of carbon dioxide as flue gasses can be used, sunlight is used as a source of illumination and some specific non-toxic waste waters can serve as a source of mineral nutrients for the microalgae cultivation.

Nowadays, most of the microalgae biomass is used as animal feed or food supplement (especially microalga *Chlorella* and cyanobacteria *Arthrospira*), but microalgae have also a great potential of use in agriculture (biofertilizers/biostimulants), waste water treatment or pharmacy.

The annual area productivity of autotrophically cultivated microalgae is approximately 10 times higher compared to the productivity of traditionally cultivated crops. For example, the annual productivity of microalga *Tetraselmis* cultivated in a flat-plate photobioreactor in Italy is 36 tones/ha.year and the annual productivity of soybean is 3.4 tones/ha.year. On the other hand, the cost of microalga biomass in much higher, in this case 5.4 EUR/kg of dry weight for *Tetraselmis* compared to 0.2 EUR/kg of soybean (Tredici et al. 2016). From this can be concluded that production of microalga biomass is a suitable option especially for non-arable areas, where the production of agronomical crops cannot take place.

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Prospects of insects as food and feed

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Abstract

The last ten year the interest to use Insects as food and feed has increased exponentially. In tropical zones insects are a common food item as they more readily available as food in nature. However, if we want to promote insects as food and feed, harvesting from nature is not an option and the farming of these animals is required. This can be done in environmentally controlled facilities. Insects are not only nutritionally excellent food; they may also have health benefits. When using organic side streams as substrate chemical and biological contaminants need to be considered. People are not used to eat insects and therefore strategies to convince consumers focus on food safety, environmental sustainability, and tastiness. The insect sector is maturing fast, but still faces many challenges, which can only be met when all stakeholders closely cooperate.

Introduction

The consumption of insects by early humans has often been undervalued in comparison to food plants and wild meat (McGrew, 2014). Therefore, Lesnik (2017) considered it a western bias that insects have been considered as a fall-back food resource, being used only in marginal environments. This notion of insects being a backward and a primitive food habit was contested by DeFoliart (1999). However, it may be understandable why insects in the western world were not eaten, while in tropical zones it was a common food habit. In the tropics, insects are bigger and available throughout the year. The harvesting is also easier as they are abundant and often they occur aggregated (Van Huis, 2018). However, recently it is being realized that insects are not only a nutritious food source, but also that they can be reared more sustainably than the common livestock species. Besides, they are a safe protein source which can be used by humans, production animals, fish and pets. Many efforts are now underway to farm several insect species in large automated facilities.

Which insect species are eaten?

Jongema (2015) listed more than 2000 different arthropod species. They belong to the following groups: Coleoptera (beetles, often the larvae) (31%), Lepidoptera (caterpillars) (17%), Hymenoptera (wasps, bees, and ants) (15%), Orthoptera (crickets, grasshoppers, and locusts) (14%), Hemiptera (true bugs) (11%), Isoptera (termites) (3%), Odonata (dragonflies), Diptera (flies), and others (9%). Some of those are eaten throughout the tropics such as termites and the larvae of palm weevils (*Rynchophorous* spp.). In central Africa several caterpillar species are eaten, and in southern Africa the mopane caterpillar, *Imbrasia belina*, is a common seasonal food item. In the Sahelian region of Africa, many grasshopper species are used as food. In Southeast Asia many insect species are eaten, but to mention just two popular ones: the giant water bug, *Lethocerus indicus*, and the weaver ant, *Oecophylla smaragdina*. In Australia, the witchetty grub, either a caterpillar of a beetle larvae, is well-known food of the aboriginals. In Mexico, chapulines, grasshoppers of the genus *Sphenarium*, a pest of agricultural crops, is popular food, while in Columbia the future queens of the ant *Atta laevigata* has been eaten for hundreds of years. The habits of insect eating, also called entomophagy, from people from all over the world has been extensively documented by Bergier (1941), Bodenheimer (1951) and DeFoliart (2002).

Why the recent interest of the western world?

The increased interest in the developed world for insects either as food and feed was prompted by the publication of the report "*Edible insects: future prospects for food and feed security*" of the Food and Agricultural Organization (FAO) of the United Nations (van Huis *et al.* 2013). This report showed that edible insects are a viable and sustainable food option for the future. Dietary change is worldwide considered a necessity as current food systems are a major driver of climate change, changes in land use, depletion of freshwater resources, and pollution of aquatic and terrestrial ecosystems (Springmann *et al.* 2018). Worldwide people are looking for meat alternatives, among which cultured meat, plant-based meat alternatives, algae, mycoproteins and insects (Van der Weele *et al.* 2019). Insect can play a role as its production has shown to have less environmental impact than livestock production (Van Huis and Oonincx, 2017). Besides several insect species can play a role in a circular economy as they are able of biodegradation and biotransformation of organic side streams (Varelas, 2019). The last ten years the number of scientific publications on edible insects has grown exponentially (van Huis, 2019) and the number of start-ups is now estimated to be more than 270 worldwide (BugBurger, 2019). Some companies have received millions of dollars to automate the production process.

Insect species as food and feed

If we would like to promote insects as food and feed harvesting from nature is no longer an option and we need to farm the insects. The number of insect species currently being reared for food and feed is limited. Those species are used that were already reared as pet food for captive reptiles, fish, and birds, or as bait for fishing. These insects are the yellow mealworms, the lesser mealworm and the superworm (larvae of beetles from the family of Tenebrionidae), several cricket species of which the most important one is the house cricket, *Acheta domestica*, and the migratory locust. As feed for animals mealworms are used, but also the house fly and the black soldier fly (*Hermetia illucens*). The last is extremely popular and many companies are now engaged in its production. This because it can tackle many types of waste streams. Even straw, being fermented first by fungi, can be tackled by this insect (Gao *et al.* 2019). To bio-convert resources high fibre waste such as almond hulls by the black soldier fly the carbon to nitrogen ratio has to be decreased, and this can be done for by nitrogen supplementation (Palma *et al.* 2019). It seems that up till now the insect species, manure being its natural habitat, has not shown to be affected by diseases.

There are insect species which can be semi-domesticated such as palm weevil larvae (Van Itterbeeck and van Huis, 2012). Other insect species such as the in East Africa very popular edible grasshopper, *Ruspolia differens*, are attempted to be reared on an artificial diet (Fombong *et al.* 2019). Probably, there are more species which need to be explored for mass rearing.

Nutrition and health

From reviewing 236 insect species (Rumpold and Schlüter, 2013) concluded that many edible insects provide satisfactorily with energy and protein, meet amino acid requirements for humans, are high in MUFA and/or PUFA, and rich in several micronutrients such as iron and zinc as well as riboflavin, pantothenic acid, biotin, and in some cases folic acid. (Payne *et al.* 2016) using nutritional models concluded that several edible insect species compared similar to different meat types.

However, the nutritional value, depends on the insect species and is influenced by numerous factors such as diet, stage harvested and environmental factors (Finke and Oonincx, 2014). The diet does not influence very much the protein content, but the fatty acid composition can be tailored to the target animals. For example, commercially produced insects are often low in n-3 fatty acids and have suboptimal n-6/n-3 ratios. Oonincx *et al.* (2019) could achieve optimal ratios by adding only 1-2% of flaxseed oil to the diet of r house crickets, lesser mealworms and black soldier flies. (Oonincx *et al.* 2018) also showed that insects can synthesize vitamin D de novo and that the amounts depend on UVb irradiance and exposure duration.

Recent publications have shown that insect may improve human gut health. For example, Stull *et al.* (2018) showed that cricket powder supported growth of the probiotic bacterium, *Bifidobacterium animalis*. Also Mota de Carvalho *et al.* (2019) also showed that powder of the yellow mealworm has a potential prebiotic effect. This prebiotic effect may be caused by the exoskeleton of insects, chitin (Komi *et al.* 2018), not only in humans (Stull *et al.* 2018) but also in fish (Rimoldi *et al.* 2019; Terova *et al.* 2019). Also insects have the largest repertoire of antimicrobial peptides and this promoted their development as alternatives to conventional antibiotics, in an attempt to address the threat of multidrug-resistant pathogens (Tonk and Vilcinskas, 2017). Water-soluble extracts of a number of insects species showed an antioxidant capacity (Messina *et al.* 2019) higher than fresh orange juice and olive oil (Di Mattia *et al.* 2019).

Industrial production

To produce insects, you need two units: a reproduction unit where adults can mate and lay their eggs; and a production unit where the eggs are sown on a substrate. The larvae are then reared until the last larval stage. In the case of mealworms and black soldier larvae trays are used. The substrate often is added during the rearing process. During this process, predators, parasitoids and microorganisms may attack and infect the insects. Eilenberg *et al.* (2015) proposed several strategies to avoid these problems.

When the harvested stage is reached, e.g. last larval stages for mealworms and prepupae for the black soldier fly, the left-over substrate should be removed which can then be used as fertilizer. Probably due chitin or its derivate chitosan which triggers plant growth and induces plant defence (Sharif *et al.* 2018; Sharp, 2013).

The larvae are then decontaminated and often, after mechanically removing the fat, dried. They can then be grinded into insect meal. However, it is also possible to extract the fat, protein and chitin. These can be used for several purposes. For example, oil can be used in feed, cosmetics (Verheyen *et al.* 2018), bio-lubricants (Alipour *et al.* 2019), or biodiesel (Wang *et al.* 2017). Proteins can be used in food and feed applications but also the technological applications such as bio-plastics (Leni *et al.* 2017). Chitin and chitosan in biomaterials and biomedical applications (Morganti *et al.* 2018).

A new area is that of breeding (genetically improving) the insect species. First of all there are several strains that can be used such as for black soldier fly (Zhou *et al.* 2013) and mealworms (Urs and Hopkins, 1973). However, it is also possible to select for better performance as was shown by 8-years selection of yellow mealworms and larger pupal size, growth rate, fecundity, and efficiency of conversion of ingested food was found in the selected strain (Morales-Ramos *et al.* 2019). Compared to conventional production animals the insects have the advantage of a short life cycle.

Food safety and legislation

When organic side streams are used, there is a risk of chemical and microbial contaminants. For example, antibiotic resistance genes and/or antibiotic-resistant microorganisms may be acquired by yellow mealworm larvae from the feed (Osimani *et al.* 2018). Concerning heavy metals, black soldier fly larvae can bioaccumulate cadmium and yellow mealworm larvae arsenic (van der Fels-Klerx *et al.* 2016).

Bioaccumulation does not always occur and several edible insect species are able to degrade those contaminants. The black soldier fly has shown to able to degrade pathogens (Erickson *et al.* 2004), mycotoxins (Purschke *et al.* 2017), insecticides (Purschke *et al.* 2017) and fungicides (Lalander *et al.* 2016). Also the yellow mealworm, when wheat was contaminated with the mycotoxin deoxynivalenol, accumulated only very low levels of the mycotoxin suggesting that it can still be used to produce a sustainable, safe protein source (Sanabria *et al.* 2019).

If patients are allergic to crustaceans or mites is there a risk of cross-reactivity to different edible insects? This is likely as it has been shown that insects and crustaceans, long considered widely separated branches of the arthropod family tree, actually belong together (Pennisi, 2015). The risk of cross-reactivity is present, but appropriate food processing methods can reduce it (Pali-Schöll *et al.* 2019). However, on labels of the edible insect products marketed, there should be a warning on the label that allergenic risks exist.

IPIFF (2019) explains the legislation in the European Union. The classification of insects as novel food has been clarified through the adoption of Regulation EU No. 2015/2283, applicable on January 2018. Applicants are required to submit information to European Commission; the European Food Safety Authority (EFSA) may be involved in the evaluation. Concerning insects as feed, manure and catering waste are not allowed as substrate to feed the insects. Insects can be fed to pets. Since the 1st of July 2017 authorises the use of insect proteins originating from seven insect species in feed for aquaculture animals. However, insects are not yet allowed to be fed to poultry and pigs yet.

Consumer attitudes

Food neophobia (people refusing to taste and eat food items or foods they are not familiar with) plays a role in insect consumption. Only for about 10 years insects have been brought on the food market. There are several strategies that are used to increase the acceptance of insect-based food products (Hartmann and Bearth, 2019; Kauppi *et al.* 2019; Rumpold and Langen, 2019; Van Huis, 2017). One of them is to disguise the food in familiar products such as protein bars, burgers, bread or pasta. Another is to provide information, not only on the sustainability of the insect product, but also on the nutritional and health benefits and on food safety. Also role models can play an important role, e.g. the endorsement of figures like Rene Redzepi, chef cook of Noma, a restaurant several times declared as the best in the world, and Kofi Annan, the late former secretary general of the United Nations (van Huis *et al.* 2012). Also the organization of bug banquets in which the consumer is able to taste insect products, is an important strategy, as the first time to taste an insect is always a challenge (Looy and Wood, 2006). Children may also be targeted as they are not biased yet (Geertsen, 2019). Of course, the tastiness of the product is extremely important for new products as the consumer is already reluctant to eat insects. Although the percentage of consumers willing to taste insect products may be low, they should be targeted first.

Conclusions

The attention to insects as food and feed is worldwide increasing exponentially. This is prompted by the urge to find alternatives for meat, as the agricultural land area available will not be enough to respond to future demands. Also, there is concern about the negative environmental impact of the production of the common livestock species. Insects can be used both as food and feed, and several species are currently being farmed, and more and more in large-scale industrial facilities. The nutritional value of edible insects is similar to meat products and sometimes even better. There may also be nutritional benefits, as the exoskeleton of insects seems to function as a prebiotic. Besides, insects have the largest repertoire of anti-microbial peptides of all animal groups. Insect products are still too expensive, but this may be justified considering the health and environmental benefits. To lower the price, research is being conducted on automating production systems and on finding cheap substrates to feed the insects on. Several insect species can transform low value organic side streams into high value protein products. More and more the combination with certain micro-organisms to facilitate this process is being investigated. Genetically improving insect strains is a new unexplored area, but promising considering the short life cycle of insects. The safety of insect products depend very much on the substrates on which insects are fed. There are several contaminants, such as pesticides and mycotoxins that can be degraded in the insect gut. However, others such as heavy metals may accumulate. Insects are new on the food market and because of neophobia consumers are reluctant to use them. However, there are quite some strategies to convince consumers. The sector of edible insects is very new, but promising. Private entrepreneurs and academics are both engaged in developing insect products that are cheap, healthy and safe, but cooperation with international and national governmental organizations is required to create an enabling environment.

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Decreasing Reactive Nitrogen Losses in Organic Systems

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Abstract

Excess reactive nitrogen in the global system has led to a wide variety of environmental and human health problems. To minimize the negative impacts of nitrogen loss from agriculture, we need to develop more sustainable farming systems that can efficiently produce food for humans while balancing ecological functioning and reducing Nr losses.

We calculated the reactive nitrogen (Nr) lost per unit food Nr consumed for organic food production in the United States and compared it to conventional production. We used a nitrogen footprint model approach, which accounts for both differences in Nr losses as well as differences in productivity of the two systems. Additionally, we quantified the types of Nr inputs (new versus recycled) that are used in both production systems.

We estimated Nr losses from organic crop production to be of comparable magnitude to conventional production losses. Conventional production relies heavily on the creation of new Nr (70-90% of inputs are from new Nr sources like synthetic fertilizer) whereas organic production primarily utilizes already existing Nr (0-50% of organic inputs are from new Nr sources like leguminous N fixation).

Areas that are advantageous to minimizing Nr losses in organic systems include the use of recycled Nr, improved ability to access nutrients in the soil, and higher residue recycling rates. However, organic agriculture typically also has lower yields, resulting in reduced crop nitrogen uptake factors.

Introduction

Humans create reactive nitrogen (Nr; all chemical species of N except N_2) both for agriculture and from energy production (Galloway *et al.* 2008). In the last 75 years, anthropogenic Nr creation has helped to dramatically increase agricultural yields and, along with it, feed a growing human population (Erisman *et al.* 2008). However, most Nr used in agriculture is lost to the environment during food production (Erisman *et al.* 2008). This Nr moves through the nitrogen (N) cycle and creates a cascade of detrimental environmental and human health impacts (Galloway *et al.* 2003). Some suggest that we have surpassed the planetary boundary for Nr creation (Rockstrom *et al.* 2009, De Vries *et al.* 2013, Steffen *et al.* 2015).

This issue will be increasingly problematic as the world's population increases over the next several decades. It is especially critical for low-income and/or high population countries, who typically experience disproportionate negative impacts from nutrient pollution. Countries with higher population densities and lower income are also more threatened by nitrogen loss avenues, such as food waste in areas where hunger is rampant, sewage contamination in areas without proper infrastructure, and fertilizer runoff into unfiltered drinking water sources.

Unless we can develop agricultural systems that maximize the recycling of currently available reactive nitrogen while reducing nitrogen loss throughout the entire food production and consumption cycle, we will see dramatic increases in nutrient-pollution based environmental catastrophes and human health issues. To minimize the negative impacts of nitrogen loss from agriculture, we need to develop more sustainable farming systems that can efficiently produce food for humans while balancing ecological functioning and reducing Nr losses (Bennett and Balvanera 2007, Erisman *et al.* 2016, Foley *et al.* 2011, Tilman *et al.* 2002).

Organic agriculture is an example of a clearly defined and certified type of agriculture that could be a sustainable alternative to conventional agriculture (Reganold and Wachter 2016, Scialabba and Hattam 2002, Tilman 1998). Organic production prohibits the use of synthetic fertilizer and other chemicals; therefore, organic farming relies on careful management of Nr through soil quality best practices, crop rotations, composting, biological soil amendments and other practices (USDA 2000). However, organic yields per unit land tend to be 10-35% lower than conventional yields (De Ponti *et al.* 2012, Ponisio *et al.* 2015, Seufert *et al.* 2012), so it is critical to observe the full Nr pathway to understand leverage points that can be taken to reduce the potential for nitrogen pollution.

The global use of Nr inputs to agriculture can be categorized into two types: new and recycled Nr. New Nr created for human use increases the total global pool and adds to the total amount of Nr that negatively impacts the environment (Erisman *et al.* 2008, Erisman *et al.* 2016). Modern agricultural production relies heavily on new Nr sources, like synthetic fertilizer and cultivation induced BNF (Erisman *et al.* 2008). It is estimated that 70-85% of the Nr inputs to conventional agriculture are in the form of new Nr, while about 15-30% are from recycled Nr sources like animal manure, compost, or crop residues (Sobota *et al.* 2013, Ladha *et al.* 2016). Due to the prohibition of synthetic Nr inputs, organic agriculture most likely relies more strongly on recycled Nr sources than conventional agriculture. But the portion of Nr inputs to organic systems from new or recycled Nr inputs has not yet been quantified.

To evaluate the localized loss of Nr within a food production system, environmental footprints, like the N footprint model, can be used. These help evaluate the potential impact of consumption choices based on current production systems, and identify areas in the food production chain where Nr are lost to the environment (Galli *et al.* 2012, Leach *et al.* 2012). Losses of Nr during food production are called virtual N, which is defined as 'N used in the food production process [that is] not in the food product that is consumed' (Leach *et al.* 2012). Virtual N losses are estimated with virtual N factors (VNF), which describe the N lost to the environment per unit N consumed (Leach *et al.* 2012).

In this paper, we examine the virtual Nr losses of organically produced foods, using conventional Nr losses in the U.S as a baseline to identify leverage points for reducing Nr loss. We also assess how much new Nr organic agriculture contributes to the global Nr pool, as a percent of total inputs, and develop recommendations for increasing the use of recycled Nr to prevent additional Nr loss to the environment.

Methods

We used the N footprint calculator as developed by Leach *et al.* (2012) to quantify Nr losses during organic versus conventional crop production and consumption. This analysis will focus only on the food production and food consumption portions of the N footprint. The Nr loss associated with energy consumption during food production was not included here because of its very small contribution to a food N footprint (Leach *et al.* 2012). The N footprint of an entity (e.g. an individual, institution or country) represents the total amount of Nr released by the entity's food consumption patterns. The associated virtual N factors used to calculate the food production N footprint depict the nitrogen losses and efficiency of the production system (from Nr created and applied all the way to Nr consumed), highlighting areas where efficiencies are low. Food consumption N is calculated based on average per capita consumption of different food groups (FAO 2016) and on the protein content of those foods (N is contained in protein). The total Nr losses during food production are calculated using Virtual N Factors (VNFs), which represent the units of Nr released per unit of Nr consumed in different food products (Leach et al. 2012); they can also be calculated as units of Nr release per units of product consumed. VNFs represent the sum of Nr losses throughout the food production process.

This analysis also quantified the sources and types of Nr inputs into both organic and conventional systems. New Nr sources include synthetic fertilizer (Nr created via Haber-Bosch), BNF by the crop itself (i.e. soybean), and BNF by a green manure (i.e. legumes). Recycled Nr sources include BNF by another crop in the rotation (such as by a soybean in a corn-soybean rotation), animal manures or any animal by-products, crop residues, non-legume green manures, and compost. Data on the Nr sources applied to organic and conventional cropping systems were collected using a literature review of peer-reviewed studies and Nr sources were categorized as new or recycled Nr input types based on the above definitions. For animal products, Nr input types were weighted based on diet composition. The calculations of Nr input types for animal products assume that different types of N sources move through the food production system (e.g. are taken up by crops; Figure 1) at the same rate.

Results

Our analysis found that there is little difference between organic and conventional food production in terms of the virtual Nr losses, due primarily to the vast variability within the systems. Both organic and conventional production systems are inefficient and a large percentage of Nr inputs are lost throughout the food supply chain before consumption.

While there were no significant differences between total Nr loss values, the organic model differed from the conventional model in four critical areas: 1) The source of Nr input in organic farms was dominated by recycled Nr, as opposed to newly created synthetic Nr (Fig. 1a). 2) Higher microbial activity increased nitrogen availability from residue recycling to crops on organic farms, leading to higher levels of total soil Nr when similar levels of Nr are added to the system (Fig. 1b). 3) Organic farms had higher levels of crop residue recycling (Fig. 1c). 4) On average, organic crops had lower yields than conventional crops, resulting in reduced Nr uptake of applied Nr by the whole plant (Fig. 1d). For the conventional model, this step is based on data from state extension agencies on recommended Nr fertilizer application rates and reported annual yields in the USDA Census of Agriculture. But as the USDA database does not report detailed or comprehensive data on organic crop production, data on Nr application rates and yields of organic crop products were collected using a literature review of peer-reviewed studies.

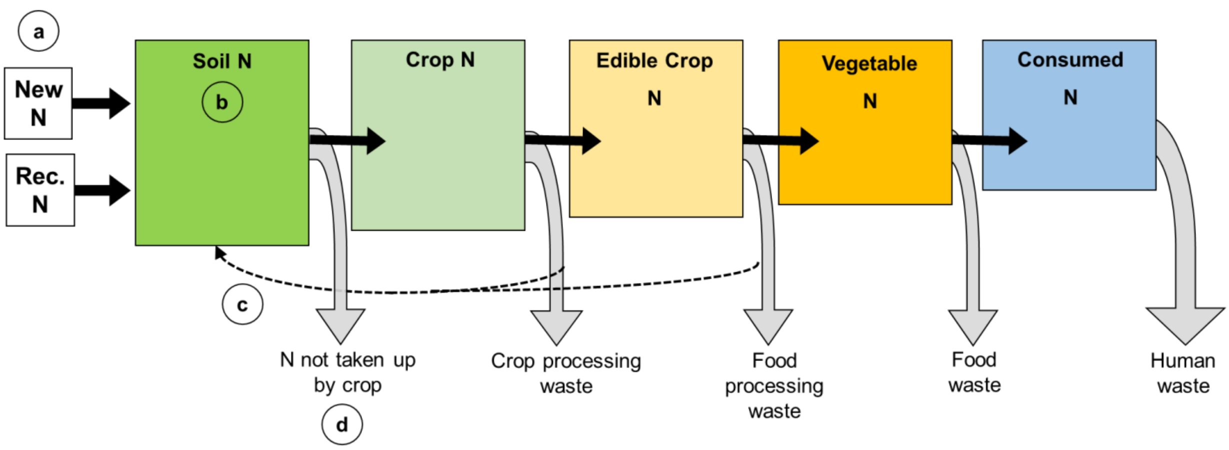
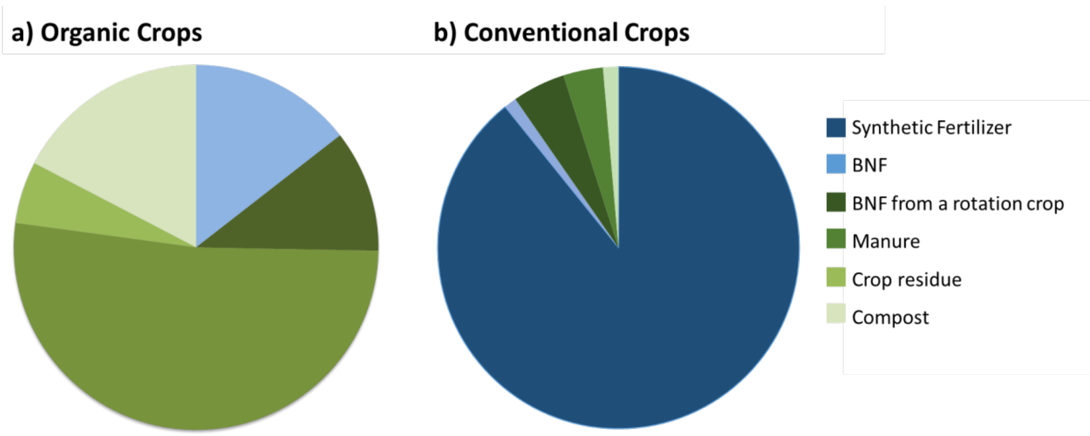


Figure 1. Reactive nitrogen (Nr) flow in crop production systems. Black arrows indicate flow of Nr from one phase of production to the next. The size of each box approximates the Nr flow through that step. Black arrows with dotted lines show Nr recycled from later steps back to earlier steps in the

production. Downward pointing grey arrows indicate Nr lost to the environment or virtual nitrogen. Organic systems use the same parameter inputs as conventional except for a) new versus recycled source of applied nitrogen, b) Soil N from applied and stored sources, c) recycling rate, and d) whole plant N uptake. These are labeled (a) through (c) in the diagram. Adapted from Leach *et al.* 2012.

The Nr input types (new versus recycled) differ between organic and conventional agriculture (Fig. 2). Organic agriculture uses less new Nr than conventional per unit Nr consumed, suggesting that organic contributes less new Nr to the global pool. Organic production primarily



utilizes recycled or already existing Nr (0-50% of inputs are from new Nr sources, all from BNF) (Fig. 2a). Conventional production relies heavily on the creation of new Nr (70-90% of inputs are from new Nr sources, primarily synthetic fertilizer) (Fig. 2b). Across all food groups, organic production in the US has the potential to release 50% less new Nr to the environment than conventional production per unit Nr consumed by people.

Figure 2. N input types for organic (a) and conventional (b) food production from new (blue) and recycled (green) sources. New N Inputs include 1) synthetic N fertilizer, and 3) BNF by a leguminous cover crop or green manure immediately before the crop. Recycled N inputs include 1) N from BNF by another leguminous crop in the rotation, 2) manure, 3) crop residue, 4) a non-legume cover crop or green manure, 5) compost, and 6) animal by-products (like blood meal). Organic crop data is based on 115 observations from 31 studies. Conventional crop data is based on 59 observations from 33 studies. Both organic and conventional animal data are scaled by livestock diet composition of crop inputs. See SM for full list of references.

Discussion

Overall, virtual Nr losses in organic crop systems in the U.S. are comparable to virtual Nr losses in conventional crop systems. However, the pathway for organic Nr losses differs from conventional pathways, with distinctive opportunities for intervening to reduce nitrogen pollution. Organic has several advantages, including the use of recycled Nr, improved ability to access nutrients in the soil, and higher residue recycling rates. However, organic agriculture typically also has lower yields, resulting in reduced crop nitrogen uptake factors.

Organic crops have increased use of recycled Nr as opposed to conventional systems. Conventional production of crop relies heavily on newly created Nr, particularly synthetic fertilizer created through the Haber-Bosch process (Fig. 2b). In contrast, organic production utilizes a wide variety of existing Nr sources, including animal manures, crop residues and composts (Fig. 2a). Our analysis thus implies that organic production adds less Nr to the global Nr pool per unit food product and therefore reduces the overall impact of anthropogenic Nr on the environment.

Organic systems also have a higher rate of crop residue recycling in the form of green manure and compost. While crop residue recycling rates are not well documented throughout the U.S. for conventional (Smil 1999) or organic production (Cavigelli *et al.* 2008, Sarrantonio 1994), crop residues are typically recycled at higher rates under organic management due to increased reliance on organic amendments and the emphasis on recycling resources. This is paired with an active soil microbiome in organic systems that allows for increased breakdown of those residues, resulting in higher levels of nitrogen storage from previous crop cycles. If the long-term storage of soil nutrients is properly tracked and monitored in organic systems, it could allow for a reduction of outside Nr addition into the system.

Despite these benefits of organic systems, lower organic yields reduce calculations of crop N uptake, i.e. the proportion of Nr applied that is taken up by the plant (Fig. 1d) and thereby decrease the efficiency of the system. In contrast to many previous studies on Nr losses from organic versus conventional systems, our analysis estimates the Nr loss per unit Nr consumed. While organic agriculture thus might lose less Nr per unit area and have reduced impact at the farm level (Cambardella et al. 2015, Hansen et al. 2000, Kramer et al. 2006, Stopes et al. 2002), due to its generally lower yields (De Ponti et al. 2012, Ponisio et al. 2012, Seufert et al. 2012), it appears as inefficient as conventional agriculture per unit output. Although organic yields are, on average, lower than conventional yields, they can, under some circumstances, almost reach the levels of conventional agriculture (De Ponti et al. 2012, Ponisio et al. 2012, Seufert et al. 2012). Improving yields in organic production and addressing non-Nr-related factors that currently limit organic yields (e.g. pest outbreaks, or the lack of crop varieties adapted to organic systems) is thus very important for improving the Nr use efficiency of organic systems.

While improving organic yields will have the most dramatic impact on increasing Nr use efficiency on the farm, we must combine this with additional leverage points to shrink Nr losses throughout the nitrogen food pathway. For example, increased recycling of processing waste beyond field residues could prevent Nr losses between the field and the consumed vegetable. In developing countries around 40% of food losses occur at post-harvest and processing levels, primarily due to harvesting constraints (Gustavson *et al.* 2011). Additionally, for non-edible residue loss, on-site composting capabilities will need to be improved, and partnerships between farms/processors and commercial composting facilities should be expanded.

Reducing and recycling edible food waste would have a positive impact on decreasing N-loss post farm-gate, as well as being critical for addressing a lack of food security. While increasing yields of organic farming is economically and environmentally important, reducing food waste may be as, if not more important for improving N use efficiency across systems. The amount of food waste far exceeds yield differences between organic and conventional crops, with 33% of the world's food produced for human consumption going uneaten (Gustavson *et al.* 2011). This means that 1.3 billion tons of food is wasted each year. While North America and Europe have the highest rates of per capita food losses, even the regions with lower rates of food loss such as South Asia and Sub-Saharan Africa still have rates of above 100 kg/year. In industrialized countries these losses are dominated by production exceeding demand, high 'appearance quality standards' from supermarkets for fresh products, sub-standard packaged product disposal, an excess of retail food options on display, abundance of food, and consumer attitudes toward food consumption. In developing countries, the primary causes of waste include poor storage facilities and lack of infrastructure, food contaminated from unsafe water, high pesticide levels, unhygienic handling, etc., lack of processing facilities, and inadequate market systems.

Examining the potential benefits and risks of land application of sewage sludge in organic systems will also be important in reducing nitrogen waste as the world's population size increases (Faerge *et al.* 2001, Magid *et al.* 2006). Currently, organic standards in the United States do not allow the use of sewage sludge as fertilizer (Singh and Agrawal 2008). While changing the standards could further optimize Nr recycling rates in organic systems, the risks associated with widespread land application of human waste would need to be addressed.

Another point that could enhance Nr recycling in organic agriculture would be to support the increased integration of crop and animal systems, e.g., as proposed by the revision of the EU organic standard (EU 2014). In addition to matching nutrient flows, integrating crops with animal systems can lead to additional on-farm benefits, including reduced dependence on inputs, improved soil health, and diversified profit streams, but also has a higher labor cost and may require additional equipment investment.

Identifying methods for improved nitrogen recycling in organic systems is not only critical for reducing environmental impacts of Nr loss, but also for developing a sustainable source of organic soil amendments. Currently, much of the recycled Nr inputs used in organic agriculture today may have been originally fixed through Haber-Bosch and used for conventional agriculture. Current organic agricultural practices are often dependent on recycled Nr inputs from conventional systems (Nowak *et al.* 2013). Organic agriculture must examine methods for improved self-reliance, especially in relation to the goal of increased land conversion to organic. To ensure that organic systems have a consistent, abundant source of recycled N, residue recycling rates must be improved and/or new sources of waste must be explored for use in organic systems.

Limitations and Uncertainties

The storage of Nr in organic matter in the soil is not addressed in this study, nor is it accounted for in most available studies on Nr balances in crop systems. Because the virtual N factor is a loss-based metric, we assume here that soil organic Nr is at a steady state and does not change over time. But in fact, many organic systems increase organic matter and thus soil Nr content (Drinkwater *et al.* 1998, Lin *et al.* 2016, Torstensson *et al.* 2006). Some of the Nr not recovered in the harvest could be accumulated in the soil rather than lost from the system. Organically managed soils also often have higher mineralization rates from increased microbial and mycorrhizal activity, as well as higher soil disturbance from increased tillage (Monokrousos *et al.* 2006, Doltra *et al.* 2010, Williams and Hedlund 2013). How much of the additional Nr in organic matter is held in the soil rather than mineralized and taken up by crops or lost from the system, and how this influences Nr loss of organic systems, is unclear. But Lin *et al.* (2016) show that accounting for differences in soil Nr content can move organic systems from lower to higher nitrogen use efficiency relative to conventional systems in an experimental farming system trial in Germany.

We also did not estimate uncertainty in the timing of Nr availability in organic systems. Nr in synthetic fertilizers is directly available for crops, while Nr in organic amendments is typically bound in organic Nr and first needs to be decomposed into plant-available Nr forms by soil microbes. The timing of Nr availability for plant growth thus does not always match the periods of highest crop Nr demand (Berry *et al.* 2002, Pang and Letey 2000).

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Organic Wastes and their Recycling Use at Suzhou city, China

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1. Status of organic wastes resource utilization in the world

The study of utilization of organic waste was begun in the 1930~40s in certain western countries. At present, the comprehensive utilization technologies of waste have reached a high level. Germany began to use anaerobic digestion for kitchen waste in the 1960s. By the 1990s, the technology was widely used in Europe and other countries. Today, 8.8 million t of kitchen waste was collected every year and mainly treated by using composting (83%) and anaerobic digestion (17%) in Germany (Yang et al. 2016). According to the 2015 Waste and Resources Action Program (WRAP), the UK produced about 15 million tons of kitchen waste per year (234 kg/person), and 20 million tons of CO_2 had been reduced from emission every year by using anaerobic digestion and aerobic composting, while the UK still plans to increase the recycling of kitchen waste to 70% by 2025 (Whiting A and Azapagic A, 2014). In the United State, the kitchen waste was used as feed, soil conditioner, compost, biodiesel and biogas, and composting of kitchen waste became common for individual households mainly based on CSI compost and sealed compost (Rajagopal R, et al, 2017).

China is the world's largest producer of organic wastes. According to statistics, the annual production of urban and rural organic wastes in China exceeded 6 billion tons in 2015, including 3.8 billion tons of livestock and poultry manure, 1 billion tons of crop straw, 90 million tons of kitchen waste, and 35 million tons of municipal sludge. Faced with huge potential of waste resources, China's overall utilization rate was low. Most of the urban municipal solid waste was in a state of “mixed dumping, mixed transportation and mixed burial”, and the traditional landfill and incineration treatments accounted for about 95%. Meanwhile, the comprehensive utilization rate of livestock and poultry manure was only 60%, and the utilization for crop straw was about 80% (Ministry of Agriculture, 2016). So there is a large space for the recycling use of urban and rural organic waste resources.

2. Status of organic waste utilization at Suzhou city, China

According to survey, the annual production of organic waste at Suzhou are as high as 6.6 million tons, mainly including human waste, crop straw, garden waste, sludge, kitchen waste, water grass, etc. (see Table 1).

Table 1: Annual production of organic waste at Suzhou (10,000 tons/year)

Type	kitchen waste	human waste	garden waste	sludge	crop straw	water grass	total
Amount	35.59	389.25	76.85	53.28	96.69	8.60	660.06

Suzhou city belongs to the Tai lake region. Such large quantity of organic wastes will cause serious pollution to Tai lake if having no good treatment and disposal. Traditional organic waste treatments included landfill, incineration, etc., which led to serious pollution to the environment. In recent years, the treatment of waste has been improved well and main technologies include: high temperature composting, insect transformation, biogas, ethanol, etc. (Zhong, 2014). In addition, with the government's special start-up capital investment and the establishment and operation of the household garbage collection, transportation and disposal system, pilot projects for comprehensive environmental improvement and the creation of civilized villages have been launched in some developed rural areas. But the effective and practical technology for widespread application for household waste are still lack and the long-term mechanism has not yet been established.

Therefore, based on the waste classification, it is necessary to transform about 60% organic waste (as kitchen and garden waste) into value-added products, as compost and soil conditioner, for further application in local agricultural production.

Organic waste has many characteristics such as high organic content, high moisture content, easy to be perishable, and less harmful components. High-humidity organic waste brings certain difficulties to collection, transportation, treatment and end use. Therefore, Bio-drying becomes a necessary pretreatment method to reduce the moisture content of organic waste. The organic waste biochemical drying machine can reduce the water content of organic waste within 1-2 days, which has paved the way for subsequent treatment and use.

3. Status of technology and application at ORRI

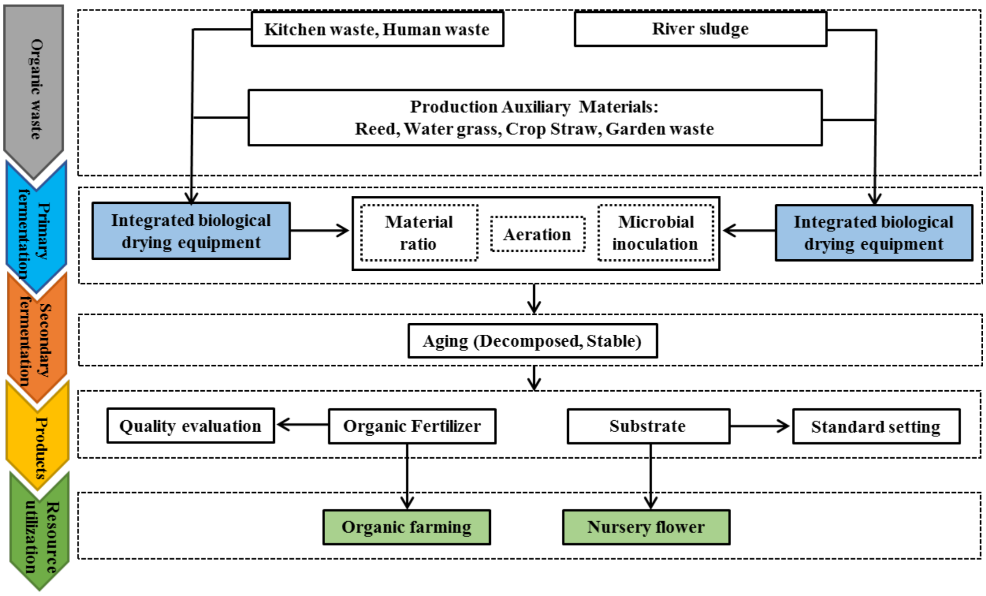
Organic Recycling Research Institute (ORRI) was jointly established by China Agricultural University and Suzhou Municipal Government in 2018. The Institute focuses on the research and development of technology and equipment in the field of organic resource recycling. It is hoped to build an open innovation incubation and transformation platform, an important transfer base for scientific research achievements of China Agricultural University, and an innovative R&D and industrial highland in the field of organic resource recycling in China.

At present, the team had developed three different types of organic waste treatment facilities, including biological drying, silo-type composting reactor and continuous dynamic lane (CDL) composting systems. Among them, more than 700 sets of the biological drying equipment have been used nationwide, of which nearly 300 sets are in Suzhou. Compared with the Japanese COMPO compost reactor, the closed-type intelligent silo composting reactor has improved processing capacity by 25%, energy saving by 17%, and greenhouse gas emission reduction by more than 60% in the same operating time, and has set-up 56 cases in China. The CDL system had lower power use (60% less), shorter fermentation time (13 days less) and lower operating cost(half) compared with BACKUS system and 66 production lines had been applied in the country.

Based on the features of wide distribution and less amount of rural organic waste, the institute will apply the latest research results, such as “closed intelligent biochemical drying reactors + closed continuous dynamic lane fermentation equipment” and the microbial agents for rapid decomposing of organic wastes into organic fertilizers and cultivation substrate for on-site agricultural use. The package of technologies will not only benefit for the resource recovery and reduction of chemical fertilizer, but also for the control of environmental pollution and support of ecological agriculture.

The technical route of the urban and rural organic waste resource utilization project is shown in Figure 1. It starts from organic wastes, goes to rapid decomposing stage (usually 1 d to 7 days) and later post-treatment stage (around 2 weeks), then development and application of end products as fertilizer and media substrate. The project can fulfill the “zero waste” of organic resources at villages and towns, and provide a typical demonstration model of new “organic waste recycling industry”.

Figure 1: Technical route for urban and rural organic waste resource utilization.



4. Technology application and benefit analysis

Suzhou has abundant auxiliary resources such as garden waste, agricultural straw, and water grass, etc., which can be used to adjust the carbon-nitrogen ratio and moisture in organic waste composting process. To assume the annual production of 6.6 million tons' organic waste in Suzhou are composted by using above technologies, 2.4 million tons of organic fertilizer will be generated. This will supply 800,000 tons of organic matter, 22,000 tons of nitrogen, 5,100 tons of phosphorus, and 57,000 tons of potassium to the soil, while achieving green production of 620 thousand ha of farmland (apply 12 t/ha of organic fertilizer). 2.4 million tons of organic fertilizer can reduce 22,000 tons of the application of chemical fertilizer, and can reduce the emission of 500 t of total N after replacing all chemical fertilizers. The resource utilization of these organic wastes will alleviate agricultural non-point source pollution, reduce agricultural input cost, and improve the agricultural economic and social benefits.

Every day, 18,000 tons of organic waste need to be disposed at Suzhou city. If the daily processing capacity of each composting reactor is 1 ton, then 18,000 units are needed. Taking Linhu Village as an example, the village level will realize an annual revenue of 380,000 yuan and the town level will achieve an annual revenue of 4.36 million yuan (Table 2).

Table 2: Investment/income accounting for organic waste resource utilization project at villages and towns: taking Linghu as an example

Content	Total population	Organic waste (t/year)	Floor area (ha)	Fixed investment / 10,000 yuan	Processing cost (yuan/t)	Output organic fertilizer / t	Organic fertilizer income / 10,000 yuan
Village	3600	2800	0.33	600	225	1018	38
Town	89000	30000	1	3000	200	10908	436

Note: 1. Organic waste includes kitchen waste, sludge, human waste, reed, water grass, crop straw and garden waste;

2. Fix investment includes site construction and equipment investment;
3. Processing costs included electricity and labor;

4. The price of organic fertilizer is estimated at 600 yuan/t;
5. The total population of Linhu Town = 49,000 permanent residents + 40,000 moving population.

5. Summary and relevance of organic recycling for the LandLess Food concept

Organic recycling project proposed at Suzhou city try to link urban and rural together by converting different types of organic wastes into organic fertilizer and soil conditioner. Such approach can reuse the organic resources and promote the development of organic agriculture in suburban regions. At present, the research team has carried out demonstration projects in typical village and town area around the Tai lake. It not only provides technical solution for local organic waste treatment and application, but also gives strong support for the improvement of Tai lake water quality and regional ecological restoration. At the same time, it can solve the problem of soil organic matter replenishment, reduce chemical fertilizer input, and improve the quality of agricultural products. The implementation of the project will provide a comprehensive and integrated model for the treatment and reuse of organic wastes for the future environmental protection and rural revitalization in the Tai lake region and even the whole country.

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Landless animal and poultry production prospects: an overview on feeding, keeping and sustainability

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Abstract

To overcome malnutrition and hunger, people need to be fed well, for which they need required quantities of animal sourced foods (ASFs) like milk, meat, fish and eggs. To produce sufficient quantities of ASFs, livestock and poultry have to be fed with balanced rations. This is often difficult, due to feed and fodder scarcity especially in developing countries like India. The scarcity is more acute for landless and smallholder livestock farmers. Some studies indicate the potential of using Fruit and Vegetable Wastes (FVWs) as feed, citing its nutritional value. This paper explores the scope for using FVW to feed livestock and poultry especially those owned by landless livestock keepers. Such efforts will contribute in accomplishing sustainable development goals (SDGs).

Introduction

Trends reveal that livestock production will become increasingly consolidated into landless systems in the future. Currently, landless systems account for 72 % of poultry, 55 % of pork, and over 66 % of eggs in world' livestock production (EC, undated). Landless livestock production systems rely on purchased inputs (FAO 2013) and external feed resources (Teufel et al. 2010) and, in the ideal case, help to face the twin challenge of ensuring sufficient food and employment (CTA, 1993). Feeding livestock and poultry sustainably under the landless production system is the challenge for the landless farmers, prompting them to explore low-cost or no-cost feeds.

Livestock relies primarily on forages, crop residues and by-products that are not edible to human (FAO 2018). Recent studies (Bakshi and Wadhwa 2013 IJAS; Ramli et al. 2009) show that fruit and vegetable wastes are alternative feed resources for livestock and poultry. Fruits and vegetables, plus roots and tubers have the highest wastage rates of any food with a global quantitative food loss of about 40-50% (FAO 2019). In 2011, almost 640 million tonnes of fruit and more than 1 billion tonnes of vegetables were gathered throughout the world. WHO and FAO recommend consuming a minimum of 400 g of fruit and vegetables per day, excluding starchy root crops, especially in less developed countries (FAOSTAT 2013). Day-by-day, global food demand is shifting from grains and other staple crops to processed food and high-value agricultural products, such as vegetables, fruits, meat and dairy (FAO, undated). This indicates that higher quantities of FVW will be generated in the future. Recycling of FVW as animal food will minimize the feed cost and alleviate environmental problems associated with these wastes (Wadhwa and Bakshi 2013).

Zero waste to zero hunger

Agricultural and food-industry residues constitute almost 30 per cent of worldwide agricultural production (Ajila et al. 2012). Feeding livestock and poultry with foods which are not fit for human consumption is the most desirable endpoint (Garcia-Garcia et al. 2017; Dou et al. 2016). By-products of the fruit and vegetable industry are organic residues (Russ and Meyer-Pittroff 2004) and commonly used in animal feed production (Elferink and Nonhebel, 2007). Although not classified as such, their physical properties are comparable to fruit and vegetable food waste. Among the recommended management practices in waste hierarchy, recycling of

FVW into animal feed is appropriate for waste that is no longer suitable for human consumption (Teunissen, undated). Profit motivation and economies of scale are influencing adoption of such practices (Dou et al. 2016). The food recovery hierarchy developed by the U.S. Environmental Agency also recommends diverting food waste that is beyond recovery for humans to animal feed (EPA, undated). Livestock fed by recovered food waste enrich the food supply for humans by providing livestock products such as meat, milk, and eggs. This option contributes to accomplish zero waste and zero hunger challenges.

FVWs for feeding livestock and poultry

FVWs are used as ingredients in livestock and poultry ration. The feedipedia has listed 166 feeds under plant products and by-products category, including 43 feeds under fruits and by-products category (www.feedipedia.org/content/feeds?category=15967, accessed September 2019). Various research studies reveal that vegetable wastes of both households and marketplace, due to the chemical compositions and nutritional potential, could be used as a feed ingredient for cattle (Gupta et al. 1993; Das et al. 2018). Some of the scientifically validated FVWs are listed below, in table 1.

Table 1: FVWs commonly used as livestock and poultry feed

S. No.	Fruit and vegetable waste used to feed livestock and poultry
1.	**Apple (*Malus domestica)***
	• Apple pomace to ruminants (Ghoreishi et al. 2007) and broilers (Zafar et al. 2005)
2.	**Banana *(Musa acuminata)***
	• Banana leaf meal to growing pigs (Garcia, Ly and Dominguez, 1991) and rabbit (Rohilla and Bujarbaruah, 2000) • Banana stem to dairy cattle (Sruamsiri, 2007). • Dried plantain leaves to broiler (Marin *et al.* 2003) • Banana peel to ruminants (Dormond, Boschini and Rojas, 1998) • Dried banana peel to growing pigs (Rios, Abernathy and Nicholas, 1975) • Sundried ripe plantain peel to rabbit (Wadhwa and Bakshi, 2013) • Banana root to chicken and pigs (Rodríguez et al. 2006)
3.	**Citrus peel**
	• Dried pulps to cattle (Bocco et al. 1998; Wing, 2003; Assis *et al.* 2004), lambs (Inserra et al. 2014; Gravador et al. 2014) lactating ewes (Fegeros *et al.* 1995), pigs (O'Sullivan *et al.* 2003) and rabbit (Hon, Oluremi and Anugwa, 2009) • Citrus pulp to goats (Salvador et al. 2014) and broiler (Mourao et al. 2008) • Ensiled sweet lime waste to Cattle (Bakshi *et al.* 2007) and Growing pigs (Cerisuelo *et al.* 2010). • Citrus molasses to cattle (Bampidis and Robinson, 2006) and pigs (Hendrickson and Kesterson, 1965) • Sweet orange peel extract to broiler chicken (Pourhossein et al. 2015)
4.	**Grapes *(Vitis vinifera L)***
	• Winery waste and by-products viz., grape stalks, grape pomace, grape seeds and yeast lees to ruminants (Nicolini *et al.* 1993) • Grape pomace in broilers (Goñí et al. 2007; Brenes et al. 2008) and laying hen (Kara et al. 2015) • Fermented grape pomace (Yan et al. 2011) • Grape seed / grape seed extract to laying hens (Kaya et al. 2014)
5.	**Pomegranate**
	• Peel extract to cow (Abarghuei et al. 2014) • By-product silage to lambs (Kotsampasi et al. 2014) • By-products to broiler (Ahmed et al. 2015)
6.	**Mango *(Mangifera indica L.)***
	• Deoiled mango kernel meal to ruminants (Gohl, 1982), broiler (Joseph and Abolaji, 1997; Diarra and Usman, 2008) and layers (Odunsi, 2005). • Fresh, dried and ensiled mango peels to ruminants (Sruamsiri and Silman, 2009) and pigs (Rao, Ravi and Yedukondalu, 2003).
7.	**Pineapple *(Ananas comosus)***

- Fermented pineapple waste to Ruminants (Sruamsiri, 2007).
- Ensiled pineapple waste to Ruminants (Gowda et al. 2016; Muller, 1978; Sruamsiri, 2007)
- Dried pineapple bran to Pig (Gohl, 1982) and chicks (Hutagalung, Webb and Jalaludin, 1973)

8. Pea (*Pisum sativum*)
- Empty pea pods ensiled with wheat straw and sundried pods in concentrate mixture to ruminants (Wadhwa et al. 2006 & 2017)
- Cabbage leaves, cauliflower leaves and pea pods to ruminants (Wadhwa et al. 2006)

9. Palm (*Elaeis guineensis*)
- Kernel meal to Ruminants (Bedingar and Degefa 1990; Nair, K.P.P. 2010), Broilers (Sundu et al. 2010), Starter and grower pullets (Onwudike, O. C., 1986) and Growing-finishing pigs (Boateng et al. 2010).

10. **Baby corn *(Zea mays Linn)***
- Fresh and ensiled form of baby corn husk with silk and fodder to ruminants (Bakshi & Wadhwa, 2012; Bakshi et al. 2017)

11. **Tomato**
- Tomato waste to dairy cattle (Sruamsiri, 2007) and goats (Romero-Huelva et al. 2012)
- Tomato powder to quail (Sahin et al. 2008; Karadas et al. 2006)
- Tomato pomace to ewes (Abbeddou et al. 2011)
- Dried tomato pomace in layer rations and starter and finisher broiler ration (Bakshi et al. 2016)

12. **Carrot**
- Dried ground carrot (Ayanwale and Aya, 2006) and tops hay (Bakshi et al. 2016) in layer ration

13. **Corn**
- Husk, silk and peel as roughage and supplemented roughage (Sruamsiri, 2007)

14. **Cornflakes**
- Cornflakes waste in starter broiler ration (Ayanwale and Aya, 2006)

15. **Cannery waste**
- Concentrate feed replacement in dairy cattle (Sruamsiri, 2007)

16. **Bakery waste**
- Starter in broiler diet (Stefanello et al. 2016)

17. **Cornflakes waste**
- Starter in broiler diet (Ayanwale and Aya, 2006)

18. **Oyster mushroom waste**
- Starter, grower and finisher in broiler diet (Fard et al. 2014)

19. **Vegetables**
- Cull vegetables to beef cattle (Davis et al. 2012)
- Processed vegetable waste to bull (Das et al. 2019)

Constraints and challenges in recycling FVWs

Anti-nutritional factors, collection, transporting, processing, high moisture, perishability, variations in nutrient content, seasonality and production, heterogeneity, adverse effects besides benefits, multi-stakeholder involvement and difficulty in implementing regulations pertaining to food and waste are important constraints and challenges in diverting FVWs into animal feed.

Way forward

Only a holistic contribution from stakeholders, scientific institutions and government can make it possible to overcome the constraints and challenges in recycling FVWs as animal feed. The way forward must aim the following strategies:

Regulations

Government should frame appropriate policies and develop the required infrastructures considering the benefits of stakeholders in fruit and vegetable value chain and environment.

The policies should enable utilizing the full potential of FVW as livestock and poultry feed by implementing the practices viz., awareness creation among public and other actors involved in fruit and vegetable value chain; segregated collection of waste from households, markets, offices, restaurants, factories and other FVW-generating places; monitoring FVW generation point to make it free from contamination and other health hazards; timely transport to collection point or dump yard; bio-processing for recycling; distribution of processed FVW to farmers and information service on FVWs through toll free helpline around the clock. Government should consider that society needs support in terms of policy, research, innovation and technology development for meaningful progress in the zero waste challenge (Dou et al. 2018).

Proper disposal aids collection

How far and how best the waste can be managed is one the challenges before world. The value of waste determines its ownership. Greater the value of waste more will be the interest in its ownership. Conversely greater supply and magnitude of disposal problems, there will be less desire for ownership (Harris et al. 2001). Maintaining waste dump points within the market ease the traders to dispose and the livestock farmers to collect the FVW (Hassan and Kikisagbe 2001). Since, these wastes have a high water content, collection of waste on daily basis is necessary (Maxwell and Zziwa 1992). High moisture content (Dou et al. 2016) and presence of contaminants such as pesticides and pesticide residues pose a threat in using FVW. Drying and ensiling help to improve the shelf-life quality and make vegetable waste suitable for feeding livestock (Bakshi et al. 2016 CAB review; Ako et al. 2016). Segregated collection is required to avoid free from contamination, animal by-products, plastic bags and broken glass (Rischkowsky et al. 2006b). Therefore, it is mandate to implement stringent regulation for pesticide usage and monitor pesticides, pesticide residues and other hazardous materials.

Role of traders, vendors and farmers

Citing the magnitude of the present and future problem, farmers and other actors in fruit and vegetable value chain should be educated with waste management practices and zero waste principles.

Farmers' startup

Nikhil Bohra, a biotech engineer, found improvement in quality milk in dairy animals after feeding them with carrot, papaya and *mosambi* waste collected from warehouses and *mandis*. With this field level solution for feed scarcity, he incubated a start-up in 2017. As a result, he can produce feed at 10 per cent cheaper rate than the market price (Balaji 2019).

Institutional initiatives

Diverting more or all the FVWs to animal feed will require more technological innovation (Dou et al. 2016). Research institutes intensify their efforts in evaluating and validating the suitability using locally available FVWs as livestock feed involving local livestock farmers considering the high moisture content and variation in nutrient content and seasonal production. One such effort is that National Institute of Animal Nutrition and Physiology (NIANP), Bengaluru, India scientifically evaluated and validated pineapple fruit residue (PFR) silage as fodder source for livestock (Gowda et al. 2016). National Research Centre on Pig, Guwahati, India identified locally available feed resources like root crop (tapioca, sweet potato etc.), brewery waste, used tea leaves and other vegetable wastes like cabbage, collocassia etc. could be used for developing economic ration for pig. The institute also identified various alternate energy sources viz., rice polish, molasses, tamarind seed, wheat bran, tea waste, pine apple waste, jackfruit waste and cashew apple and protein sources viz., silk worm pupae, sunflower cake (NRCP 2014). Besides the benefits, adverse effects caused by FVW, for e.g., retarted growth in broiler fed on diets supplemented with grape seed extract (Chamorro et al. 2013) necessitates the research institutes to carryout research on the adverse effects in feeding FVW and develop suitable mitigation practices.

Role of extension

The extension functionaries have to disseminate technologies developed and practices recommended in using FVWs as feed. To speed up the dissemination, create public awareness and motivate farmer level innovation, policymakers should frame support policies. The potential outcome of such dissemination must be utilized to develop entrepreneurship and incubate new start-ups. Information on know-how, benefits and adverse effects of feeding FVWs is essential for farmers and other actors in fruit and vegetable value chain. The extension functionaries should develop themselves competent to offer such needy information.

Conclusions

FVW is a menace for traders, threat to environment but a scope for livestock farmers especially landless farmers. Feeding FVW to livestock and poultry needs knowledge of the animal nutrition and nutritional value of those FVW. The research community should standardize the inclusion level of FVW in feeding balanced ration to the livestock and poultry. Such efforts should be extended to explore and invent new technologies involving local people to maximize the suitability of and minimize the constraints in feeding FVW. Parallel efforts by the extension system should develop awareness among the stakeholders involved in fruit and vegetable value chain, disseminate technologies among the farmers and motivate new start-ups. Thus, utilization of FVWs as animal feed will ensure animal food security, low-cost production of animal products environmental protection and thereby, a future without waste.

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Effect of bioreactor-grown biomass from Ganoderma lucidum mycelium on red hybrid tilapia (Oreochromis sp.) for sustainable aquaculture

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Abstract

Efficient aquaculture systems fed with a pre-grown mushroom mycelial biomass has been proposed as an alternative to ineffective cash crops practices that destroy arable land. In the present study, fish feed mixtures supplemented with heterotrophic 1-m^2-bioreactor-grown biomass from the mycelium of *Ganoderma lucidum* (MGL) were fed to red hybrid tilapia *Oreochromis* sp. (RHTO). For a fungal source, MGL biomass had high protein (32.2%), carbohydrate (48.4%), and fibre (13.8%) content compared with other common fish feed sources (fishmeal, soybean meal, rice bran, and corn). MGL biomass (4.45%) also had high lipid content, which was half the proportion of lipid in rice bran (8.76%). The utilisation of 15 g/kg of MGL in the feeding trial resulted in 100% survival rate (SR), full utilisation of test feed, longer body length (13.7 cm), and higher (35 g) body weight gain (BWG) among RHTO compared with control (30 g) after 6 weeks. Surprisingly, the feed conversion ratio (FCR) of RHTO fed with 15 g/kg (1.13) treatment was significantly lower compared with control (1.98), indicating better-quality feed and efficient utilisation by RHTO. The specific growth rate (SGR) of RHTO at 15 g/kg MGL (2.14) indicated a significantly greater growth compared with control (1.28). Internally, the condition factor (CF: 1.85), hepatosomatic index (HSI: 2.47), and visceral somatic index (VSI: 11.06) yielded the most significant organosomatic indices for treated RHTO compared with control, resulting in superior yield and fish health. Furthermore, blood analysis of MGL-treated RHTO showed that haemoglobin (HGB: 6.43 g/dl), packed cell volume (PCV: 35%), red blood cells (RBC: 2.47×10^6 mm^3), and white blood cells (WBC: 1.64.3×10^5 mm^3) were significantly increased (p <0.05) at 5 g/kg. Taken together, these findings show that high MGL biomass diets can enhance RHTO survival and growth performance and thus may be used as a fish supplement in landless food production.

Keywords: *Ganoderma lucidum*, mushroom biomass, red hybrid tilapia, liquid fermentation, sustainable aquaculture, landless food production

Introduction

Given the rapid growth of the human population and global decrease in available cropland per person, researchers are investigating solutions that can supply more food in less time, using

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a smaller area of land for production. One such solution is a landless food concept in which a circular agricultural system is established using bioreactors. Mushrooms, which are widely cultivated using agricultural waste, can be grown in bioreactors with significant benefits (Grimm et al. 2018). By evaluating the different benefits of utilising mushrooms in bioreactors and cultivation technological improvements the possibility of replacing 100 m^2 of cropland with 1 m^2 of bioreactor has been proposed (Rahmann et al. 2019).

Mushrooms, particularly the popular Ganoderma lucidum species, have beneficial biological, health-preserving, and therapeutic effects traditionally used in Chinese medicine for the prevention and treatment of human disease (Wan-Mohtar et al. 2016; Kozarski et al. 2019), and also represent an important fungal biomass with a significant protein content (Wan-Mohtar et al. 2018). Similar to G. lucidum, the fruiting bodies (g/100 g) of Omphalotu olearius (Aremu et al. 2009), Hebeloma mesophaeum (Aremu et al. 2009), and Lentinus tigrinus (Tiger Sawgill mushroom) possess high protein (18–25%) and carbohydrate (50–67%) content (Dulay et al. 2014) and can be used as a cost-effective source of protein in animal feed for livestock and aquaculture industries. Furthermore, G. lucidum has been shown to enhance the immune response of carp protecting the fish against respiratory burst activity, lysozyme activity, phagocytosis, and circulatory antibodies as well as effectively preventing bacterial infections caused by Aeromonas hydrophila (Yin et al. 2009).

The cultivation of medicinal mushrooms using artificial media has been practiced for centuries. In order to decrease cultivation time and improve quality, controlled cultivation in heterotrophic bioreactors has been developed. Recently, technology for fast cultivation (10 days) of mycelial cultures of G. lucidum has been developed as a promising cultivation strategy (Hassan et al. 2019) compared with the average 6-month period required for traditional mushroom cultivation. Such efficient mushroom liquid cultivation systems using bioreactors can be adopted into the food and biomass chain for landless food production, particularly in aquaculture systems that require effective protein-rich food sources (Pikaar et al. 2018).

Tilapia is among the most important aquaculture fish species at present due to its unique characteristics including high market value, adaptation to poor water quality, ability to withstand water temperatures of 21–29 °C, early sexual maturity, and fast growth which can surpass that of carp and other fish species for production (Fitzsimmons, 2010). Tilapia grow rapidly, attaining a marketable size of 250–450 g within 8 months even when fed a plant-based diet (Josupeit, 2004). In the present study, we evaluated the effect of high-protein mycelial biomass of G. lucidum on red hybrid tilapia growth performance, organosomatic indices, and haematological parameters through supplementation as feed additives to evaluate the nutritional benefit of G. lucidum biomass and its potential to improve the quality of feed in the aquaculture industry.

Materials and Methods

Feed production and heterotrophic bioreactor system

Feed ingredients were as described by Taufek et al. (2016) (sourced from a local market), and the Malaysian *G. lucidum* strain QRS 5120 mycelial pellets (biomass) from Supramani et al. (2019) were designed according to the fungal heterotrophic bioreactor blueprint of Wan-Mohtar et al. (2016).

Aquaculture system

A total of 120 RHTOs were purchased from a reputable hatchery in Sungai Buloh, Selangor, Malaysia, and transferred to eight tanks filled with 70 L of de-chlorinated water equipped with closed recirculation filtration. The RHTO fingerlings were acclimatised to environmental conditions for 2 weeks prior to the feeding trial in accordance with the requirements of the American Public Health Association, 1992.

Fish biophysical analysis

RHTO body weight gain analysis, organosomatic indices, and haematological parameters were determined as described previously Taufek et al. (2016).

Results and Discussion

Proximate analysis of the feed component

The proximate composition of the individual feed sources is presented in Table 1, and includes the protein, fibre, carbohydrate, ash, moisture, and lipid content (g/100 g). On average, fishmeal (54%) contained the highest protein followed by MGL biomass (32%), soybean meal (43%), rice bran (11.23%), and corn (6.64%). Compared with regular feeds, MB biomass was found to represent a good source of protein. Overall, there was no significant differences in fibre content between fishmeal (14.54%) and MGL biomass (13.80 %), although the latter contained significantly higher carbohydrate and lipid (48.38% and 4.45%, respectively) compared with fishmeal (5.60% and 2.41%). Furthermore, the high carbohydrate and lipid content of MGL biomass indicate that it may represent a potential dietary supplement for tilapia.

Table 7 Proximate composition (g/100 g) of the feed mixtures for the fish-mushroom treatment.

Components (%)	Protein	Fibre	Carbohydrate	Ash	Lipid
Mycelial biomass	32.23 ± 0.37^{e}	13.8 ± 7.1^{a}	48.38 ± 8.06^{b}	1.14 ± 1.12^{a}	4.45 ± 0.2^{c}
Fishmeal	54.27 ± 1.1^{c}	14.54 ± 11.34^{a}	5.6 ± 9.84^{a}	23.158 ± 0.49^{b}	2.411 ± 0.1^{ab}
Corn	6.64 ± 0.29^{a}	9.81 ± 0.85^{a}	79.23 ± 1.62^{c}	1.73 ± 1.06^{a}	2.6 ± 0.01^{b}
Rice bran	11.23 ± 0.32^{b}	19.4 ± 8.21^{a}	55.30 ± 9.16^{bc}	5.3 ± 1.39^{a}	8.76 ± 0.12^{d}
Soybean Meal	43.01 ± 0.22^{d}	9.64 ± 3.34^{a}	40.04 ± 1.43^{b}	5.16 ± 1.59^{a}	2.14 ± 0.09^{a}

*Mean value in the same row with different superscript are significantly different (P<0.05)

Weekly body weight gain of RHTO

Figure 1 shows the weekly body weight gain (BWG) of RHTO fed with different MGL biomass diets for 42 days at 2-week intervals (Week 2, Week 4, and Week 6). The weight of each treated RHTO increased significantly every week with 5, 10, and 15 g/kg of MGL biomass. The highest mean fish body weight (35 g) was observed at week 6 in the group supplemented with 15 g/kg of MGL and the lowest was 29 g (5 g/kg of MGL), compared with 30 g for the control group (standard feed). Hence, supplementation of 15 g/kg of MGL produced a better result throughout the feeding trial in terms of weight gain.

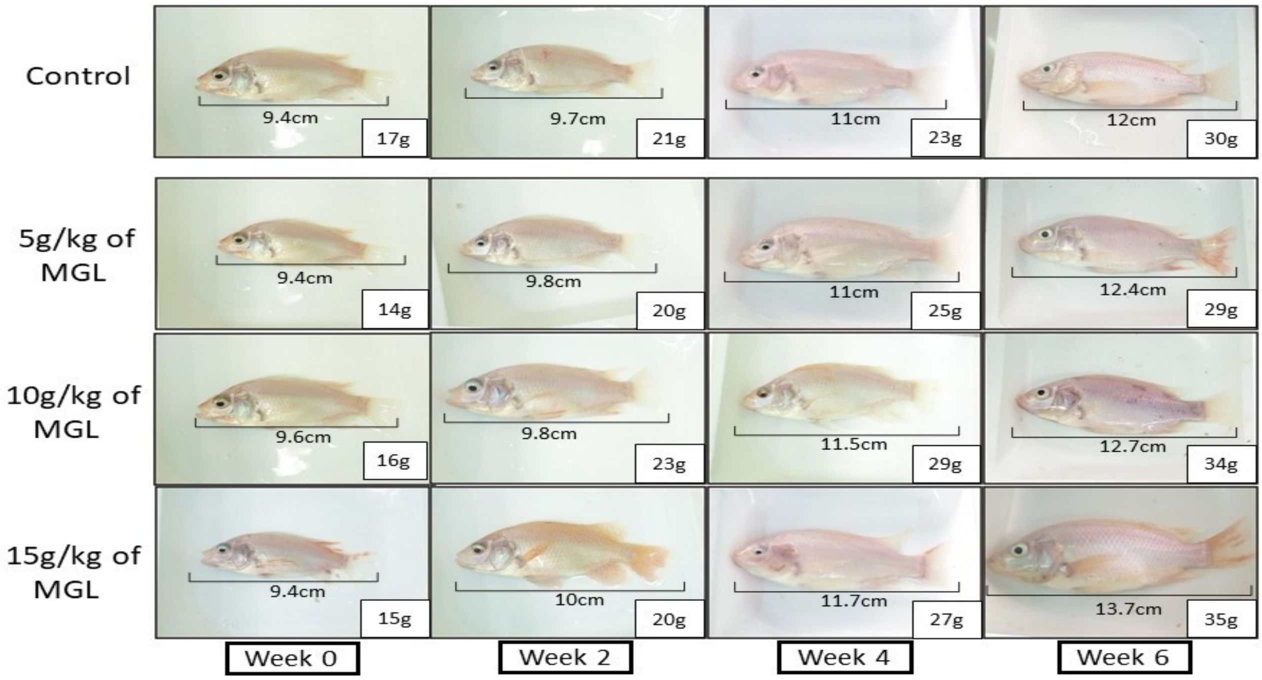

Figure 4 Weekly body weight gain (BWG) of red hybrid tilapia *Oreochromis* sp. (RHTO) fed with different mycelium of *G. lucidum* (MGL) biomass treatments at Week 2, 4, and 6 in a small-scale 3 m × 6 m fish house.

Effect of RHTO organosomatic indices on G. lucidum mycelial biomass treatment

As shown in Table 2, CF, HSI, and VSI showed the most significant differences for treated-RHTO compared with control. Higher CF (>1.0) values indicate that the MGL treatments result in better-quality fish (Araneda et al. 2008), isometric growth, and good fish health (Anani et al. 2016), and reflect the biophysical state due to different feeding conditions (Le Cren 1951). The highest value of fish CF, associated with the 15 g/kg diet (1.85) for MGL-incorporated feed, was 0.25 higher than the control value (1.60).

Table 8 Performance and organosomatic indices of red hybrid tilapia *Oreochromis* sp. (RHTO) with different mycelium of *G. lucidum* (MGL) biomass treatment and body composition after 6 weeks.

Performance Details	**Control**	**5g/kg**	**10g/kg**	**15g/kg**
Initial Weight (g/fish)	17.45 ± 1.05^{a}	14.40 ± 0.5^{a}	16.2 ± 0.9^{a}	14.55 ± 2.45^{a}
Final weight (g/fish) (Week 6)	29.8 ± 0.2^{ab}	28.60 ± 1.10^{a}	34.4 ± 1.1^{ab}	35.4 ± 2.9^{b}
Body weight (BWG) (g/fish)	41.42 ± 3.92^{a}	49.64 ± 0.19^{ab}	52.94 ± 1.11^{b}	59.191 ± 3.58^{b}
Feed intake (FI) (g/fish)	24.05 ± 1.32^{a}	22.88 ± 1.52^{a}	25.5 ± 1.42^{a}	23.72 ± 4.37^{a}
Survival rate (SR) (%)	100	100	100	100
Specific growth rate (SGR)	1.28 ± 0.16^{a}	1.63 ± 0.01^{ab}	1.8 ± 0.06^{ab}	2.14 ± 0.21^{b}
Feed conversion ratio (FCR)	1.98 ± 0.31^{b}	1.61 ± 0.04^{ab}	1.4 ± 0.06^{ab}	1.13 ± 0.19^{a}
Organosomatic indices				
Condition factor (CF)	1.60±0.08^{a}	1.62±0.04^{ab}	1.61±0.04^{b}	1.85±0.26^{b}
Hepatosomatic index (HSI)	1.97±0.06^{a}	2.51±0.50^{ab}	2.47±0.21^{ab}	2.47±0.30^{b}
Vicerosomatic index (VSI)	8.00±1.55^{a}	11.34±0.29^{ab}	13.62±1.15^{ab}	11.06±0.91^{b}

*The results represent mean± SEM of 15 fishes per tank (duplicate). Means in the same column with different letters are significantly different ($p< 0.05$). BWG = Body Weight Gain, FI = Feed Intake, SR = Survival Rate, SGR = Specific Growth Rate, FCR = Feed Conversion Ratio

Haematological indices of fish fed with different diets

Table 3 shows the haematological indices of fish fed with the different experimental diets (MGL biomass). Haemoglobin (6.43 g/dl), packed cell volume (35%), red blood cells ($2.47 \times 10^{\wedge 6}$ mm^3), and white blood cells ($1.64 \times 10^{\wedge 5}$ mm^3) were significantly increased (*P>0.05)* in fish fed the 5 g/kg diet compared with the control group, while the mean corpuscular volume (155.5 pg), mean corpuscular haemoglobin (28.78 pg), and mean corpuscular haemoglobin concentration (18.53%) were marginally higher with both the 10 g/kg and 15 g/kg diets compared with control. Serum total protein shows significant differences (*P>0.05*) in all treatment groups, with the highest value was observed with the 10 g/kg diet. All measurement data were within the normal range of healthy tilapia and indicated that supplementation with MGL biomass had no negative effect on tilapia serum biochemistry (Sebastião et al. 2011; Fazio 2018; Xiao et al. 2019).

Table 9 Haematological indices of RHTO after the 6-week feeding trial

Tank	**Control**	**5g/kg**	**10g/kg**	**15g/kg**
HGB (g/dl)	5.75 ± 0.35^{ab}	6.43 ± 0.09^{a}	6.23 ± 0.33^{a}	5.58 ± 0.11^{ab}
PCV/HCT (%)	30.00 ± 1.73^{a}	35.00 ± 0.58^{ab}	33.50 ± 0.58^{c}	31.50 ± 2.06^{a}
RBC ($10^{\wedge 6}$ mm^3)	2.04 ± 0.14^{a}	2.47 ± 0.04^{ab}	2.15 ± 0.17^{a}	2.08 ± 0.13^{a}
WBC ($10^{\wedge 3}$ mm^3)	133.88 ± 13.92^{a}	164.30 ± 2.79^{ab}	143.13 ± 13.27^{c}	161.85 ± 22.10^{d}
MCV (pg)	148 ± 1.73^{b}	141.25 ± 0.25^{a}	155.50 ± 3.18^{c}	149.25 ± 1.31^{b}
MCH (pg)	28.20 ± 0.34^{a}	26.05 ± 0.38^{a}	28.78 ± 1.02^{a}	26.65 ± 1.54^{a}
MCHC (%)	19.08 ± 0.11^{a}	18.45 ± 0.26^{a}	18.53 ± 0.36^{a}	17.83 ± 0.89^{a}
PLT (g/L)	16.50 ± 4.37^{b}	12.25 ± 2.87^{ab}	7.00 ± 0.71^{ab}	13.00 ± 0.82^{ab}
Serum Protein(g/dl)	3.20 ± 0.06^{ab}	3.10 ± 0.04^{ab}	3.40 ± 0.23^{a}	3.16 ± 0.07^{b}

*Mean value in the same row with different superscript are significantly different (P<0.05). Haemoglobin (HGB), packed cell volume (PCV), red blood cell (RBC), white blood cell (WBC), mean corpuscular volume (MCV), mean corpuscular haemoglobin (MCH) and mean corpuscular haemoglobin concentration (MCHC), platelets (PLT)

Relevance of mushroom biomass as fish feed in landless food production

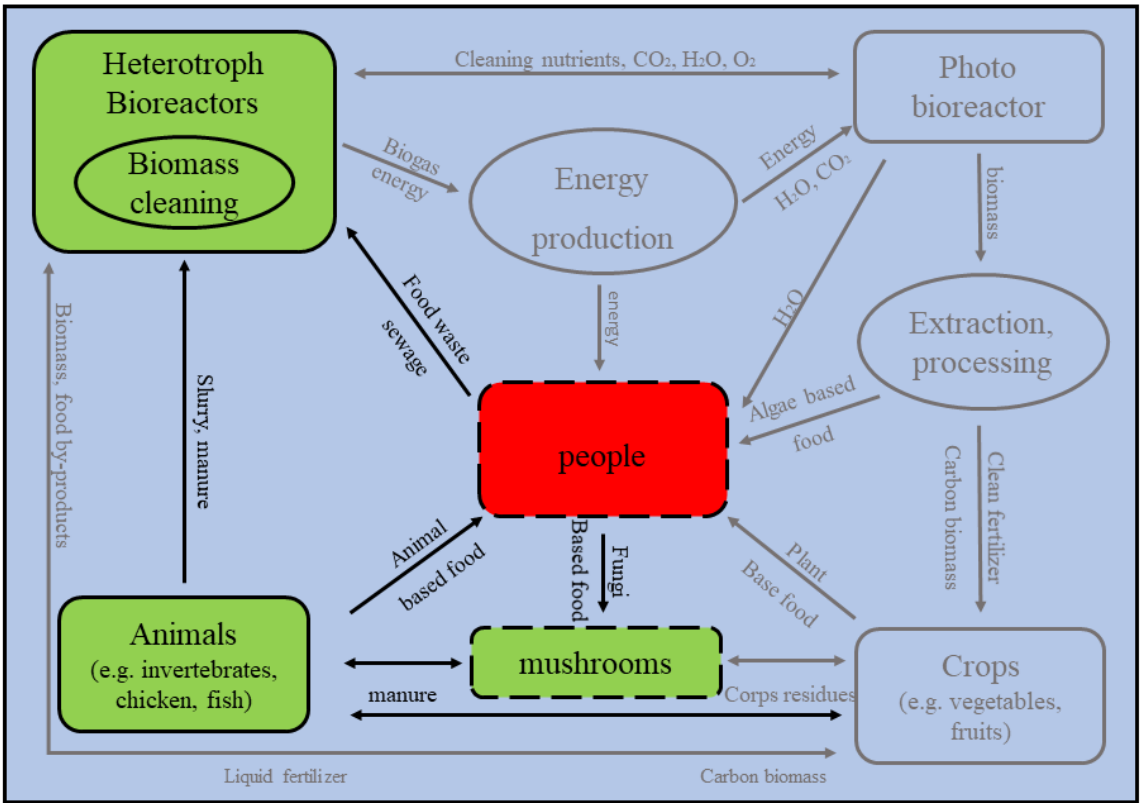

Figure 5 Relevance of mushroom biomass as fish feed in landless food production.

Based on the landless food concept of Rahman et al. (2019), our strategy produced mushroom biomass using a heterotrophic bioreactor in liquid form to feed fish for human consumption. Such a circular strategy is self-sustainable as the mushroom (*G. lucidum*) is the most efficient natural decomposer of waste generated by both animals and humans (Fig. 2), converting it to fish feed. In our proposed system, the fungal biomass was successfully fed to the RHTO to provide a sustainable, sufficient protein supply via efficient fish farming for a growing human population. This bioreactor-grown MGL biomass not only benefitted the RHTO growth rate and internal health but may also occupies less land compared with crop production and may be advantageous in high-population, low-income countries with small-scale farming practices as an economical bioreactor system with low environmental burden. Taken together, this strategy complimented the objective of Rahman et al. (2019) to replace one hectare of cropland with one square meter of bioreactor space via sustainable high protein animal-feed production, thus countering the “Assumptions for 2100” unavailability of animal feed production.

Conclusion

In the present study, bioreactor-grown MGL biomass (15 g/kg) was shown to have a considerably high protein (32.23%) content, resulting in faster growth and higher body weight gain in RHTO compared with other diets. Organosomatic and haematological indices of MGL biomass-treated RHTO indicated that treated fish had better quality, isometric growth, and health.

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Fungal solutions for circular food chains

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Abstract

Edible mushrooms are cultivated mainly on ligno-cellulosic plant materials, thereby turning agricultural wastes to high quality products. In this review, several ways in which mushroom cultivation could help in the transition towards a circular agricultural economy are discussed, including food, feed and compost production. To improve resource use efficiency in agricultural systems, the central role which fungi play as recyclers in natural ecosystems should be imitated. This could for example be achieved by using spent mushroom substrate as feed for invertebrates such as earthworms, which produce high-quality compost and can serve as feed for other animals. In the context of an increasing world population, as well as limited resources and agricultural land, as described in the Landlessfood project, mushroom cultivation could fulfill the need for protein-rich, “quality” food and for the recycling of nutrient-poor agricultural wastes.

Introduction

Population growth, climate change and the depletion of finite resources like phosphate and fossil fuels are major challenges to the global agricultural system and threaten food security, especially in densely populated and less developed regions of the world. One of the most promising strategies for tackling these challenges is the improved usage and recycling of non-consumable organic material. Among these wastes are large quantities of nutrient-poor plant material from cropping, which are of little value as food, feed or fertilizer and are therefore often burned or disposed of in other unsustainable ways (Arai et al. 2015; Feng et al. 2011). These materials include straw, various husks, leaves and stems, corncobs and all other parts of plants which are rich in the cell wall components cellulose, hemicellulose and lignin. Since fungi are the most efficient decomposers of such materials and especially of lignin (Stamets 1993), a more clever integration of edible mushrooms into the food and biomass chain could be the most sustainable way of utilizing this biomass. To realize this potential, it is however necessary to look at mushroom cultivation in a different way than is the case today: not primarily as a method of food production, but rather as the first step in a value-adding composting process which also provides feed for animals and nutrients for plants.

Mushroom production

Mushrooms have been cultivated by humans for more than a millennium (Stamets 1993). However, in recent decades the scope and methods of cultivation have changed dramatically.

Market

According to Royse et al. (2017) the consumption of mushrooms increased from 1 kg to 4.7 kg (fresh weight) per person and year from 1993 to 2013. The mushroom market was valued at around 63 billion USD in 2013, only 8 % of which was accounted for by wild mushrooms. The global production of cultivated edible mushrooms has increased around 30-fold since 1978, to around 34 million tons annually. China is by far the largest mushroom producer in the world, accounting for around 87 % of the global production in 2013.

Mushroom production methods

Most cultivated species of mushrooms naturally grow on dead wood, while others are found on compost-like materials and nutrient-rich soils, often in association with manure (Stamets 1993). Virtually all cultivated species of mushrooms have a saprotroph lifestyle, meaning they are decomposers of organic matter. Wild edible mushrooms, like truffles (*Tuber* *melanosporum*), porcini (*Belotus edulis*) and chanterelles (*Cantharellus cibarius*) on the other hand are mycorrhizal fungi which require a symbiotic tree partner to grow and can therefore not easily be mass-produced. The world's leading cultivated mushroom is shiitake (*Lentinus edodes*), followed by oyster (*Pleurotus spec.*) and wood ear mushrooms (*Auricularia spec.*) of different species and finally by button mushrooms (*Agaricus bisporus*), which are the most popular mushroom species in western countries.

Stamets (1993) describes the production of shiitake, oyster and wood ear mushrooms. They are categorized as primary decomposers, all of them inhabiting wood in the wild. The traditional cultivation method of these fungi is simply to transfer mushroom mycelium onto logs of wood. These are kept outside, in a sufficiently moist and temperate environment (or in some cases buried) until mushrooms can be harvested. Nowadays they are usually cultivated in plastic bags filled with sterilized sawdust or other ligno-cellulosic materials, like straw. To optimize yields it is important to keep these bags at the right temperature and moisture conditions for the chosen species of fungus. Fruiting will often occur by itself but can be induced through changes in the temperature or light conditions, depending on the mushroom species (most do not require any light). Usually two to three flushes can be harvested at intervals of around a week before the substrate has been depleted. To increase yields, nitrogen-rich supplements are often added to the substrates. However, even without supplements high yields can be achieved. The common measure for efficiency in mushroom cultivation is biological efficiency (BE). A BE of 100 % means that the mass of fresh mushrooms harvested is equal to the dry weight of the substrate. Given the water content of mushrooms of around 90 %, the conversion ratio in this example would be 10:1. Skilled cultivators produce mushrooms with a BE of between 75 % and 125 %. BE of up to 250 % has been reported but is an exception and can only be achieved with high amounts of nutrient-rich supplementation.

The button mushroom is usually categorized as a secondary decomposer (Stamets 1993). Such organisms depend on the prior activity of other microorganism and their metabolites to grow. However, it has been demonstrated that the button mushroom can also be cultivated on non-fermented substrates (Till 1962). The basis for substrate-formulation depends on local availability of substrates but most often a combination of straw and animal manure is used (Royse & Beelman 2007). The most common substrates are compost-like materials, which are prepared in a two-phase fermentation process. A complete production cycle for button mushroom production takes roughly 14 weeks, according to Royse and Beelman (2007) from whom the information of the following short summary was taken.

Phase 1: Phase 1 of composting takes about 6 to 14 days, depending on materials and facilities, such as the availability of forced aeration. The substrate materials are gathered in a large heap and mixed to achieve homogeneity. Water is added, as well as gypsum to stabilize pH. During this phase very high temperatures are reached due to microbial activity. Since temperatures should not rise above (but also not fall substantially below) 80 °C in the center of the pile, it is necessary to turn and water the compost at intervals of about 2 to 3 days. The metabolic activity of the thermophilic microflora helps to create a more selective substrate for A. bisporus. When the compost has a chocolate brown colour, a strong smell of ammonia, soft, pliable straws and a water content between 68 and 74 %, it is ready for phase 2.

Phase 2: The purposes of phase two are to assimilate ammonium, to stimulate the growth of beneficial thermophilic microflora and to kill nematodes, insects, molds and other possible pathogens of the button mushroom. The thermophilic microorganisms which thrive in this phase and help to metabolize the ammonium will not be competitive at the lower temperatures during cultivation and will serve as a food and nitrogen source to the mushroom. The optimal temperature range of the substrate during phase 2 is between 50 to 55 °C. Unlike in phase 1, it is very common for cultivators to use a climate-controlled chamber during this phase, instead of relying purely on self-heating of the substrate and on turning and watering to decrease substrate temperatures. Once the phase is completed, after roughly 5 days (Gerrits 1988), it is necessary to let the substrate cool down to room temperature (ca. 23 °C) before mixing the substrate with mushroom spawn.

A typical spawning rate for button mushrooms (as for many other species) is about 2 % (spawn to substrate, dry weight). The mushroom will colonize the substrate in 13 to 20 days and is then filled into trays and covered with casing soil (although it is also possible to cover the substrate with casing soil directly after spawning). Although hygienic conditions are important in button mushroom cultivation, the “semi-sterile” process described above is sufficient for very effective cultivation. The activity of some bacteria in the casing soil even seems to be beneficial, as it removes volatiles from the button mushroom which suppress fruiting (Noble et al. 2009). In general, the button mushroom prefers temperate over hot climates. China has therefore set up most of its button mushroom production in the northern parts of the country (Royse 2017). In tropical countries, heat-resistant oyster mushroom species, or paddy straw mushrooms (*Volvariella volvacea*) are particularly suited for cultivation (Stamets 1993).

Mushrooms as food and feed

While the quality of mushrooms as food has received increased recognition and is reflected in rapidly increasing consumer demand, the potential of mushrooms as feed is largely unknown and unexploited. Since considerable amounts of mushrooms never reach the market for human consumption, for example due to “low visual quality” (misshaped mushrooms), using mushrooms as feed would be a sustainable solution even if mushrooms are not cultivated primarily for consumption by animals.

Mushrooms as human food

Edible mushrooms are calorie-poor but rich in protein, minerals and vitamins. Due to the high water content (ca. 90 %) of fresh mushrooms (FM), their energy density is relatively low, with only ca. 30 kcal per 100 g FM (Mattila et al. 2002). Leaving aside the water content, the most common cultivated mushrooms – shiitake, various oyster mushrooms and button mushroom – have a protein-content of approximatly 20 % and are a good source of all essential amino acids for human diets (Mattila et al. 2002). Mushrooms consist of around 50 % carbohydrates, around a third to a half of which is dietary fiber, while the fat-content is usually low, with around 3 – 4 % of the dry weight (Mattila et al. 2002). Mushrooms are a good source of the vitamins B2, B3, B9 compared to vegetables and contain vitamin D, C and trace elements of vitamin B12 (Mattila et al. 2001), which is often lacking in vegetarian and vegan diets. Additionally, many mushrooms contain macromolecules with anti-carcinogenic, immuno-stimulating or other medical effects, such as enhanced neurogenesis (Rop et al. 2009; Ryu et al. 2018; Stamets 1993).

Mushrooms are often equated to vegetables, even in the scientific literature, although they are more closely related and more similar to animals in their metabolism and nutrient composition. Supplementing mushrooms for meat can have significant health benefits for obese people, including weight loss, improved systolic and diastolic pressure, improved lipid profile and a decrease of inflammatory markers in their blood (Poddar et al. 2013). Studies such as this, as well as their dietary profile, show that mushrooms are a healthy food and especially suitable as meat substitutes. In sensoric tests, meat-analogues made from fungi were found to taste better than those made from vegetables. Additionally, the concentration of proteins and essential amino acids was found to be higher (Kumar et al. 2017). These meat analogues are most commonly produced from the mycelium of fungi such as *Fusarium graminearu*, which do not form mushrooms and are cultivated in liquid medium rather than on solid substrates. Given the increasing world-wide need for protein, mushrooms and fungal meat analogues could play an important role in the future of the agricultural system, where high animal numbers might not be supportable.

Mushrooms as animal feed

Very few studies have been carried out on mushroom as feed. Slightly more literature is available on the use of spent mushroom substrate as feed (see 5.1).

Supplementation of 2 % shiitake mushroom extract in the diet of the rainbow trout *Oncorhynchus mykiss* significantly improved their immunological parameters and survival rate during exposure to the bacterial pathogen *Lactococcus garvieae* (Baba et al. 2015). A positive impact of mushrooms on weight gain of fish was found in a study where the feed of the fingerlings *Labeo rohita* and *Hemigrammus caudovittatus* was partly replaced with mushrooms. This study looked at the effect of replacing half of the fish meal with shiitake or earthworm meal in a regular feed composed of 18% fish meal, 32 % ground nut oil cake, 28 % tapioca and 22 % rice bran. The diet with earth worm meal showed an approximately 2-fold higher growth rate compared to the fish meal diet, while the diet with mushrooms showed a 1.2 to 1.7-fold increase, depending on species of fish (Paripuranam et al. 2011). Similarly, shiitake extracts had positive effects on health parameters of chicken (Willis et al. 2007). Feeding button mushrooms to chicken at the rate of 20 g per kg of feed led to significant growth promotion and improved antioxidant-protective activity (Giannenas et al. 2010).

It is interesting to note that there are no published feeding trials with animals that are known to be fungivores. Insects and other invertebrates have so far received very little attention from scientists, even though they are the largest group of fungivores in nature, and often depend on wood-inhabiting fungi to complete their life cycle (Vega & Blackwell 2005, Boddy & Jones 2008). Some mammals, such as squirrels and chipmunks also have a strong reliance on fungi as a primary food (Fogel & Trappe 1978) and wild boars are known to consume truffles and other types of mushrooms. Nevertheless, the only feeding trials with mushrooms found for this review were conducted on chicken and fish.

Mushroom compost

On average, roughly 5 kg of spent mushroom substrate are produced per kg of mushrooms (Finney et al. 2009). Therefore, since 34 million tons of mushrooms are produced globally per year (Royse et al. 2017), the amount of spent substrate might be roughly 170 million tons. However, Stamets (1993) speaks of a 2:1 ratio of spent substrate to (oyster) mushrooms, without specifying if this is on a dry weight or fresh weight basis (just as Finney et al. fail to specify this). The lack of clarity on this subject in the mushroom literature is altogether surprising.

The amount and quality of spent mushroom substrate as compost is dependent on the substrate ingredients, species of cultivated mushroom and method of cultivation. The cultivation of a single mushroom species will not result in complete decomposition of the materials. The cultivation of several species of mushroom in succession on the same substrate or further composting of spent mushroom substrate will however result in the production of rich topsoil (Stamets 1993). It is also possible to use spent mushroom substrate as animal feed – and use the manure as fertilizer. In the following paragraphs, both recycling pathways are discussed.

Spent mushroom substrate as feed

As with mushrooms themselves, spent mushroom substrates have mainly been investigated as feed for common production animals – cows and pigs – rather than as feed for animals that naturally rely on fungal biomass as a primary food. The notable exception being earthworms, which were studied in the context of vermicomposting.

Spent mushroom substrates as feed for pigs and cows have produced bad to mixed results. Song et al. (2007) measured a negative effect on body weight gain of pigs with addition of 5 % fermented spent oyster mushroom substrate, while 3 % had no effect. Chu et al. (2012) also found negative to neutral effect of spent mushrooms substrate on growth. However, they describe an improvement in meat quality. Also, spent mushroom substrate could be a good bedding material for pigs. Durrell et al. (1997) found that enriching sow pens with spent (button) mushroom compost reduced aggressive behavior, injuries, floor sniffing and lying down with open eyes.

Even though chemical analyses have shown that the cultivation of mushrooms should increase the digestibility of straw by reducing the amount of lignin and cellulose (Nasehi et al. 2017), feeding trials showed that cows refuse eating more than 17 % of straw-based spent oyster mushroom substrate in a maize and hay based diet (Adamovic et al. 1998). The same study showed that supplementation above 10 % had negative effects on weight gain. However, in another study the growth performance of post weaning calves was improved by 8 % by supplementing their feed with 10 % fermented, sawdust-based spent oyster mushroom substrate (Kim et al. 2010).

Since fungal biomass is one of the main nutrient sources for earthworms (Schönholzer et al. 1999), they (and other invertebrates) could be more suitable than mammals for using spent mushroom substrate. This would be a combination of composting and feed production, since earthworms are an even better fish (or chicken) feed than mushrooms themselves. However, while the quality of vermicompost from spent mushroom substrates was analyzed, there has been no investigation of the feed conversion ratios. Nevertheless, there is good reason to assume that conversion ratios are high. Edwards (2010) writes that earthworms convert cow dung with an efficiency of 10 %. In an experiment in which cow dung and spent oyster mushroom substrate were vermi-composted together, the treatment where earthworms grew fastest consisted of 60% spent mushroom substrate and 40% cow dung (Nik Nor Izyan et al. 2009). Therefore, the feed conversion ratio for spent mushroom substrate might also be 10 % or higher. This assumption is supported by another experiment: in a vermicompost consisting of 25 % sewage sludge and 75 % spent oyster mushroom substrate the earthworm biomass increased by 896 % in only 70 days (Bakar et al. 2011).

Mushroom Compost

Many studies have found mushroom composts to be of excellent quality and rich in nitrogen (N), phosphorous (P) and potassium (K). Nevertheless, the production of great amounts of spent mushroom substrate can lead to similar disposal problems as other kinds of organic wastes (Grimm & Wösten 2018). This is especially the case for substrates which contain animal manure, such as used for the button mushroom. Spent button mushroom substrate is used for crop production in horticulture and agriculture. However, some authors recommend that, to convert this spent substrate to high-quality compost, it should be subjected to a weathering period of at least 6 months, during which it is spread in heaps of roughly 1.5 m height and subjected to the elements. In this way salts and minerals, which reduce the quality of the compost (Courtney & Mullen 2008), are washed away and the decomposition of the material continues. In a comparison of spent button mushroom substrate, forced aeration compost and mineral "NPK" fertilizer, it was shown that of all treatments, a 100 t per ha application of spent substrate had the strongest positive effect on grain yield (59 % increase compared to no-fertilizer control), and that even 50t/ha came close to producing the same yields as the mineral fertilizer treatment. Also, the amount of soil phosphorous, potassium and nitrogen, as well as soil organic matter were greatly increased. The authors of this study remark that salinity problems are unlikely to occur "as the P content of soil and compost would limit further large applications" (Courtney & Mullen 2008). The application of mushroom compost, as for any other compost or fertilizer, should nevertheless be case-depended. For example, magnesium-deficiency could arise at high application rates due to antagonism with potassium, which is abundant in mushroom compost (Uzun 2004).

Spent substrates of oyster or shiitake mushrooms have been shown to not only improve plant growth but also their health status and to be able to suppress plant pathogens in soils. In a bio-essay experiment with cucumbers and the fungal pathogen *Colletotrichum lagenarium*, it was shown that spent shiitake substrate greatly reduced anthracnose symptoms (Di Piero et al. 2006). The effect was largest in unsterilized spent substrate. Fresh (unused) shiitake substrate showed a much slighter reduction in these symptoms. Therefore, metabolites from shiitake mushroom cultivation must be responsible for the positive effect. Spent oyster mushroom substrate, as well as extracts and live mycelium from the oyster mushroom were shown to suppress the sugar beet nematode *Heterodera schatii*: the addition of 100 g and 200 g of spent substrate per 3 kg of soil reduced the numbers of nematode cysts by 85 % (Palizi et al. 2008). In another study, spent oyster mushroom substrate suppressed root-knot nematodes in field conditions, though not as effectively as other organic wastes (El-Sherbiny & Awd Allah 2014).

Even though these results show that further composting is not strictly necessary for spent shiitake or oyster substrate, it can be very beneficial to do so. Through co-composting, it is also possible to recycle other organic wastes such as pig manure or sewage-sludge. This was shown in the context of vermicomposting, where high-quality composts were produced from sewage sludge and spent mushroom substrate (Bakar et al. 2011).

Discussion

This review showed the potential of mushrooms and spent mushroom substrate for food, feed and compost preparation from crude fiber and lignin-rich biomass. An improved integration of mushroom production into the food production chain could make important contributions to food security and human health, to soil fertility and carbon sequestration, as well as to animal and plant health, which could even help to reduce the use of antibiotics and pesticides. Other usages of mushrooms and spent mushroom substrates, which were not discussed in this review, include bioremediation and the production of materials and enzymes (Grimm & Wösten 2018). The application of mushroom compost could also be used to increase biodiversity in agricultural landscapes and in forests. However, no studies on this have yet been conducted.

Mushroom cultivation can be integrated into many different agricultural systems, due to the sheer number of different ways in which mushrooms and mushroom compost ca be used. Industrial nations could include this in strategies for reaching their self-set climate and sustainable development goals, while the main incentive for developing nations to promote mushroom cultivation in circular food chains, is likely to be food security and public health. Small scale farmers could profit most, as they have all the materials necessary for cultivation and need few materials to get started. Mushroom cultivation would be an additional source of income and food. The limited access to fertilizers in most African nations would be less of a problem if high quality compost was available (Rahmann et al. 2019). Also, the feeding of chicken or fish with mushrooms and earthworms would reduce the need for other, unsustainable feed.

The contribution to food security can best be visualized in an example. We assume that on a field of 1 hectare, 4 t of wheat and 4 t of straw are produced (on a dry weight basis). 5 % of the grains are used for the production of oyster mushroom spawn, while all of the straw is used as substrate. Fanadzo et al. (2010) produced oyster mushrooms on un-supplemented wheat straw with a biological efficiency of 71 %. If we assume such a low efficiency, the amount of mushrooms produced from the 4 t of straw (dry) would be 2.8 t (fresh) – and therefore 280 kg in dry weight. If we assume a 20 % mass reduction from in the substrate during colonization, as Nasehi et al. (2017) found with an oyster mushroom, then the amount of spent mushroom substrate would be 3.2 t. If this spent substrate was vermicomposted and if the conversion efficiency of mushroom compost by earthworms is indeed 10 % then 320 kg of earthworms could be produced. If the mass reduction of the compost during vermicomposting is again 20%, and we also subtract the weight of the earthworms themselves, the amount of compost would be roughly 2.2 t. The calculations for the amount of earthworms and compost are by necessity inaccurate, as no literature on this exists. However, it might not be unrealistic, to produce 280 kg of dried mushrooms, 320 kg of earthworms and 2200 kg of compost from one hectare of wheat straw. Given that fungal biomass is one of the main food sources for earthworms (Schönholzer et al. 1999) and that most of the fungal biomass is mycelium, rather than mushrooms, it is possible that the mass of earthworms might exceed that of mushrooms. Nevertheless, it is also possible that the amount of earthworms here is exaggerated. To make a more accurate assessment of the potential of such a mycological recycling pathway, experiments will have to be conducted. These should investigate mushroom cultivation in the context of agricultural systems, rather than as an isolated industry. In this way, great contribution to the agricultural system could be made.

Relevance of mushroom production for the LandLessFood concept

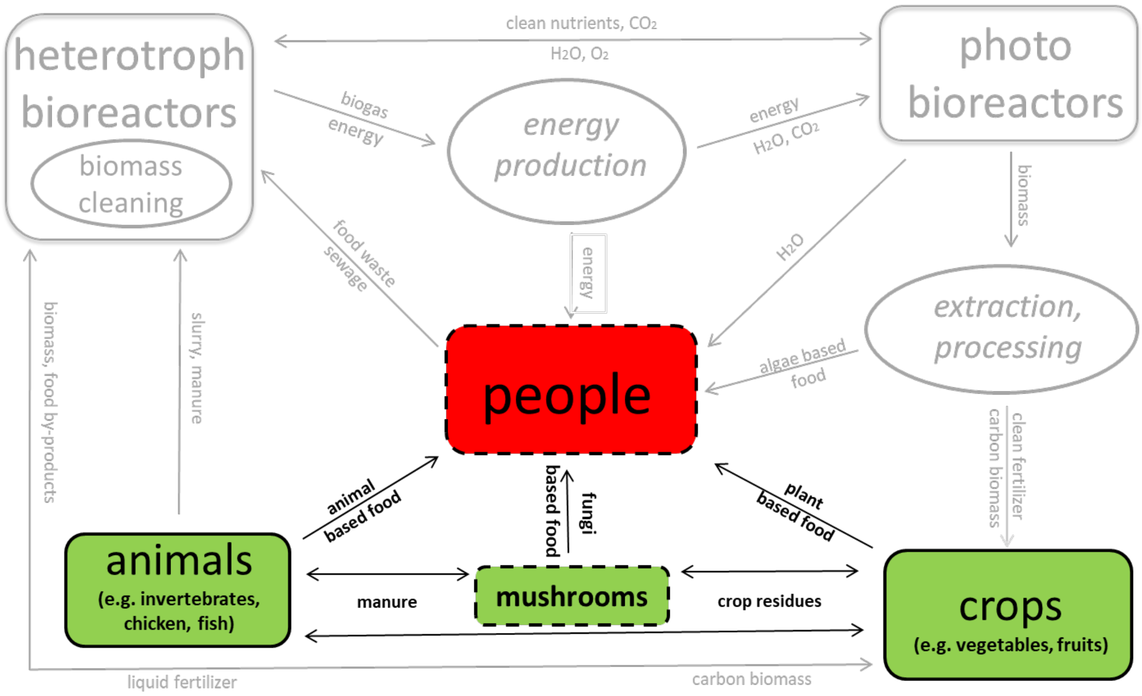

Figure 6: The position of mushroom cultivation within the LandLessFood concept.

To sum up, mushrooms could be used to recycle wastes from animal husbandry and especially crop production. The integration of mushroom cultivation between these two systems could lead to more productivity and improved resource use efficiency. Mushrooms themselves are "quality" rather than "energy" food. Since they are particularly suited as a meat alternative, they could be used to create more sustainable agricultural ecosystems with relatively low animal densities. In such a system, ligno-cellulosic plant waste would be used for mushroom production instead of as ruminant feed. This would not only be more effective but also avoid methane emissions. Since animals such as fish and chicken have much better feed conversion ratios than most other livestock, and since mushrooms are a healthy feed supplement for them, these species would be the ideal animals in such a "mycological" agricultural system. By vermicomposting of spent mushroom substrate this system could be improved even further by providing earthworms as feed, as well as compost for plant production in one step. If large amounts of spent mushroom substrates are produced, this could be an ideal bulking agent for the composting of sewage sludge, thus also offering a pathway for the recycling of nutrients that would otherwise be lost from the agricultural system.

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Small-scale biogas facilities to enhance nutrient flows in rural Africa - relevance, acceptance, and implementation challenges in Ethiopia

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Abstract

As resources needed for crop production like organic matter and land are increasingly scarce, alternative methods for food production are needed to feed the rising population in Sub-Saharan Africa. To use available resources efficiently, organic waste is to be reduced and recycled, to form a closed production system. Problematic are the multiple uses of organic materials competing with each other, as for example manure and straw can be used for fuel or for fertilizer. Burning organic matter removes valuable on-farm nutrients and soil carbon, which could otherwise be used to fertilizer crops. Competition between these two applications can be eliminated by a biodigester. In a biodigester, organic waste is transformed to biogas utilized for light and cooking, and bioslurry, a nutritious organic fertilizer and source of organic matter. Through capturing nutrients in agricultural by-products, nutrients become available to the food system again. A total of 47 farms with biogas systems in the central Ethiopian highlands were analyzed using qualitative and semi-quantitative methods. The analysis deepens the understanding of the present practices and provides a base line for further improvements in the application of biogas technology in Ethiopia. The study identifies a series of inadequate handling practices and thus a significant potential to optimize the farming system around a biodigester. Nevertheless, the integration of a biodigester should be encouraged as it fulfills the production of energy, and a nutritious and economic fertilizer without additional resources as is proposed in the LandLessFood concept.

Introduction

With increasing population and decreasing availability of agricultural land, pressure on resources required for crop production is growing (Rahmann et al. 2019). To cover food demand for the rising population with limited resources, waste is to be avoided and resources recycled (Smith et al. 2014). The current situation shows that valuable nutrients and organic matter are often lost, as organic residues are removed for fuel, feed, and construction purposes. As a result, soils in Sub-Saharan Africa are largely degraded and contain a low organic matter content. To improve soil productivity, accessible fertilizers are required (Rahmann et al. 2019). Although chemical fertilizers can be applied to replace nutrients by harvested crops, its application is expensive, requires fossil fuels, and is harmful to the environment. Additionally, the low organic matter content in soil cannot be replenished by chemical fertilizers. There clearly is a need for an alternative nutritious fertilizer, accessible to farmers.

The use of organic fertilizers like cover crops and undersowing of crops requires additional land which is scarce, and similarly is not an option (Rahmann et al. 2019; Siegmeier et al. 2015). A contribution to a solution is the integration of a household biodigester on a farm, in which organic waste is transformed to biogas utilized for light and cooking, and bioslurry, a nutritious organic fertilizer and source of organic matter. Accordingly, the competition of using organic resources for fuel or fertilizer can be eliminated. Available nutrients are recycled and stay on the farm to create a closed cycle (Figure 1). If quality fertilizer like bioslurry is available, limited access to fertilizers would be less of a problem.

To understand the impact of a biodigester on nutrient flows, understanding the transformation of substrates during anaerobic digestion is only a first step. Through looking at how bioslurry and biogas are managed in practice, challenges and barriers to nutrient cycling can be identified. The present analysis covers a number of biodigesters implemented in the Ethiopian central highlands. Material presented here was collected using 2 research methods: (1) literature and internet research, and (2) data collected during a field study in the Arsi Zone in Ethiopia. During this field study, 47 semi-structured interviews with farmers were carried out in late 2017. Questions focused on changes in energy sources and fertilizer practices after biodigester implementation. Based on observations, additional information on resource management was collected.

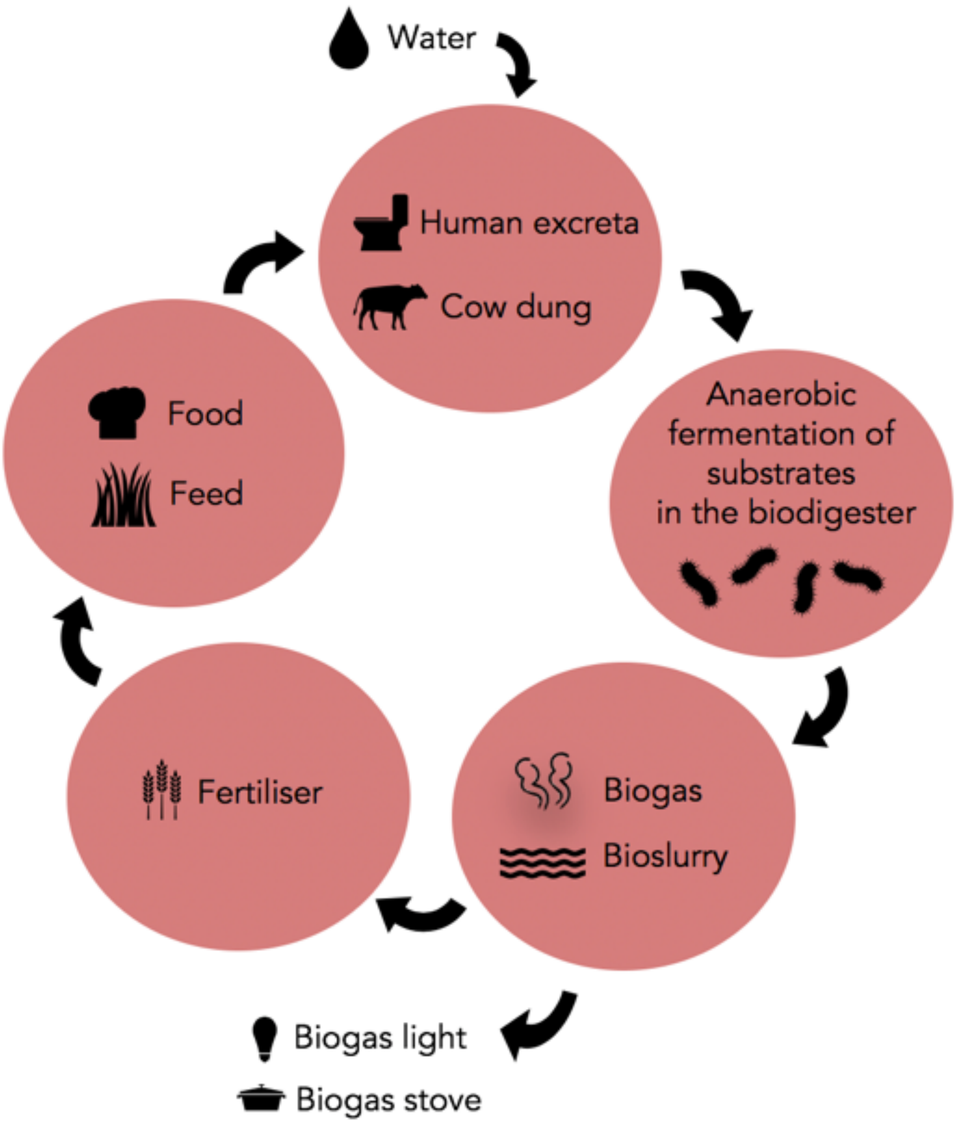

Figure 1: Nutrient cycle on a biodigester based farm system

Anaerobic digestion

Vögeli et al. (2014) describes the process of anaerobic digestion. During anaerobic digestion, organic matter is decomposed in an oxygen deprived environment through microbial processes. Microorganisms acquire oxygen from substrates, producing a gas consisting to the greatest part of methane and carbon dioxide, and a non-gaseous product bioslurry. In this way, the energy content of the substrate passes largely into the biogas, whereas the nutrients stay in the bioslurry. This allows the use of the energy content without losing the nutrients for agricultural purposes.

Suitable substrates can originate from a variety of organic sources, each causing a different gas yield and bioslurry quality depending on carbon and nutrient contents (Smith et al. 2014). A common substrate in Sub-Saharan Africa is cow manure, as this is abundantly available. However, livestock are usually fed with low nutritious feed, so the bioslurry produced is of a low nutrient content as well. The biogas is only produced from the organic dry material; the complex biochemical structures like proteins, carbohydrates, and lipids (Bonten et al. 2014). Substrates high in lignin like wood are not suitable as lignin cannot be decomposed by anaerobic bacteria. The same applies to substrates that are very high in nitrogen, which can prohibit methane production.

A latrine may also be connected to the biodigester, allowing to produce energy and a fertilizer from an otherwise wasted resource. Compared to modern toilets, bio-latrines do not need water to flush and hence can be installed in water-scarce environments (Amruta & Sarah, 2013). Remaining risks associated with pathogens in bioslurry originating from human excreta are arguable. While pathogens exponentially die-off with increasing temperatures, it is unsure whether pathogens are persistently removed (Avery et al. 2014; Bonten et al. 2014). In conditions where the retention time is hard to control, it is only recommended to use bioslurry originating from human excreta when additional measures are taken (Bonten et al. 2014).

Biogas for energy

Biogas consists of mostly of methane (50-75%), carbon dioxide (25-50%), and depending on the substrate also traces of water vapor, oxygen, and sulfur (Wellinger et al. 2013). The methane content in biogas is the most important, as at least 45% of methane is needed for biogas to be flammable (Deublein & Steinhauser, 2011). Since biogas replaces the use of organic residues and wood as a fuel, it supports the circulation of nutrients on the farm. Two common uses of biogas in a household is for light and cooking. The use of a biogas lamp is particular useful for households that have no or unreliable access to electricity or to alternative sources like solar lamp or kerosene as they show greater light efficiency (Kossmann & Pönitz, 2011). With farmers no longer relying on biomass for fuel, deforestation rates are reduced, and health is improved through the reduction of smoke in the kitchen. On a global scale, greenhouse gas emissions are reduced, permitting countries to install biodigesters to help realize their climate goals.

Bioslurry for fertilizer

Nutrient value

Bioslurry contains the macronutrients nitrogen, potassium, and phosphorus, and micronutrients like sulfur, calcium, and magnesium in addition to amino acids needed for crop growth (De Groot & Bogdanski, 2013; Fulford, 2015). A typical bioslurry consists of 93% water, 7% dry matter, of which 4.5% is organic and 2.5% inorganic matter (Warnars & Oppenoorth, 2014). As unstable compounds are broken down during anaerobic digestion, there is a big benefit of bioslurry as compared to the application of fresh organic material through the direct availability of nutrients (Smith et al. 2014). Since during this process carbon, hydrogen, and oxygen are removed and released as biogas, the nutrient concentration on dry matter is higher compared to the substrate (Fulford, 2015). As described by Smith et al. (2014), another benefit of bioslurry is its flexible application in times during the season when crops require nutrients. Preferably, bioslurry should be applied in low doses and many times to reduce nutrient losses through volatilization and leaching. As stable compounds remaining after the digestion in the bioslurry continue mineralization when applied to the field, more nutrients are released during the growing season (Smith et al. 2014). These characteristics allow nutrients availability to be the highest when crops require nutrients the most, while ensuring nutrient availability throughout the entire growth season.

Bonten et al. (2014) studied the transformation of the macro-nutrients nitrogen, potassium, and phosphorus during anaerobic decomposition. With the exception of small losses by sedimentation, nutrients are not lost. Hence, the quantity of nutrients present in the substrate are practically equal to their quantity in bioslurry. Further losses may occur during handling through volatilization of nitrogen, thus correct storage and management is crucial. As organic bonds are broken during digestion, between 45-80% of total organic nitrogen is converted to its mineral form ammonium. Phosphorus is little affected by anaerobic digestion, however it has been mentioned that changes in pH after digestion alter its solubility. To sum up, bioslurry has a higher ammonium to total nitrogen ratio, reduced volatile compounds, more stable organic matter, and a lower carbon to nitrogen ratio compared to its substrate. As a result of this transformation, new forms of nutrients are introduced to the farm, allowing to improve nutrient use efficiency by the farmer (Fulford 2015; Siegmeier et al. 2015).

Organic matter content

As volatile compounds are removed during anaerobic digestion, bioslurry contains stable organic matter, benefiting physical, chemical, and biological soil characteristics resulting in greater nutrient holding capacity (Smith et al. 2014). Fulford (2015) describes that the left-over carbon rich material is arranged in a lignin matrix. Lignin is a strong molecule that holds structures together in biomass. When volatile solids are removed, it “acts as a sponge, absorbing and retaining moisture and plant nutrients in the top layer of the soil” (Fulford, 2015, p. 86), preventing nutrient losses through leaching. When bioslurry is added to the soil, it becomes a constituent of humus, acting as a sponge to keep nutrients and water in crop distance. Bioslurry is regarded as being ‘alive’, as bioslurry will further degrade once applied to the field due to present organic compounds further mineralized by microorganisms.

As organic matter determines the water holding capacity, an additional benefit of bioslurry is improved water supply to crops (Smith et al. 2014). With increasing extreme weather events, fluctuating rainfall, and climate change, this buffer system becomes crucial for improving farm resiliency. Although water is needed to mix the substrate with, a potential water source could be waste water from the food-based bioreactor system as proposed by the LandLessFood concept to increase water use efficiency.

The Ethiopian case

Background

Traditionally, livestock manure in Ethiopia is primarily used as a fuel and the remainder as fertilizer on fields. To eliminate this competition and address the energy gap, the implementation of a household biodigester is increasingly receiving attention in Ethiopia. Key results of a field study carried out on the evaluation of installed biodigesters are now presented.

Biogas uses in practice

Prior to installation of a biodigester, charcoal, wood, and manure were primarily used for fuel. After installation, farmers substituted biomass with a biogas cooking stove to a certain extent. Although biogas is sufficiently produced to cover household demand, food habits and cooking traditions leave farmers to further rely on traditional fuel sources. The primary struggle is that the implemented biogas stove does not support the cooking of the locally favored injera, a staple food based on teff. Such a stove requires a plate like structure with uniformly distributed heat and a certain temperature. There have been initiatives developing such a mitad in both the private and public sector, however, manufacturing on a country wide scale is still not available. Although efforts for developing such a mitad are continuing, it can be concluded that the translation of cultural habits in a technology is key when aiming for higher resource use efficiency.

The use of the biogas lamp received mixed responses. Generally, farmers prefer to use other light sources like a solar or a kerosene lamp, as the biogas lamp has lower light power. Farmers were also struggling with technical problems like broken glass shades and mantles, which require a long time to be replaced, as materials are not locally produced. Given the technical problems, the low energy efficiency, and little light power of a biogas lamp, it is only encouraged for farmers to use a biogas lamp if sufficient biogas and no other light sources are available. Other uses for biogas like cooling devices has been developed, and show that there is potential for further uses. The private sector is encouraged to develop biogas appliances with materials available on the local market.

Bioslurry management in practice

Crop production in the central Ethiopian highlands is characterized by production in the homegarden and on fields. The homegarden is used to grow horticultural crops, maize, and spices, while fields are used to grow grain crops like wheat and barley. Results on the application of bioslurry show that bioslurry is only applied to the homegarden, while field crops are to the greatest extend fertilized chemically. This is because the homegarden is usually located near the biodigester, allowing easier transportation and application, as bioslurry is bulky. Furthermore, bioslurry production is insufficient to cover all crops.

It is difficult to estimate nutrient content in bioslurry without detailed analyses. However, using literature, it is possible to get some idea of the fertilizer value of bioslurry using cow manure as a substrate. This, as it is of interest to know, how many cows are needed to produce sufficient bioslurry after fermentation for each hectare of agricultural land. As a model assumption, the nitrogen demand of wheat is used, as wheat is an important crop in Ethiopia. Based on a study by Habte et al. (2015), the quantity of nitrogen fertilizer needed to produce a locally attractive 4 t/ha wheat per annum is 92 kg/ha per annum in the Ethiopian highlands. On average, Snijders et al. (2009) report the production of 5-77 kg N/cow/year, depending on feed quality, manure handling, and cattle holding. With feed in Ethiopia largely originating from crop residues containing little nitrogen, and manure exposed to nitrogen volatilization, the quantity of nitrogen per cow and per year is likely to be at the lower end. This results in correspondingly small amounts of nutrients available for recirculation on a farm via a biodigester. Besides, for manure to be suitable as a substrate, it should be wet to allow it to be mixed in a homogenous mixture. Manure on grassland dries fast, limiting suitable manure originating from the stable. As cows are in the stable during the night time, manure availability is limited by short stable periods. Given these reasons, an average of 9 cows per farm, and an average farm size of 3.3 ha, the amount of bioslurry produced from cow manure is unlikely to cover the nitrogen demand for even 1 ha of wheat. This calculation is only a rough estimate, and does not include substrates from other sources. However, it shows a good picture of the potential impact of improvements like higher quality feed on greater biodigester efficiency.

Although a biodigester is well accepted by farmers, a biodigester is a new technology that they first need to get acquainted with. While farmers where satisfied with the biogas stove (with the exception of the missing *mitad*) as it reduces smoke and cooking time, farmers are more hesitant with applying bioslurry. Bioslurry is an unfamiliar fertilizer, and is connected with risks if not familiarized with its management. Moreover, farmer knowledge on the benefits of bioslurry is insufficient, impeding application. Nevertheless, observations showed that farmers willing to apply bioslurry have experienced positive results after a first application regarding number of plant tillering and color. As a solution to inadequate knowledge, farmers with bioslurry experience should teach other farmers, in addition to the use of a demonstration farm to allow farmers to become more acquainted with bioslurry.

Discussion

Arguments for a biodigester are the various impacts it has for the farm through provision of energy, organic matter, and nutrients to stabilize soil and improve crop growth. Integrating a biodigester into the farm system makes important contributions to the production of nutrients without requiring additional land and natural resources. Bioslurry is a high-quality fertilizer accessible by farmers, enabling agricultural systems to reshape to a resilient and stable system, and providing new economic opportunities to the farmer. Although compared to other fertilizers the impact of bioslurry on yields is disputed, the integration of bioslurry on a farm will benefit crop production as low access to fertilizers is a vast limitation in Sub-Saharan Africa (De Groot & Bogdanski, 2013; Rahmann et al. 2019). Smith et al. (2014) describes that introducing a nutritious fertilizer like bioslurry to the farm will have a positive impact on yields for two reasons. Firstly, the macronutrients nitrogen, phosphorus, and potassium are main limitations to crops. Introducing these nutrients to the farm will improve the nutritional status of crops. Secondly, the addition of organic matter on largely depleted soils improves the water holding capacity and soil structure, which is beneficial for healthy root growth and for the roots' access to nutrients.

A household biodigester can be integrated into a farm system in different ways. Different types with variable sizes exist, allowing customized installations. Main motivation for farmers to install a biodigester is higher food security, access to clean energy to reduce health problems, and economic returns through higher yields and fewer expenditures on fuel and chemical fertilizers. Next to the use of biogas for light and cooking purposes, its uses for other appliances like radiant heating, incubators, and refrigerators have been mentioned (Kossmann & Pönitz, 2011). Their installation could potentially further increase efficiency in food production, requiring fewer additional resources. However, as the use of these appliances are not yet widely spread, more research and development are needed.

Bioslurry and biogas show to have high potential in the recycling of nutrients, depending on substrate quality, and challenges concerning installation. The case in Ethiopia shows that quality and quantity of manure is limited by relatively short stable periods and low-quality feed. Further resource recycling is limited by an unavailable *mitad,* causing farmers to further rely on biomass for fuel to cook the locally favored *injera*. Social challenges include inadequate knowledge on functioning and management of bioslurry. Increased knowledge can therefore accelerate nutrient use efficiency and help increase motivation for farmers to apply bioslurry.

Further recommendations include the addition of forage legumes and shrubs, and grasses into the farm system to provide quality feed, thereby increasing manure production and nutrient availability on the farm. For the production of these crops, no additional land is required as they can be incorporated into unused land like field margins and boundaries, into the homegarden, or incorporated into the existing cropping system through intercropping. This system perspective allows to increase biodigester efficiency and restructure an agricultural system in a clean way.

Relevance of a household biodigester for the LandLessFood concept

Increasingly scarce resources in a biodigester based circular agricultural system are recycled through the production of energy and a fertilizer from organic residues, allowing nutrients to be kept in the farm system. With the peak phosphate rate to be reached in the near future, reduced land availability, and degrading soils, higher resource use efficiency through recycling of on-farm nutrients is crucial (Rahmann et al. 2019; Siegmeier et al. 2015). Through the redistribution of nutrients, a biodigester allows nutrients to become available to the food system again. This allows sustainable agricultural intensification using landless production methods.

The ability of bioslurry to compensate for organic matter and nutrients allows an agricultural system to be integrated into more harsh environments like areas with high temperatures and little rainfall which so far are excluded from the production system. A biodigester offers a clean link between crop production and the waste system, through opening new pathways for nutrient circulation, fertilizer production, and organic food production. In the landless system model, a biodigester acts as a redistribution unit of resources between farm elements like bioreactors through its use of waste water, and provision of energy to the household. If sufficient and good quality bioslurry can be produced, a sustainable farm system independent of additional resources can be realized.

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What Do We Understand About Our Food? A Review in context of sensory sciences

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Definition

What is food? This seemingly simple question that could be many interpretations and definition or sometime needs a comprehensive analysis to define it. By the simple way, food can be defined as a substance can fulfil human energy for metabolism with several requirements. Food make our body work, grow and repair itself. Food in fact the one with the most complicated set of chemical structures as well as composed of macronutrient and micronutrient. The chemical nature of food is changed by cooking, storage and preservation. The size of food particles can affect to which nutrient are digested and ready for absorption.

The relationship between human and food, a universal necessity, has a complex history dating back in the first human civilization. As humans gained more aptitude and ability, primitive processing techniques have grown more sophisticated and incorporated machinery. This transformation has long been a discussion topic of the scholar focus on nutrition, quality and safety, while others focus on culture, behaviour and habit. Multidisciplinary research is often performed to capture the changing aspect of food cultures and consumption. Nowadays, food refers to the practices, beliefs, and attitude humans as well as networks and institution surroundings the production, distribution and consumption of food.

In all cultural tradition, foods have many dimensions. Nations and countries are now frequently associate to a certain foods or certain staple foods, and many cultures or individual have one food specific memory, whether taste or smell. More than that food is also translated as a symbol of hospitality, social status, and a religion identity.

Food discussion encompass not only what is eaten, but how it prepared and served, and how its related to the identity and lifestyle of human who eating it. Particularly when comparing modern time to ancients. There is a significant difference in the processing of food which related to environment and “human appetite” landscape. The swing trend of food is based on trend create by humans, or by nature based on geographical where the humans are situated. Furthermore, humans are very intelligent, and have their ability to manipulate and create food according to their wishes.

Food Sources

The diversity of food is mainly based on how humans interact with their environment, and how their adopted to the changing of the environment. Main sources of the food are come from biological living and very small of them from the mines (such as salt and etc). In this perspective we can see, most of the food product come from plantation (plant-based food) and animal (animal-based food).

In the response of the landless food concept (Rahmann et al 2019) as can be seen in the fig 1, Algae is a promising as a food source. As we all know that, human is familiar with plant based, animal based and fungi-based food. But Algae based food it seems to be not familiar. Even though, algal has been used for long time for ingredient of many food, nutraceutical as well as cosmetics. Algae is considered as efficient in term of energy production compare to other food-based, high calorie as well as macro and micronutrient. Furthermore, the ability of algal grow with no need land, this becoming opportunity how we fulfil energy demand for human being.

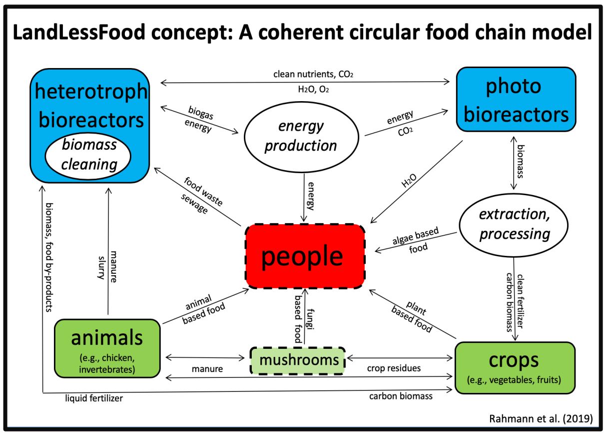

Fig. 1 Flow model of circular sustainable land based and landless food production systems (Rahmann et al 2019)

Most people have no idea how many daily use products contain algae. Algae are an ingredient in thousands of products for food, feed, colour, nutraceutical, medicinal, personal care, biofertilizer, fine chemical and biofuel. Algae are a group of plants, most of which are capable of performing photosynthesis. There are 80,000 to 100,000 different algae species with widely varying characteristics, and globally, there is growing interest in algae as production organisms. There is substantial evidence for the health benefits of algal-derived food products, but there remain considerable challenges in quantifying these benefits, as well as possible adverse effects. They are primary producers which are a source of many nutrients, and it has high protein content. Not only food but also nutritive ingredient and medicinal value also exist in marine algal source. Over 15,000 individual compounds have been identified in microalgae that are responsible for producing numerous useful products. About 70 species of algae are used for food, food additives, animal feed, fertilizers and biochemicals. They are grown for animal and aquaculture feeds, human foods, biochemicals and pharmaceuticals. Microalgae in the ocean, called phytoplankton, are the base of the food chain and support all higher life (Usmani et al 2015).

Processes

Food is not simply cooking and eating only, as the wider view, food must also include discussion agriculture and environment. Likewise, culture must also be examined not only as individual habits and behaviour, but also the society and other aspect as whole systems. There are many forms of food processing to which food may be subjected before we eat it. All these processes have some effect in the nutrient content. In the response to the landless concept, particularly algae as food based. For example, drying technology would be an important aspect to kept macro and micronutrient not spoilt. Other example, fermentation can be used to improve the sensory attribute of algal. The selections of appropriate processor can affect the quality of food both Physio-chemical as well as sensory.

Idea to be considered

In response to the concept of landless food (Rahmann et. al 2019), we must understand the basic aspect of food:

1) Physiological function; Food provides energy, food helps in body buildings as well as food regulates body processes and provides protections against the disease.
2) Psychological function; in this function, food becomes as objects free to be valued, love and affection.
3) Social function; Food is integral for festivity at any cultures as well as religious.

If we can obtain energy/calories from algal, then the question begins to the sensory preference (psychological functions). Sensory preference has the major impact on the food choice of the consumers. Before we start with discussion on the relationship between preference and intake, it may be good to make a distinction between various term. In general liking and palatability refer to degree of the pleasantness that subject have when tasting a particular food; Liking i.e the pleasantness of the taste is different from "wanting" which refers to pleasantness to consume a food. Wanting may be measured by asking people for their desire to eat a particular food at a particular occasion. The term of preference refers to the preference of one food over another, as suggested by Frewer and Van trijp (2007), (See figure, 2).

Algae are very popular among the vegetarian, who use them as starters addition in the main courses (Cofrades, Serdaroglu, and Jimenez-Colmenero 2013). In food for human consumption algae have been mostly introduced to meat and bakery products. The addition of algae, including Enteromorpha, *Himanthalia elongata, Undaria pinnatifida,* and *Porphyra umbilicalis* resulted in changes in the antioxidative potential of meat and cereal based products (Gupta and Abu-Ghannam, 2011). In this context, we could see that algal-based food is relatively has been exposed by consumers (as ingredient). However, we have other scenarios that algal can be extracted in the form which human can widely consumed it.

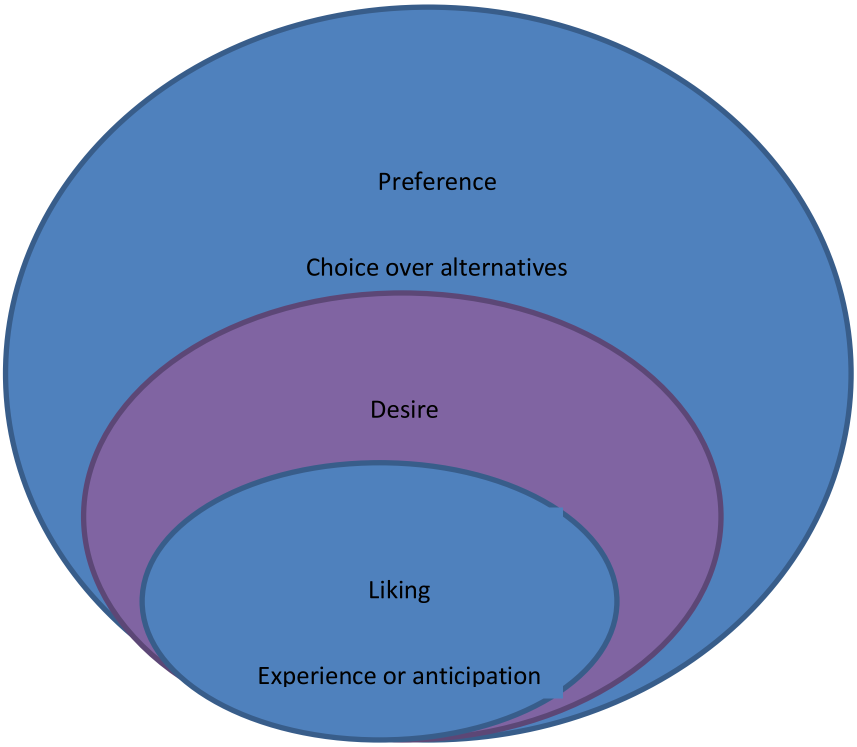

Fig. 2 Food preference (Adopted from Frewer and van Trijp, 2007)

In the African context, according to West African composition table (FAO, 2012) compile 472 foods and 28 components, none of the list has been exposed by algal ingredient. This is one of the challenges to introduce the algal, it can be accepted to the most African consumers or not depend on how algal is severs as a food. Furthermore, algal source is the major initiative to sustainable agriculture to meet the food supply in global population. The remaining questions is, Do Algal from bio-photoreaction are accepted as a food? and how consumer perception on this matter?

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Is Organic the Interface Between Smart Agriculture and Ecological Intensification?

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Abstract

Organic agriculture must adopt a culture of continuous improvement toward best practice and innovation in order to remain relevant as a sustainable model of food production. Here we discuss the intersection of Organic 3.0, smart agriculture, and ecological intensification. While smart agriculture technologies are often associated with conventional systems of input application, these technologies can also be used to better understand the agroecosystem and thus could support approaches to ecological intensification. The future of organic agriculture should include a coupling of smart technologies with ecological knowledge in order to achieve the features of Organic 3.0.

Introduction

Despite its continued growth in land base, global farmer population and marketplace (Willer and Lernoud, 2018), the rate of adoption of organic agriculture has not been rapid enough to address global agri-environmental issues. While it is well-recognized that land under organic management is more likely to support attributes of higher biodiversity, conversion of natural land to address yield gaps or to capture market opportunities continues to be a concern (Reganold and Wachter, 2016; Seufert and Ramankutty, 2017). The organic sector must grow and evolve in order to address the many challenges associated with conventional agricultural intensification and population growth (Arbenz et al., 2016).

Organic 3.0 is a vision for the next stage in the evolution of the organic sector (Arbenz et al., 2016). Its goal is to expand the impact of organic agriculture globally by focussing on six features: 1) A culture of innovation, 2) Improvement towards best practice, 3) Diverse ways to ensure transparency, 4) Inclusive of wider sustainability interests, 5) Empowerment from farmer to consumer, 6) True value and cost accounting. Thus the relevance of organic agriculture as an impactful production system that addresses global issues depends on an evolution of thinking and practice in the organic sector.

Ecological intensification is a concept which involves understanding and utilizing ecosystem processes to enhance productivity while minimizing environmental impacts. It is described by Bommarco et al. (2013) as: “Ecological intensification is based on managing service providing organisms that make a quantifiable direct or indirect contribution to agricultural production. The supporting and regulating ecosystem services provided by these organisms can be incorporated into cropping systems, such that production is maximized while environmental impacts are minimized through the decrease, but not necessarily exclusion, of anthropogenic inputs, such as inorganic fertilizers, pesticides, energy, and irrigation.”

Smart agriculture involves the use of new technologies (e.g. sensing, communication, big data, internet of things, machine learning) to track, monitor, analyze and automate agricultural operations. Ultimately, it is expected to allow producers to be more proactive, productive and resource efficient through more informed management decisions and use of automated systems.

The organic sector is sometimes regarded as reluctant to adopt new technologies in favour of ecological approaches to management. Are these approaches of ecological intensification and smart agriculture complementary? Are they consistent with Organic 3.0? Can smart agriculture technologies be used to support ecological intensification and support the evolution of organic agriculture? Here the interface between ecological intensification, smart agriculture, and the Organic 3.0 will be explored.

Ecological Intensification

Chevassus au Louis and Griffon (2008) describe ecological intensification as “intensification in the use of the natural functionalities that ecosystems offer”. Ecological intensification would be characterized by high internal regulation processes, moderate resources inputs, low nutrient losses and high productivity (Bender et al. 2016). Ecological intensification requires a better understanding of the ecosystem and how it functions in order to inform management choices that lead to higher levels of sustainable production. From the perspective of enhancing productivity, ecological intensification would involve understanding the localized interface between the crop, soil, environment, pests, beneficial organisms, and inputs used to support the crop.

As an example, healthy interactions between soil biology and crops requires a healthy soil environment. However, a healthy environment may not be enough. Ecological intensification may also require more intensive management through soil ecological engineering by introduction of functional soil biology. In this approach, functional soil biology is identified and applied to the field or crops that will enhance productivity by enhancing cycling of nutrients, support more efficient capture of nutrients and water, interacting with plants to promote growth, and suppressing pathogens. In order to be effective, the soil biology must be customized to match soil conditions and/or the soil conditions must be managed to optimize function of the soil biology. Thus, the practical application of this approach requires an understanding and monitoring of the soil environment including its variability over time and across a landscape. Bender et al. (2016) suggest that “Combining targeted soil biological approaches with state-of-the-art technological advances in agricultural science could serve to reduce external resource use to a minimum while yields could be maintained or even increased”.

Smart Agriculture

Smart agriculture at a minimum involves the use of sensor systems + data transmission systems + analytical systems providing either a recommendation or through a digital user interface (e.g. computer or smart phone) or an action (e.g. turning a control switch on or off). The system can be further supported by data storage and networking systems and enhanced through automated tools and robotics. The vast volumes of data collected by sensors must be analyzed and provided to the producer through a user-friendly interface that enables the producer to make informed decisions.

Smart sensor technologies are commonly used to measure soil properties (e.g. moisture, temperature, electrical conductivity, pH, organic matter, nutrients) environment (e.g. air temperature, humidity, precipitation, carbon dioxide, light/radiation), crop properties (e.g. radiation reflectance, chlorophyll content, leaf moisture, crop height, density, yield, composition). Global positioning systems are used in combination with sensing technologies to either provide the precise location where the data is gathered, or on mobile platforms (e.g. tractors, drones, satellites) to map the sensor data gathered from across a landscape.

Smart technologies are applied in agriculture in a variety of ways. Environmental sensors and analytical systems can be used to optimize irrigation systems, predict crop development or predicting the timing and extent of pest pressure. Precision crop production uses soil and crop data to develop prescriptive maps for input application. These maps combined with global positioning guidance systems and equipment equipped with control switches allow precise and variable rate application of inputs. Real-time sensing and analytical systems can allow detection of actionable targets (e.g. weeds, bare soil, ripe fruit etc.) for precise input application while equipment is in motion.

Connecting Smart Agriculture with Organic Ecological Intensification

It becomes clear that smart technologies can lead to an improved understanding of a production environment which can lead to more effective, efficient, and precise management decisions. Thus ecological intensification, could be supported through use of these technologies.

The most common production challenges in organic agriculture relate to maintaining soil fertility and controlling pests. Organic inputs are less available and more expensive than conventional counterparts. Thus strategic and targeted use of these inputs is essential. Using field level sensing and mapping technologies can optimize input use by allowing variable application of soil amendments, seeding rate and seed mix composition according to soil type. Similarly, seed could be precisely placed to optimize competition with weeds and productivity when intercropping.

Camera sensing equipment can be used for precise weed control in organic systems. Camera guidance systems can detect crop plants/rows and apply mechanical control of weeds both between rows and in the row. Smart weed control systems can detect weeds, differentiate them from the crop and apply targeted mechanical or chemical control. Robotic systems for physical and/or chemical weed control are becoming available for large- and small-scale operations. While some herbicides have been formulated with organically acceptable ingredients, they have not been widely commercialized or adopted due to cost and high application rates which may impact the cash crop. Precise targeting of weeds could greatly reduce the volume of herbicide application as well as non-target impacts, making organic herbicide application more feasible.

Cultural practices are sometimes insufficient for providing adequate pest control. It is essential that organic pesticides are applied at an optimum time and place to be cost-effective. Smart pest monitoring systems including environmental models predicting pest pressure are key to timely and effective control. Similarly, in livestock, smart sensors could be used to give very early warnings of changes in health of livestock and allow early organic management before more severe intervention is needed.

Beyond Productivity

Organic agriculture is also expected to maintain ecosystem services beyond production of food fibre, fuel etc. It is expected, for example, to achieve outcomes such as maintaining or enhancing biodiversity, minimizing nutrient losses, and enhancing animal welfare. Smart technologies could be used to monitor these ecological and animal welfare benefits of organic farming systems. For example, remote sensing to monitor land use, cover type and composition data could be used to determine impacts on biodiversity and soil quality. Acoustic monitors could be used monitor bird populations. Smart cameras could be used to monitor ground beetle or pollinator activities. Ground water sensors could monitor leaching losses of nutrients. And sensors in or on livestock could document their wellbeing throughout their lives. This improved understanding of how organic farming systems function could be used to inform standards development, government policy and consumer behaviour.

Linking with Organic 3.0

Both ecological intensification and smart agriculture technologies could contribute toward addressing all six features of Organic 3.0. Certainly these approaches individually can bring a culture of innovation and continuous improvement of practices. Utilizing these approaches strengthens relationships with like-minded as well as other parts of the agricultural community, potentially enhancing receptivity toward adoption of organic practices. Lastly, the use of smart technologies can empower not only producers but producers as well through improved understanding of the outcomes of organic production coupled with consumer friendly systems of tracing information back to the producer (e.g. by using QR codes). While ecological intensification alone is a useful concept, the power of smart sensing, communication, and analytical systems has tremendous potential to enhance the effectiveness of practices supporting ecological intensification.

Conclusion

In conclusion, the organic movement has engaged in a bold new vision for the future of our sector titled Organic 3.0. Ecological intensification can be applied to enhancing productivity, however, its application requires a high level of understanding of the growing environment and processes within it. Smart agriculture technologies can be used to support this understanding in an integrated way, and potentially provide tools that could support ecological intensification. Smart agriculture technologies could also be used to understand and monitor other ecosystems services. Capturing the synergy between these two approaches could contribute toward addressing all six features of Organic 3.0.

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