The opportunities and challenges of circular agriculture in Taiwan

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Abstract

Changes from the consumer side towards a healthier and less-meat diet and from the production side to reduce environmental pressures are urgently needed in response to the continuous growing population and concerns of unsustainable agricultural practices. Circular agriculture (CA) can be a technology measure for keeping the food system within environmental limits. Although the concepts, definition and principles of CA are various and might not be able to directly transfer from the concepts of circular economy (CE), some principles and strategies from CE can be quite useful after adapted. Narrowing, closing and regenerating are the three main strategy aspects, which aims for optimizing the use of resources, reusing agricultural materials and preserving and enhancing natural capital, respectively. However, all the existing indicators of evaluating the effect of the strategies have their own strength and weakness. Therefore, the effect of a CA practice needs to be evaluated using multiple indicators that cover different aspects. National meta-analyses summarizing the existing CA experiments will be needed for evaluating and presenting the geographical, climatical, and agronomical variances to allow policy makers to interpret and make relevant decision easily. Within all the technical strategies to improve CA, the reuse of biomaterials (food wastes, plant residuals, and animal manures), either as biofuel, biofertilizers or the feedstock of biochar, has great potential to both closing the nutrient loop and enhancing soil health. However, as these biomaterials are not standardized, the nutrient balance (both macro- and micro-nutrients), toxic element contents in the materials and their following effects on soil properties, crop nutrition and environment highly depend on their sources, the processing methods and the application methods, of which careful and comprehensive evolution is required. In Taiwan, except for cereal crops, most of the vegetables, fruits, eggs and meat are produced locally, which make the implementation of mixed crop-livestock strategy more possible. The re-utilizing livestock manure can be therefore the most promising approach to improve the sustainability and circularity of agriculture in Taiwan. However, evaluating and tracking data of quantifying the reduced application of artificial fertilizers, especially those dominantly imported, driven by the application of organic fertilizers from different sources, and their further impact on soil and crop nutrition is currently lacking. This makes it difficult to strategically evaluate the impact of the sources and types of organic fertilizers and, in turn, difficult to adjust and improve the systems. Relevant investigation and national meta-analyses of the effect of different approaches and the use of different biomaterials will be most required and challenging.

Keywords: Sustainability, Circular agriculture strategies, Manure management, Nutrient cycling

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How to maintain the sustainability of agriculture?
– we need to change

The global population is expected to grow by about a third and the global income is expected to triple in 2050. Over this period of time, it is projected that about 2 billion people are going to enter the global middle class with expected increased wealth and more resource-intensive consumption, including eating more animal product (Grumbine et al., 2021). However, in the 2023 UN summit, the United Nations reported that there were still above 30 percent of the world population moderately or severely food-insecure, lacking regular access to adequate food. This implies that the current global food production and distribution system is problematic and unsustainable.

The fourth goals of SDG2 by 2030 is “to ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality.” The global averaged agricultural land use per capita drastically dropped in 1910 and has been decreasing in the last century from 1.56 ha in 1910 to 0.66 ha in 2016 (Our World in Data, https://ourworldindata.org/land-use). This implies that the current land use efficiency is actually increasing, which can be partly attributed to the use of artificial fertilizers and agricultural mechanization that greatly increase the quantity of food production. However, ‘how long can we produce food like this?’ has been questioned, especially in face of global growing population and more extreme weather events. It is projected that within 60 years, all of the world’s topsoil could become unproductive if the current agricultural practices and soil degradation continue (Maximillian et al., 2019).

Springmann et al. (2018) published an article on Nature, in which they estimated that the environmental pressure of the food system is going to increase by 50-92% for each indicator in 2050 (GHG emissions 87%, cropland use 67%, blue water use 65%, phosphorus application 54%, nitrogen application 51%) in the absence of technological change and other mitigation measures. They proposed some potential options for keeping the food system within environmental limits. With regards to the effect on reducing environmental pressures, compared to the projected pressures in 2050, dietary change contributed the most (29%: change to a healthier diet, 56%: change to a plant-based diets) to the reduction of GHG emissions. Technological changes that increase the efficiency of production, such as increasing N use efficiency, P recycling, water management, improving manure management etc., can reduce the most (by 3-30%) in other environmental pressures (including cropland use, blue-water use, N application and P application) of food systems. However, they also reported that no single measure is enough to keep the effect on reducing environmental pressures within all planetary boundaries. The goal of keeping the environmental impacts within 15% or less than the present impacts can only be achieved by combining all the measures. In other words, to maintain the sustainability of agriculture, it is clear that we need a systematical change from both the production side (for example, increasing nutrient and water use efficiency) and the consumption side (reducing food waste and changing to a healthier or plant-based diets) (Dobermann et al., 2022). It is deemed that the coming 10-20 years will be critical for making transition to a global food system in which we produce and consume food in a more sustainable way (Dobermann et al., 2022).

In terms of the dietary changes, Chen et al. (2019) studied the nutritional quality and impacts on environment, economy (daily food expenditure) and human health of nine alternative dietary scenarios (healthy Swiss diet, healthy global diet, vegetarian, vegan, pescatarian, flexitarian, protein-oriented and meat-oriented diets and a food greenhouse gas tax diet). They found that achieving a sustainable diet requires a high reduction in the intake of meat and vegetable oils and a moderate reduction in cereals, roots and fish products and at the same time increased intake of legumes, nuts, seeds, fruits and vegetables (Chen et al., 2019). However, dietary choice of humans is highly depending on personal habits and preferences, of which the alteration requires time, education and societal consensus.

The technology measure in Springmann et al. (2018) include increasing N use efficiency and P recycling, improving water use efficiency, adopting agricultural mitigation strategies, changing manure management strategies etc. Since resource use efficiency and recycling is a large part of circular agriculture (CA), the following discussion will be focusing on how the design and concept of CA can serve the ultimate goal of agricultural sustainability, what are the technologies and practices we can use, and what are the challenges we are faced with.

The concept, definition and principles of circular agriculture

The concept and definition of circular agriculture (CA) varies. Some describe it from the technical side as a closed-loop system in which nothing is wasted, and some explain it as a system that mimics the natural processes of regeneration (Marinova & Bogueva, 2022), and some recognize it as a concept transferred from circular economy (CE) (Velasco-Muñoz et al., 2021). One of the challenges of designing CA is related to debates about whether to narrowly frame food systems as only about technological issues (increase crop yields, close nutrient loops, re-couple crop-livestock links, etc.) or whether to include social and demand-side issues (improve smallholder livelihoods, create sustainable supply chains, promote dietary shifts, etc.)(Grumbine et al., 2021). For the convenience of discussion, this article is only focusing on the discussion of technological design, of which the advances can reduce the environmental pressure by 3-30% according to Springmann et al. (2018).

In regards to the boundaries of CA, Marinova & Bogueva (2022) argued that it is better to differentiate CE and CA, with the latter only relates to the closed-loop cycle of food production. Marinova and Bogueva (2022)'s argument makes sense since the concepts and models of CE cannot be directly transferred and applied on CA, because CE focuses on technical products and CA, biological products. For example, the idea of 'repaired' and 'remanufactured' of a technical product cannot be applied on biological product, such as tomatoes, which cannot be repaired once it is damaged.

Even though, Velasco-Muñoz et al. (2021) reviewed about 700 existing studies that have tried to adapt the concept of CE to agriculture. In their literature review, some useful strategies and indicators that we might be able to use in improving and monitoring the effect of CA were proposed, which are presented in the next paragraph. Some main principles were also well extracted from about 700 studies and summarized by Velasco-Muñoz et al. (2021), which include three main principles:

(i) Resource efficiency (資源有效利用): adopting technological or economic practices to ensure greater added value and maintain resources within the production system for as long as possible. Methods include optimizing processes to minimize resource use and avoid waste.

(ii) Sustainability (經濟、環境與社會永續性): (1) economic sustainability: CA should become a pillar of the economy rather than a subsidized sector (2) environmental sustainability: ensure the conservation of biodiversity and productivity over time in its agroecosystems (3) social sustainability: provide food security, eradicating poverty, and improve health and living conditions.

(iii) Regenerative (再生性): agriculture must evolve to include regenerative systems that close nutrient loops, minimize leakage, and maximize each loop’s long-term value.

Based on the above principles, the authors defined CA as “the set of activities designed to not only ensure economic, environmental and social sustainability in agriculture through practices that pursue the efficient and effective use of resources in all phases of the value chain, but also guarantee the regeneration of and biodiversity in agro-ecosystems and the surrounding ecosystems”

Strategies, practices and indicators of circular agriculture

Some strategies, practices and relevant indicators of a CA system are extracted from literature and summarized in Table 1. The listed three aspects of strategies: narrowing, closing and regenerating are adapted from CE, which aiming for optimizing the use of resources, reusing agricultural products and regenerating, respectively. Practices that relate to each strategy is extracted from studies and allocated to each column in Table 1. In the aspect of narrowing, focuses have been lasered on the use efficiency of land (to produce crops, animal feed or biofuel), water and fertilizers. In the aspect of closing, much attention is placed on reducing and reusing agricultural wastes. In the aspect of regenerating, the maintenance of soil health by means that reduce soil erosion and increase soil fertility and biodiversity has been predominantly discussed. The indicators to assess the level of circularity of each practice is strategically important. However, it should be noted that each indicator has its strength and weakness, and no single indicator is able to reflect all the aspects of a CA system (Velasco-Muñoz et al., 2021).

A good meta-analysis example

Studies of a farming practice conducted at different conditions, such as crop species, soil properties, time frame, and regional climates, can have different effect and outcomes. To provide comprehensive information for farmers and policy makers, a study that summarizes the outcomes of different studies and delivers visualized and clear messages is required. A good example of such study is presented by (Zhao et al., 2020). Using meta-analysis method, they calculated the results extracted from 214 observations of 45 studies that involved ‘crop rotation’ in China, which were filtered from 4392 English and 586 Chinese publication, respectively, and excluded those reporting on the same trial. The effect of crop rotation was well presented as confidential intervals (effect % on yield) compared to monoculture (0%). They showed that crop rotation overall could improve about 20% on yield. However, the effect varied by geographical location (the most in southwest and least in east), weather, soil (such as soil texture, organic carbon and nitrogen contents), and crops. They also showed that the rotation effects were greatest when legumes were the pre-crops; when the rotation was conducted over three cycles, the effect became insignificant.

Study like this, presenting variances between factors and the overall effect of a farming practice (crop rotation here) in a visualized way, can help readers understand and interpret the meaning of the data easily. More studies like this are required in Taiwan to summarize the existing studies that evaluated the effect of different CA practices. Building on such comprehensive analysis, researchers and government can have opportunities to allocate resources and scientific power to those has not been investigated and can have stronger scientific evidence for policy making.

Enhancing nutrient cycling with agricultural wastes

Within the strategies of ‘closing’ and ‘regenerating’ in a CA system, reusing agricultural wastes, such as food wastes, plant residuals, and animal manures, as alternative soil fertilizers has great potential of both closing the nutrient loops and improving the soil quality. Additionally, animal manures can also be a source of biogas, which serves as a source of renewable energy. However, farmed animals per se consumed more than one third of the world’s cereal grain, leading to low nutrient use efficiency in the whole food chain and causing large GHG emissions (Dobermann et al., 2022). The current livestock production system therefore needs to become more sustainable, which can involve shifting to pasture-based systems and introducing mixed crop-livestock systems (Dobermann et al., 2022), in which the plant residuals can be used as the feed for animals and animal manures can be used as alternative source of fertilizers and soil organic matter.

Despite of the multiple functions of animal manures, some challenges still exist and need further investigation. For example, by spreading manures on farmland based on the N content of manure, farmers often end up applying onto soils 5-10 times the crop P requirement, because of the low N:P ratio (3:1 or less) of stored manures compared to the ratio required by crops (close to 5:1 or 6:1) (Rosemarin et al., 2020). The over-applied P from manures can accumulate in soil and becomes so-called legacy P, of which the accessibility to crops, the potential toxicity driven by high concentrations, and the impact on the uptake of other nutrients need to be carefully evaluated.

Another concern of applying those agricultural wastes in soil, especially animal manures, is that for some micronutrients, their phyto-availability in soil can be reduced by the application of animal manures. For example, Kao et al., (2023) reported decreased concentration and accumulation of selenium (Se) in perennial ryegrass than the control when the soil received sheep excreta (Fan et al., 2008) reported decreased Se concentrations in wheat grains after farmyard manure application in a long-term experiment at Rothamsted Research, UK. Wang et al. (2016) also reported lower Se accumulation in wheat and maize compared to the control and the soil applied with inorganic N, P K fertilizers. This raised a concern that although utilizing agricultural wastes can benefit the recycling of nutrients, such as N and P, its long-term effect on nutrient balance and the recycling rate of some micronutrients may be hindered.

Micronutrient deficiencies are a widespread and growing problem in both crop plants and human populations worldwide (Assunção et al., 2022). Prof. Ismail Cakmak has raised the concern of hinder hunger (micronutrient deficiency) in a FAO report (https://www.fao.org/fsnforum/comment/9021), which may be driven by the current agricultural fertilizer practices. Micronutrient deficiency can affect the tolerance of crops against pest, pathogens and other environmental stress and, in turn, affect the crop production and nutritional quality. Assunção et al. (2022) called for awareness of the importance and relevance of micronutrients in crop production and quality, of which science is relatively lacking. Although the deficiency of micronutrients can be easily balanced by applying foliar fertilizers and synthetic chelators, it was commented that some deficiency symptoms are often related to nutritional imbalance rather than the lack of a single element per se (Assunção et al., 2022). It therefore deserves further research to understand the impact of applying different agricultural wastes, on the ultimate nutrient recycling and crop nutrition from a more holistic point of view.

Using biochar – benefits, risks and prospects

The application of biochar that derived from agricultural wastes has been thought to be a potential solution of reducing wastes and increasing soil carbon sequestration simultaneously. However, applying biochar in agricultural soils is still a highly controversial topic, because there have been trade-offs between increasing soil C and improving crop growth and nutritional quality. Furthermore, biochar application might be beneficial to some aspect, for example increasing soil organic carbon, it can be harmful to other aspects, such as increasing soil heavy metal concentrations (Jindo, Sánchez-Monedero, et al., 2020). The effects of biochar on crop growth and nutrient cycling highly depends on the feedstock types and the pyrolysis conditions, and, sometimes, the soil application rates. For examples, biochar pyrolyzed at low temperature can enhance denitrification and, in turn increase N2O emission, whilst biochar pyrolyzed at high temperature was reported to decrease denitrification and N2O emissions; whether or not the application of biochar can reduce soil NH3 emissions is determined by both the adsorption capacity of NH4+ and the pH of a substrate, which depends on both physiochemical properties of both soil and biochar; although more phosphorus (P) will be transformed into orthophosphate (a plant-available P form) with increasing pyrolysis temperature, the ultimate P availability to crops still highly depends on soil pH (in acidic soil, biochar application has more positive effect on increasing plant-available P) (Jindo, Audette, et al., 2020).

Other than used as alternative soil fertilizer or soil amendment, biochar has also been tested as growing media and composting additive. Huang & Gu (2019) reviewed 32 studies and reported that the application rate of biochar under 25% generally resulted in similar or higher plant growth compared to the commercial substrates. Nevertheless, there are still concerns regarding the high salinity, high alkalinity and potentially high concentrations of heavy metals and polycyclic aromatic hydrocarbons (PAHs) of biochar in comparison to peat, which would require pre-washing, addition of natural acids, and a careful selection of the appropriate feedstock and pyrolysis conditions, respectively (Jindo, Sánchez-Monedero, et al., 2020). Adding biochar into composts is probably the most promising use of biochar. Studies have shown that adding biochar in composts changed the bacterial communities, accelerating composting rate, enhancing humification, and reducing losses of NH3 and N2O (Agyarko-Mintah et al., 2017; Gong et al., 2023; Wu et al., 2017). Furthermore, the combination of biochar and compost can significantly improve soil conditions and crop performance compared to traditional agricultural practices or the single use of biochar (Jindo, Sánchez-Monedero, et al., 2020).

Overall, when it comes to using biochar in agriculture system, because biochar is not a standardized material, the differences in the feedstock type and pyrolysis conditions should be taken carefully into account, especially when used as alternative substrates, soil organic fertilizers and soil amendment. Some possibly negative impact of biochar amendment to soil, such as potential increase in P leaching and high salinity, should also be taken into consideration (Jindo, Audette, et al., 2020). When used as soil fertilizers, due to the low N content (generally less than 0.01%), it requires adding extra N fertilizers to ensure a good C-N ratio for plant growth.

To evaluate the general impact and variance between different variables of using biochar, national or global meta-analyses like (Zhao et al., 2020) is needed. It should be awarded that there is still lacking experimental data regarding the effect of long term and repetitive additions of biochar to the soil, and a proper combination among biochar type, the purpose of its use and optimum application rate should be explored (Jindo, Sánchez-Monedero, et al., 2020).

The opportunities and challenges of circular agriculture in Taiwan

A great part of a CA design is using the land efficiently. In 2022 in Taiwan, 8,139 and 78,000 hectares of land was used for animal husbandry and arable farming, respectively, which were approximately 0.225% and 2.16% of the national land, respectively. They overall provided in average 31.3% of food (including 26.3% cereals, 84.3% vegetables, 86.0% fruits, 100% eggs, and 76.5% meat, calculated by calories), with the rest imported. For those imported, it is difficult to use their agricultural wastes to close the nutrient loop and benefit the production land. Fortunately, most of our vegetables, fruits, eggs and meat are produced locally, of their agricultural by-products and wastes have great potential to be used for the ‘closing’ and ‘regenerating’ strategies. However, as mentioned in the previous paragraphs, the use of agricultural and/or urban wastes needs careful evaluation on their sources, contents of harmful substances and their nutrient balances (including macro- and micro-nutrients).

The challenges of using animal manures as alternative fertilizers include social acceptability, their proven and perceived risks for heavy metals and pathogens, and the geographical mismatch between livestock farms and crop production systems, which hinders the transportation from the manure production site to where it is needed (Rosemarin et al., 2020). Fortunately, since 1999, Taiwan has started a series work related to reusing husbandry resources, including setting up soil treatment standards, evaluating the potential pollutions in soil and water bodies, and investigating different manure management techniques (Fig. 1).

The estimation of replaced quantity of artificial fertilizers by livestock manures is currently lacking. The available statistical data from the Ministry of Agriculture in Taiwan (Table 2) provided information of the quantities (by weight) of the imported and exported fertilizers and the amount of production and use. Within the commonly-used artificial fertilizers, only potassium sulfate and calcium superphosphate are produced locally, and the production of calcium superphosphate requires phosphate rock powder which is imported. Other artificial fertilizers, including calcium ammonium nitrate, calcium cyanamide, phosphate rock powder, urea and potassium chloride are dominantly imported, meaning that the agricultural land is still highly dependent on imported fertilizers. Furthermore, Fig. 2 shows that the use of chemical fertilizers (or artificial fertilizers), although is decreasing, is still outweighing the use of organic fertilizers. It should be noted that the data of organic fertilizers shown in Table 2 and Fig. 2 only include oil meals with the data of animal manures unavailable. Therefore, without the statistical data of the use of organic fertilizers derived from animal manures and composts, the results of Fig. 2 might be misleading. Further investigation and calculation of the replacement of inorganic fertilizers (quantified by total N, P and K) replaced by organic fertilizers from difference sources are needed for the evaluation of the improvement of agriculture circularity.

Finally, a national evaluation of the effect of the different CA strategies, such as implementing cover crops and crop rotation to improve soil health, using meta-analysis technique is important and required. Such meta-analysis, as mentioned previously, can help estimate the geological, climatical, agronomical and other environmental variances, with which the circularity of agriculture can be hopefully improved more precisely. Currently, the government has built a data platform (https://agriinfo.tari.gov.tw/), from which some shared data can be retrieved. However, it is still lacking relevant data extracted from individual field experiments of CA practices in the past. The lack of adequate amount of local data and the relevant meta-analysis will be another challenge for improving the sustainability and circularity of agriculture.

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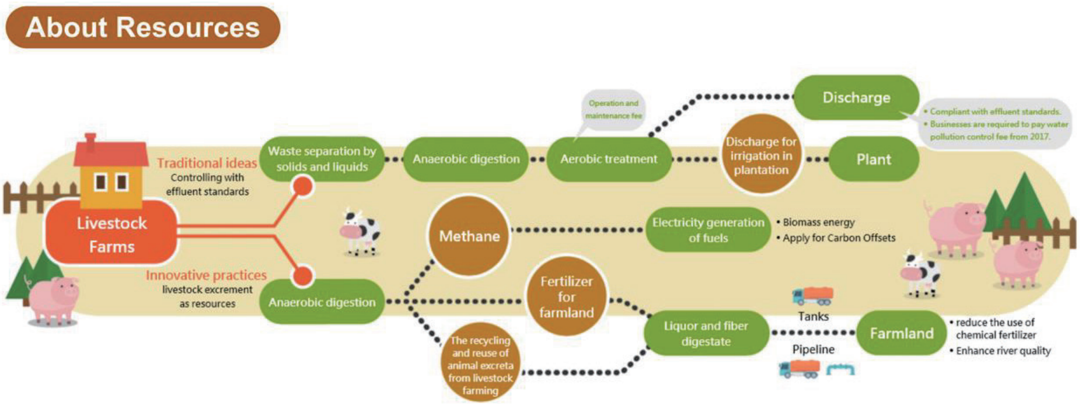
Table 1 The strategies, practices and indicators of CA systems

	Strategies (adapted from CE, (Velasco-Muñoz et al., 2021))		
	Narrowing (限縮)	Closing (封閉)	Regenerating (再生)
Strategy aims	Aimed at optimizing the use of resources	Aimed at reusing agricultural materials, but for different applications than the original, following the resource cascading approach	Aimed at preserving and enhancing natural capital
Practices	‧ [1,3]Reducing meat consumption ‧ [1]Smart land-use - Agroforestry - Urban agriculture - Vertical farming - Drip irrigation - Adopting drones for planting and monitoring - Applying N-fixing bacteria - Floating vegetable gardens	‧ [1,10]Reducing food loss and waste ‧ [1,3,11]Using residual biomass as animal feed or bio-fertilizers ‧ [4,10,12] Using urban wastes in agriculture (opposed to the principle of 1) ‧ [3,12]Manure management techniques: - Anaerobic digesters - Biogas production - Membrane filtration systems - Worm composting - Solid-liquid manure separation - Manure drying and pyrolysis (biochar) - Algal cultivation - Fungal digestion	‧ [1]No-till farming ‧ [1,11] Using leguminous plants, animal manure and other bio-wastes to replace synthetic fertilizers ‧ [1]Organic farming ‧ [1,2]Crop rotation ‧ [12]Planting of buffer zones that can help trap runoff water containing N and P ‧ [12]Planting cover crops that can trap and fix N
4Indicators	‧ [5]The allocation and tenure of land for new bioenergy production ‧ [6]Food and feed autonomy ‧ [7]N use efficiency and recycling index ‧ [8]Overall greenhouse gas balance	‧ [9]Circularity indicator of components ‧ [10]Self-sufficiency index ‧ [10]Waste output index ‧ [7]N use efficiency and recycling index	‧ [5]Soil quality ‧ [5]Biological diversity in the landscape ‧ [11]Botanical species richness ‧ [5]Consumption of fossil-P fertilizers

[1](Marinova & Bogueva, 2022); [2](Zhao et al., 2020); [3](Grumbine et al., 2021); [4](Velasco-Muñoz et al., 2021); [5](Zabaniotou, 2018); [6](Fernandez-Mena et al., 2020); [7](Tadesse et al., 2019); [8](Casson Moreno et al., 2020); [9](Cobo et al., 2019); [10](De Kraker et al., 2019); [11](Mosquera-Losada et al., 2019); [12](Rosemarin et al., 2020)

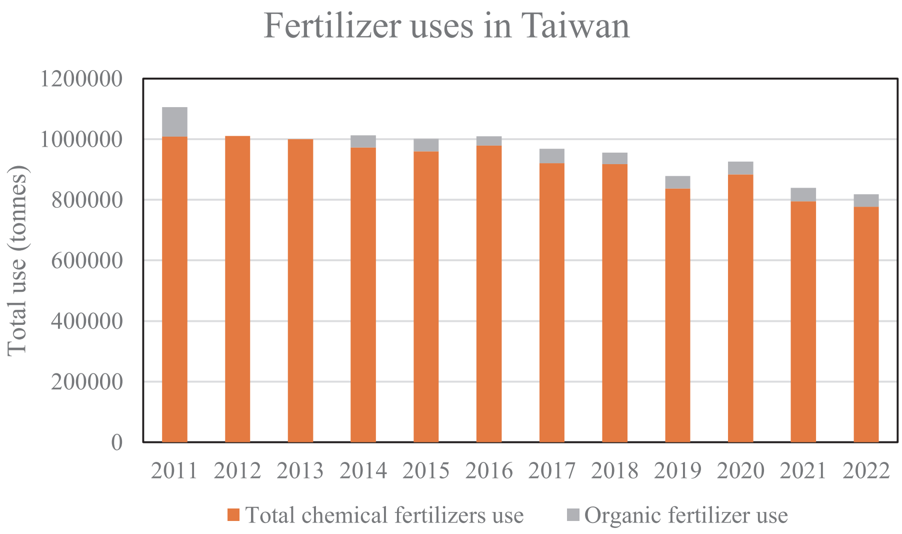


▲ Fig. 1 The concept of treating and reusing livestock excreta in farmland (retrieved from the website of Husbandry Excrement Resources Web of Taiwan https://epafarm.epa.gov.tw/EN/Default.aspx)

Table 2 Fertilizers production, export, import and use in Taiwan (year 2022)*

Fertilizers (Unit: tonnes)	Production in Taiwan	Export	Import	Usage
Total chemical fertilizers	1274084	375546	424569	777380
Calcium ammonium nitrate (硝酸銨鈣)	1,151	N.D.	N.D.	750
Ammonium sulfate (硫酸銨)	317,852	174,450	5,385	84,235
Potassium sulfate (硫酸鉀)	206,185	188,267	228	5,281
Calcium Cyanamide (氰氮化鈣)	N.D.	N.D.	1,171	N.D.
Phosphate rock powder (磷礦粉)	N.D.	N.D.	89,627	1,151
Urea (尿素)	N.D.	304	48,937	30,513
Potassium chloride (氯化鉀)	N.D.	N.D.	180,078	11,112
Calcium Superphosphate (過磷酸鈣)	68,270	N.D.	N.D.	20,588
Compound fertilizers (複合肥料)	681,640	12,044	53,296	616,190
Other artificial fertilizers(其他化學肥料)	137	481	44,696	8,711
Organic fertilizers (有機質肥料)	40,900	4,944	65,900	41,356

*Data is retrieved from the statistics of the Ministry of Agriculture of Taiwan (https://agrstat.moa.gov.tw/sdweb/public/official/OfficialInformation.aspx). N.D.: No available data.



▲ Fig. 2 The uses of chemical (orange bar) and organic (gray bars) fertilizers in Taiwan. The organic fertilizers only include oil meals from animals and plants (fertilizer number: 5-01). The organic fertilizers produced from the animal manures are not included.