



Review

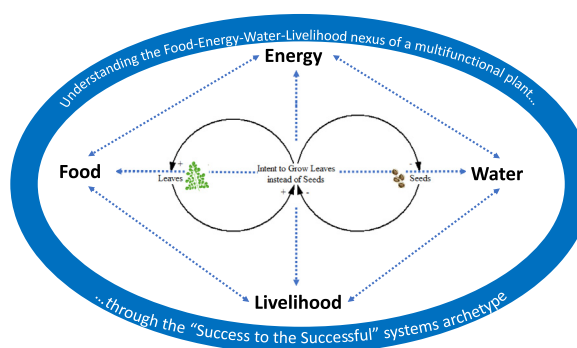
A systems approach to analyzing food, energy, and water uses of a multifunctional crop: A review

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HIGHLIGHTS

- *Moringa oleifera* selected to show a multifunctional crop's Food-Energy-Water nexus.
- "Success to the Successful" archetype characterized competing leaf and seed yields.
- Causal loop diagrams provide a useful tool for mapping multifunctionality.
- Management of multifunctional crops can benefit from a systems approach.
- Similar approaches can be adopted to maximize benefits to livelihoods.

GRAPHICAL ABSTRACT



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ABSTRACT

Multifunctional crops can simultaneously contribute to multiple societal objectives. As a result, they represent an attractive means for improving rural livelihoods. *Moringa oleifera* is an example of a multifunctional crop that produces nutritious leaves with uses as food, fodder, and a biostimulant to enhance crop growth. It yields seeds containing a water purifying coagulant and oil with cosmetic uses and possible biofuel feedstock. Despite *Moringa oleifera*'s (and other multifunctional crops') various Food-Energy-Water uses, optimizing the benefits of its multiple uses and livelihood improvements remains challenging. There is a need for holistic approaches capable of assessing the multifunctionality of agriculture and livelihood impacts. Therefore, this paper critically evaluates *Moringa oleifera*'s Food-Energy-Water-Livelihood nexus applications to gain insight into the tradeoffs and synergies among its various applications using a systems thinking approach. A systems approach is proposed as a holistic thinking framework that can help navigate the complexity of a crop's multifunctionality. The "Success to the Successful" systems archetype was adopted to capture the competition between the need for leaf yields and seed yields. In areas where there is energy and water insecurity, *Moringa oleifera* seed production is recommended for its potential to coproduce oil, the water purifying coagulant, and a residue that can be applied as a fertilizer. In areas where food insecurity is an issue, focusing on leaf production would be beneficial due to its significance in augmenting food for human consumption, animal feed, and its use as a biostimulant to increase crop yields. A causal loop diagram was found to effectively map the interconnections among the various uses of *Moringa oleifera* and associated livelihood improvements. This framework provides stakeholders with a conceptual decision-making tool that can help maximize positive livelihood outcomes. This approach can also be applied for improved management of other multifunctional crops.

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1. Introduction

Agriculture is one of the most significant sectors influencing the United Nations Sustainable Development Goals (SDGs) (Food and Agriculture Organization (FAO), 2019). Owing to the SDGs' interconnected nature, it has the potential to affect all 17 SDGs (Crumpler et al., 2019). Agriculture also operates in a complex system and has a multifunctional nature (Mcintyre et al., 2009). This multifunctionality creates connections between society, the economy, and the environment (Baulcombe et al., 2009; Bretagnolle et al., 2018; Peng et al., 2015; Yu et al., 2019). Therefore, capitalizing on crops' multifunctional characteristics presents an attractive means for achieving the SDGs and a more sustainable society.

There are many calls for adopting a systems approach to assess the multifunctional nature of agricultural systems (Hammond and Dubé, 2012; Snapp et al., 2018; van Ginkel et al., 2013; Zhang et al., 2018). A system can be defined as a set of parts or elements that are interconnected and function to achieve a purpose (Meadows, 2009). Using a systems approach calls for adopting a perspective that considers analyzing an entire system instead of focusing on its components. Systems thinking has been used to study various societal problems. Adopting such an approach is also helpful for managing nexus problems (Alcamo, 2015).

Due to the increasing complexity and nonlinear behavior of food and nutritional security (Hammond and Dubé, 2012) and the continued rise in demand for edible and nonedible agricultural goods, biomass-based value webs (as opposed to value chains) have been proposed to account for linkages among many overlapping biomass value chains (Virchow et al., 2014). Biomass-based value webs capture relationships among multiple value chains and products sourced from a single biomass feedstock. They provide a more holistic framework for capitalizing on synergistic interlinkages and reducing conflicting ones among multiple value chains while also providing insight into their governance (Virchow et al., 2016, 2014). As a result, biomass-based value webs can identify opportunities to sustainably increase production on the local, national, or international scale.

Valuable insights were obtained using biomass-based value webs for sugarcane production in Brazil (Scheiterle et al., 2018). In this particular application, physical feedstock flows and associated bioeconomy products were mapped, creating a sugarcane value web. Scheiterle et al. (2018) then used their sugarcane value web to identify the stakeholders that constitute the network of innovators in Brazil's sugarcane industry. Poku et al. (2018) also used a biomass value web approach to analyze

Ghana's biomass production of the multipurpose cassava plant to identify deficiencies in institutional linkages between value web actors and policy. These studies, and others (e.g., Loos et al., 2018), focus on using biomass-based value webs as the basis to identify linkages among various byproducts of a biomass source to realize strengths and shortcomings in biomass production and governance.

In contrast, a linear value chain approach does not capture interconnections between multiple products or stakeholders like the value web approach. For example, a value chain on *Moringa oleifera* (*M. oleifera*) and *Moringa stenopetala* (*M. stenopetala*) leaves in Ethiopia highlighted the need for commercialization and how that could be achieved (Kelemu and Alemu, 2013). However, this value chain does not consider an alternative seed value chain and the pathways' interactions. Thus, biomass-based value webs demonstrate an improved representation of the complex interactions among traditionally siloed agricultural byproducts with a more holistic approach.

The biomass-based value web described by Virchow et al. (2014) presents a valuable tool for exploring tradeoffs and synergies among various products and provides insight into the power and societal relations influencing them. However, it is focused on economic output and efficiency and limited to the food-energy nexus. Biomass-based value webs do not consider impacts on water quality and quantity, a necessity for sustainable production of biofuels (Berndes, 2002; Gopalakrishnan et al., 2009; National Research Council (NRC), 2008) and water security. Impacts on livelihoods are also difficult to assess from biomass-based value webs. Therefore, as emphasized by Tapia et al. (2019), biomass value chains need to integrate systems thinking into biomass-based value web design by accounting for feedback mechanisms to fully understand and exploit the interactions between biomass value chains and the Food-Energy-Water (FEW) nexus.

The FEW nexus provides context that extends traditional sectoral approaches by considering the interrelation between these three tightly interconnected resources to improve their management (Boas et al., 2016). The FEW nexus is also flexible and can be extended to include livelihood, forming FEWL (Biggs et al., 2015). Although the approach of linking biomass-based value webs and the FEW nexus adopts a systems approach, providing an explicit measure of resources, and exploring tradeoffs and their integration increases complexity (Tapia et al., 2019). A method that could facilitate the characterization of this complexity is the adoption of a systems archetype to describe the behavior of a system and the interaction of its elements.

System archetypes are recurring themes in complex systems with known intervention strategies to mitigate unwanted system behavior. Establishing a sound conceptual model is essential for improving understanding of the FEW nexus (Bazilian et al., 2011). Systems thinking tools can be utilized to fulfill this need. However, few studies have applied system archetypes to nexus problems. For example, Sohofi et al. (2016) found system archetypes to be useful tools in condensing fragmented knowledge on FEW nexus interrelationships scattered in literature as well as conceptual precursors to quantitative system dynamics modeling. System archetypes were also used to conceptualize the complexity of the water, energy, food, and land nexus for the Jatiluhur reservoir in Indonesia (Bahri, 2020). It demonstrated the utility of system archetypes in serving as precursors to quantitative system dynamics modeling and as a tool to inform decision-makers on nexus resource management (Bahri, 2020). In addition to the lack of studies that apply system archetypes to a FEW nexus, no studies were identified that apply a systems archetype to a multifunctional crop's products and byproducts. Therefore, this study seeks to address that research gap.

Accordingly, our objective is to use a systems approach to explore the tradeoffs and synergies in the context of FEWL linkages between potential applications of the multifunctional plant *M. oleifera*. This paper provides a critical literature review that assesses the many uses of *M. oleifera* while exploring a systems approach to characterize and analyze their interactions with an appropriate systems archetype.

M. oleifera is selected as the multifunctional crop of focus in this study due to its variety of uses (Dhakad et al., 2019; Saini et al., 2016), large global reach that includes tropical and subtropical countries (Saini et al., 2016), and *M. oleifera*'s potential to address multiple SDGs (Adeyemo, 2017; Keatinge et al., 2017). *M. oleifera* is being explored for many functions that include the purification of waters (Jahn, 1988; Ndabigengesere and Subba Narasiah, 1998), food production (Gopalakrishnan et al., 2016; Sahay et al., 2017), and biodiesel generation (Azad et al., 2015; Rashid et al., 2008). Seeds of *M. oleifera* also contain an oil that can be used for cooking, cosmetics, or industrial uses. *M. oleifera* is an example of a fast-growing, drought-tolerant multifunctional tree in the Moringaceae family. Examples of *M. oleifera*'s FEWL linkages are summarized in Fig. 1.

M. oleifera cultivators tend to maximize the production of either leaves for food or seeds for oil. Both the leaves and seeds have various

other uses that are explained to a great extent in literature but underutilised in practice. While there are existing review papers that focus on single uses of *M. oleifera* as animal fodder (Su and Chen, 2020), a biofuel feedstock (Azad et al., 2015), source of nutrition (Gopalakrishnan et al., 2016), and water purifier (Dorea, 2006), some have also discussed the multiple applications of *M. oleifera* (Dhakad et al., 2019; Saini et al., 2016). Existing literature reviews on *M. oleifera* fall short of identifying and addressing the tradeoffs and synergies among its multiple uses. Furthermore, cross-disciplinary research gaps are often not identified in such reviews since interactions among uses are typically not considered.

Notably, a systems approach similar to what is presented here can be readily applied to other multifunctional crops. As illustrated in this study, qualitative approaches are not only precursors to quantitative analyses but also offer advantages in terms of gaining insight into difficult to quantify attributes such as livelihoods and multifunctionality. Widely cultivated multifunctional crops such as soy, sugarcane, and oil palm are expected to gain importance as society transitions to a bioeconomy (Bastos Lima, 2018). During this transition, holistic approaches such as what is used in this study could be useful for responsible management of biomass production (Martinez-Hernandez and Samsatli, 2017) and livelihood improvements by leveraging multifunctionality.

This paper begins by discussing the multifunctionality of agricultural products, providing some examples of multifunctional crops, and discussing how the multifunctionality of *M. oleifera* is typically managed. Literature on *M. oleifera* is then reviewed, and an appropriate systems archetype is selected to inform the creation of a causal loop diagram structure. The causal loop diagram (CLD) is used to map the positive and negative interrelations among the various uses of *M. oleifera*. Finally, the CLD is discussed, the findings are summarized, and areas that could benefit from future research are identified. This study focuses more on the analysis of *M. oleifera* leaf and seed-derived products due to their prevalence. *M. oleifera* root and wood products were not considered to limit the system boundary to the most important products and develop a CLD that can convey the key messages. The challenge of securing markets for products and training of communities on the variety of *M. oleifera* uses are outside of the scope of this analysis.

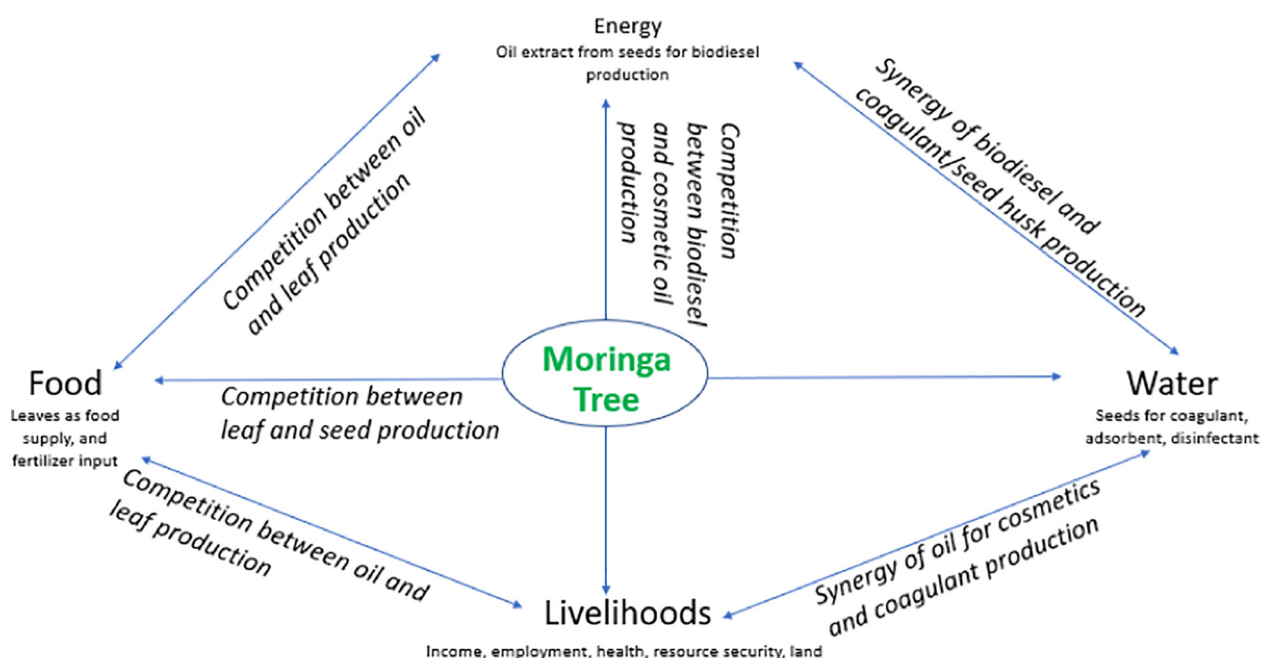


Fig. 1. Examples of different *M. oleifera* Food-Energy-Water-Livelihood nexus uses and the competitions or synergies that arise among the different nexus components.

2. Multifunctionality in agriculture

The Organization for Economic Cooperation and Development (OECD) defines multifunctionality as an economic activity that produces multiple outputs and contributes towards multiple societal objectives at once (OECD, 2001). Although the concept of multifunctionality is relatively new in academic circles, it has always been displayed in agriculture (Mcintyre et al., 2009; Wilson, 2007). For example, it is established that agriculture serves as a provider and receiver of multiple beneficial services and harmful ecosystem impacts (Swinton et al., 2007). Examples of harmful ecosystem impacts would include biodiversity loss or groundwater contamination from nitrogen in fertilizers and pesticides. Additionally, the release of carbon dioxide from the oxidation of soil carbon (Batjes, 2014) and loss in water holding capacity of soils (Bhadha et al., 2017) are other negative impacts of agriculture. Desirable services would include the production of food, fuel, and fiber. Resource conserving multifunctional agricultural practices have the potential to improve social, economic, and environmental sustainability (Leakey and Asaah, 2013).

Some examples of widely cultivated multifunctional crops are soy, sugarcane, oil palm, and shea. Soy, a multifunctional legume, is a highly nutritious source of human food and animal feed (Stein et al., 2008) that also yields a valuable cooking oil (Liu, 1997) that can be used as a biofuel feedstock (Kinney and Clemente, 2005). Additionally, soy can fix nitrogen in soils (Muñoz et al., 2016), reducing the need for fertilizers and the risk of groundwater contamination. Sugarcane is another example of a multifunctional crop widely grown in the tropics and subtropics. The primary sugarcane products are ethanol and sugar, while many byproducts such as bagasse and molasses are also produced (Paturau, 1988). Efforts have been directed towards maximizing profits while reducing biomass waste from sugarcane byproducts (Almazán et al., 1998; Guerra et al., 2020). Bagasse fibers, for example, can be used as an energy source in the processing plant, in the paper and pulp industry, and animal feeds (Almazán et al., 1998). Oil palm is another example of a widely cultivated multifunctional plant with two primary products, oil from its fruit and oil from its kernel. Palm oil produced from the fruit is typically used in cooking, while the oil produced from the kernel has industrial uses such as soap or detergent production. Byproducts such as empty fruit bunches, palm fiber, and shells, and palm oil mill effluent can be utilized in a way that reduces the environmental footprint of palm oil production (Hansen et al., 2015; Yusoff, 2006). Products derived from the shea tree also exhibit multifunctionality and can be used as edible oil, soap, cosmetics, and medicine (Naughton et al., 2015). Shea is unique because women primarily control it, from extraction to commercialization (Naughton et al., 2017). This is an example of an interaction between multifunctionality and livelihoods where the outcome is the economic empowerment of women (Chen, 2017).

Multifunctional trees, such as *M. oleifera*, provide many of the same benefits as other multifunctional crops, as a source of food, fuel, pharmaceuticals, industrial products, and fodder. Additionally, they may help offset biodiversity loss (Acharya, 2006), contribute to afforestation efforts (Noulèkoun et al., 2017), and reclaim nonarable lands (Chaer et al., 2011). *M. oleifera* is promoted in many rural communities for its potential to address malnutrition and improve rural livelihoods (Shonde, 2017). Kumssa et al. (2017) performed a survey of *M. oleifera* and *M. stenopetala* growing households in Kenya and Ethiopia, with 32% of households growing these trees for food, medicine, and feed. An additional 20% of households used the trees for shade as well. Despite the awareness of *M. oleifera*'s multifunctionality to some degree, some of its other uses, such as water purification and oil extraction, are not commonly exploited (Kola-Oladiji et al., 2014). This shortcoming prevents its multifunctionality from impacting rural livelihoods beyond food security and hence limits its socioeconomic impact. Therefore, there is a need to explore the different ways *M. oleifera* can improve the rural livelihoods of growers and the structural complexity of allocating its various uses optimally.

3. Methodology

The studies referenced in the following sections were retrieved from Google Scholar, Web of Science, and ScienceDirect. Keywords searched include "*Moringa oleifera*," "Multipurpose moringa," "Multi-purpose moringa," and "Multifunctional moringa." Additional search terms such as "nutrition," "phytochemicals," "antibacterial," and other terms were used with "*Moringa oleifera*" to find studies that provide insight into the nutritional and medicinal benefits of *M. oleifera*. Terms such as "animal feed" and "fodder" were added to "*Moringa oleifera*" in the search to find papers that report the effect of *M. oleifera* use as animal feed. The terms "biostimulant" and "fertilizer" were included to find studies that discuss how the application of *M. oleifera* leaf and seed products affect crop growth. To find studies on *M. oleifera*'s use in water purification, additional search terms such as "water" and "coagulant" were added to refine the search results. Studies that examined the potential of *M. oleifera* oil use as a biofuel were found by including the terms "biofuel" or "biodiesel" in the search. In some cases, the studies cited in review papers were located and examined. No results were found when the term "systems thinking" was added to "*Moringa oleifera*."

Since *M. oleifera* is typically grown for its leaves and seeds, the papers reviewed focused on the use of its leaf and seed-derived products. Therefore, studies that focused on the roots, bark, or cuttings were excluded. Limits for the publication year or document type were not set. Articles were grouped according to the function of *M. oleifera* relevant to the study. Categories include nutrition, animal feed, biostimulant/biofertilizer, water purification, biodiesel, and planting density were used to group the selected articles. Studies were initially screened by reading their titles and abstracts to determine if the full text should be analyzed. Articles that demonstrated potential FEWL applications were selected so that these applications were depicted. A total of 80 articles on *M. oleifera*'s various uses are cited in this review. Twenty-two studies included in this review were associated with nutrition. Eleven articles on *M. oleifera*'s use in animal feeds were selected. Seven articles on the use of *M. oleifera* as a biostimulant or biofertilizer were included. Twenty-two studies related to the use of *M. oleifera* as a water purifier were included in this review. Ten articles that focus on the use of *M. oleifera* as a biodiesel feedstock were included. Finally, eight articles on planting density are analyzed and included in this review as well.

This literature review is not meant to be exhaustive. Rather, it aims to provide the foundation for a systems analysis of *M. oleifera*'s uses. The different uses of *M. oleifera* are highlighted in this literature review are presented as a precursor to analyze interactions and interrelations among these uses. After selecting the literature included in this study, a CLD was constructed to map FEWL relationships. The construction of the CLD is discussed in greater detail in Section 6.1 Systems Thinking Tools and Archetypes.

4. Multifunctionality of *M. oleifera*

4.1. *M. oleifera* for nutrition

The global fight against hunger and malnutrition calls for measures that can be taken and sustained by smallholder farmers in rural communities. As a widely adopted plant that can be grown and used with local resources (Thurber and Fahey, 2009), *M. oleifera* can play a key part in combatting malnutrition (Zongo et al., 2013). Of the 13 species in the moringa genus native to Africa and Asia, *M. oleifera* is the most consumed, widely cultivated, and studied species (National Research Council (NRC), 2006).

Olson et al. (2016) performed a nutritional survey of protein, macronutrients, and micronutrients in the leaves of 11 of the 13 species of the moringa genus. Some of the macronutrients surveyed in the study included calcium, potassium, magnesium, phosphorous, and sulfur, while the micronutrients included copper, iron, manganese,

molybdenum, sodium, nickel, and zinc. Noteworthy variability of macronutrients and micronutrients between the species was recorded. *M. oleifera* and *M. stenopetala* had the two highest total protein levels. *M. oleifera* also contained relatively high values for most of the nutrients, justifying the attention it has received over the years. Besides being a great source of nutrients such as calcium, phosphorous, magnesium, and iron, *M. oleifera* leaves offer a high-quality protein with nearly all essential amino acids (Freiberger et al., 1998; Moyo et al., 2011).

Many biologically active phytochemicals such as tannins, steroids, triterpenoids, flavonoids, saponins, anthraquinones, alkaloids, and reducing sugars have been detected in *M. oleifera* leaves (Kasolo et al., 2010). *M. oleifera* leaves are also reported to have significant levels of glucosinolates and cinnamate esters (Bennett et al., 2003). The bioactivity of the phytochemicals in *M. oleifera* leaf extracts has resulted in studies that display *M. oleifera*'s antimicrobial (Dzotam et al., 2016; Fouad et al., 2019; Zaffer et al., 2014), antiviral (Biswas et al., 2020), anticancer (Al-Asmari et al., 2015; Berkovich et al., 2013), antifungal (Chuang et al., 2007; Patel et al., 2014), and antiprotzoal (Bernal et al., 2020) properties. Studies have also shown *M. oleifera* leaf extracts to have an antihypertensive effect (Acuram and Hernandez, 2019; Okorie et al., 2019). Additionally, Owens et al. (2020) conducted a literature review on the effect of *M. oleifera* on blood glucose levels. They found strong evidence that *M. oleifera* extracts and powdered leaves reduced blood glucose levels.

The culmination of *M. oleifera*'s abundant supply of nutrients and various medicinal uses gives legitimacy to its description as a "nutraceutical" (Kou et al., 2018) and "miracle tree" (Daba, 2016). The synergy between *M. oleifera*'s use as a food source and its medicinal properties can be further exploited by properly educating communities on these two tightly interconnected uses (Thurber and Fahey, 2009; Zongo et al., 2013).

4.2. *M. oleifera* as animal feed

Over the years, livestock production has grown and is anticipated to grow (Alexadratos and Bruinsma, 2012). Similarly, growth in feed production, which accounts for 31% of global calories, is anticipated to increase (OECD-FAO, 2020). Increases in livestock production will also be accompanied by increases in greenhouse gas (GHG) emissions. The livestock supply chain is estimated as contributing 7.1 gigatons of CO₂ equivalent per year or 14.5% of all anthropogenic emissions (Gerber et al., 2013). The largest contributor of GHG from the livestock supply chain is enteric fermentation, a process by which microbes decompose and ferment plant material into soluble products in the digestive tract (Gerber et al., 2013). Methane is a byproduct of enteric fermentation, and one way to mitigate methane emissions from enteric fermentation is by altering the diet of livestock (Haque, 2018; Wanapat et al., 2015). Efforts to reduce GHG emissions from enteric fermentation must also preserve the nutritional quality of animal feeds (McCartney et al., 2006).

Many parts of the *M. oleifera* tree have been studied as animal feed supplements. *M. oleifera* supplemented animal feeds' nutritional quality and methane emissions have been extensively analyzed. Methane emissions from ethanol/acetone *M. oleifera* leaf extracts were 17% lower than methane emissions from soybean and rapeseed meals, while methane emissions from oven-dried *M. oleifera* leaves were 10% lower (Soliva et al., 2005). Soliva et al. (2005) attributed this reduction to the presence of either saponins, tannins, or the high fatty acid content in *M. oleifera* leaves. Additionally, the fiber and nitrogen degradability of *M. oleifera* leaves was comparable to soybean and rapeseed treatments.

M. oleifera's fatty acid content and the presence of phytochemicals such as tannins and saponins have drawn attention to its prospect as a natural alternative to synthetic feed additives (Hoffmann et al., 2003). The potentially digestible protein content is also higher than various protein supplements commonly used in livestock feeds (Makkar and Becker, 1996). Sarwatt et al. (2002) found that *M. oleifera* leaves were sufficient substitutes for sunflower seed cake. A difference in growth rates was not observed between the goats fed the different treatments.

Dry matter intake and digestibility were both highest for the animal feeds supplemented with *M. oleifera*.

Similarly, in a study that considered the supplementation of *M. oleifera* leaf extract and live yeast culture (*Saccharomyces cerevisiae*), reductions of 11.7% of methane and 50.3% of CO₂ equivalent were reported compared to the control diet without these supplements (Pedraza-Hernández et al., 2019). Many other studies found that *M. oleifera* leaves as animal feed can reduce methane emissions without adverse nutritional effects at appropriate dosages (Dey et al., 2014; Elghandour et al., 2018, 2017; Parra-Garcia et al., 2019).

Additionally, *M. oleifera* oil press cake (i.e., seed cake) has been studied for its use as fodder. Olivares-Palma et al. (2013) performed an in vitro study that compared the ruminal fermentation, digestion kinetics, and methane production of seven different seed cakes, byproducts of biodiesel production. Their study found that *M. oleifera* seed cake was the only one to exhibit a reduction in methane production without compromising nutrient degradability, making it the least environmentally harmful oil press cake and the most nutritious (Olivares-Palma et al., 2013).

The use of *M. oleifera* leaves as an animal feed supplement is promising. However, it presents a tradeoff with the consumption of leaves to combat malnutrition. From an environmental sustainability perspective, direct human consumption may be considered more sustainable and efficient. However, in a smallholder farming community, livestock may display multifunctionality as a sign of wealth, dowry, finance, insurance, and manure for fertilizer in addition to being a source of milk and meat (Weiler et al., 2014). A case could be made that seed cake use as animal feed is the more efficient and sustainable use of resources in this context.

The use of *M. oleifera* seed cake is particularly attractive from a systems perspective, as it would capitalize on the synergy from *M. oleifera* oil production. Reducing GHG emissions through altering livestock diets is an important climate-smart agriculture strategy. *M. oleifera* can contribute to this effort through its leaf and seed products without adverse nutritional effects.

4.3. *M. oleifera* as a biostimulant/biofertilizer

The productivity of smallholder farms needs to improve in order to combat global food security (Tscharnkte et al., 2012) while reducing the usage of land, water, nutrients, and energy (Keating et al., 2010). Although synthetic fertilizers can help increase land productivity, their production and application have negative environmental consequences (Hasler et al., 2015). Additionally, high costs and lack of availability in parts of the world are deterrents to their widespread adoption (Morris et al., 2007). These factors have led to an increase in calls for plant-based alternatives to synthetic fertilizers. As a result, biostimulants have been gaining more attention as a means of improving crop yields while reducing the environmental impacts of traditional agricultural practices.

M. oleifera, as a plant with many phytochemicals, phytohormones, and a variety of nutrients, is seen as a possible low-cost, effective, and sustainable biostimulant. Foidl et al. (2001) reported increases in stem diameter, number of nodules, number of axels, number of flower buds, and number of fruits per flower bud in several crops treated with *M. oleifera* leaf extract foliar spray. Increases in crop yields that ranged from 20 to 35% for peanut, soya bean, maize, bell peppers, and other crops were observed as well when *M. oleifera* leaf extract foliar spray was applied. Growth traits such as yield and chemical composition of snap beans were found to increase with increases in *M. oleifera* leaf extract concentration resulting in a 26.5% and 22.5% increase in yield in the first and second growing seasons of the experiment, respectively (Elzaawely et al., 2017). Similar results have been obtained for other crops (Zulficar et al., 2019). The application of *M. oleifera* foliar spray can generate a net profit for farmers if the increase in yields offsets the cost of the spray.

The use of *M. oleifera* extracts as a foliar spray can also improve crop yields in stressed environments. El-Mageed et al. (2017) found that applying *M. oleifera* leaf extracts as foliar sprays under deficit irrigation and salt stress improved plant water use efficiency, growth and yield characteristics, and leaf anatomy of squash. Squash yields under these conditions increased by 15% compared to the tap water sprayed control scenario.

In addition to being used as a biostimulant, *M. oleifera* leaves can be used as an organic fertilizer supplement to synthetic fertilizer. For example, Moji et al. (2018) compared the growth and yield of maize with different combinations of organic and inorganic fertilizers. The subplot of maize where 50/50 *M. oleifera* leaves and NPK fertilizer was applied produced a maize yield 18% higher than the plot treated with NPK fertilizer alone. As a result, the combination of *M. oleifera* leaves + NPK was also the most economical application. The combination of inorganic and organic fertilizers in their study is believed to have resulted from improved sustenance of nutrients released compared to the other scenarios.

M. oleifera seed cake has also shown some promise as an organic fertilizer. For example, the macro and micronutrients in *M. oleifera* seed cake, when applied to soil, increased maize yield by a factor of 3.5–4.3 (Emmanuel et al., 2011). The equivalent of 5555 kg of seed cake per hectare was applied in the study. *M. oleifera* seed cake can also reduce the stress of plants growing in soils with high heavy metal contents. Hassanein et al. (2017) experimented with the effect of *M. oleifera* and *Moringa peregrina* (*M. peregrina*) defatted seed cake on cadmium accumulation in wheat plants. The results show that when the soil is treated with *M. oleifera* seed cake and *M. peregrina* seed cake, less cadmium accumulates in the roots and shoots of the wheat. Additionally, the weights of both the roots and the shoots increased in the soils treated with seed cakes.

Although the use of *M. oleifera*'s leaves and leaf extracts as biostimulants and biofertilizers seem to present a direct tradeoff with human consumption of *M. oleifera* leaves, both applications contribute to food security. This synergy of indirect and direct contributions to food security from *M. oleifera* leaves works to increase the resilience of farming communities growing *M. oleifera* and other crops. Similarly, the *M. oleifera* seed cake presents an opportunity to contribute to food security through its application as a fertilizer. Since it is a byproduct of the *M. oleifera* oil extraction process, it forms a promising synergistic linkage between energy production from *M. oleifera* oil use as a biofuel feedstock and enhanced food production by using the seed cake as a fertilizer.

4.4. *M. oleifera* for water purification

An estimated 29% of the global population are without access to a safely managed drinking water source (WHO-UNICEF, 2018). The agricultural sector consumes the largest amount of freshwater at over 70% (FAO, 2019), straining freshwater supplies globally. The use of treated wastewater for irrigation may help offset its freshwater footprint. Thus, revisiting the use of natural, locally available materials that can be used to treat water on multiple scales could result in improved water quality with an affordable, maintainable, and environmentally responsible approach. *M. oleifera* seeds have been used for water purification for centuries (Foidl et al., 2001). The water purification properties have been widely studied since the 1970s (Jahn and Dirar, 1979), and the detailed steps for use are described (Jahn, 1988).

The *M. oleifera* coagulant is highly effective for high turbid waters but less effective for low turbidity waters (Ghebremichael et al., 2005; Sengupta et al., 2012). For waters spiked with clay that had initial turbidities of 50–150 NTU and 250–500 NTU, reductions in turbidity of 92–99% were observed when *M. oleifera* seed extract was applied (Muyibi and Evison, 1995).

Similar reductions in turbidity by 80–95% were obtained by Madsen et al. (1987) in addition to a bacterial reduction of 1–4 log₁₀ units. The *M. oleifera* seed extract has also been shown to be effective in treating waters infected with parasites. Studies have shown reductions of cercariae in surface water by up to 90% (Olsen, 1987) and helminth eggs

in recycled irrigation water when used in combination with sedimentation by 94% (Sengupta et al., 2012).

M. oleifera seed extract's coagulant activity and its effectiveness in reducing water turbidity have led to comparisons with the commercial coagulant alum. A case study in Colombia found that *M. oleifera* seed extract reduced turbidity in natural waters by 90% while alum resulted in a decrease of 96% (Salazar Gámez et al., 2015). A comparison of *M. oleifera* seed extract and alum-treated waters by Ndabigengesere and Subba Narasiah (1998) found that unlike alum, the *M. oleifera* seed extract did not significantly increase pH, conductivity, alkalinity, or cation and anion concentrations. In the same study, water treated with *M. oleifera* seed extract was also determined to produce four to five times less sludge volume than alum treated water while having the benefit of producing a biodegradable sludge that could potentially be used as a fertilizer.

Ndabigengesere and Subba Narasiah (1998) also reported high residual organic content in water treated with crude *M. oleifera* seed extract. This limits the time the treated water can be stored, may affect the taste or odor of the water and could lead to the creation of disinfectant by-products. This is a significant drawback that hinders its large-scale application for drinking water treatment. The high organic load that remains in *M. oleifera* treated water calls for an additional post-processing step to reduce the organic concentrations.

One way to reduce *M. oleifera* seed treatment's organic load is to isolate and extract the *M. oleifera* coagulant protein (MOCP) from the *M. oleifera* seed (Agrawal et al., 2007; Gassenschmidt et al., 1995; Ghebremichael et al., 2005). A barrier to coagulant purification methods is that they involve high-cost technologies. To address this, Dezfooli et al. (2016) developed a lower-cost and affordable extraction method that may facilitate large-scale adoption.

While the kernel of the *M. oleifera* seeds is used to purify water, the husks, which are often discarded, also have value. Warhurst et al. (1997) presented a steamed pyrolysis procedure to produce high-quality activated carbon from *M. oleifera* seed husks. Activated carbon derived from seed husks has been shown to be effective biosorbents of heavy metals (Garcia-Fayos et al., 2016; Ghebremichael et al., 2010; Tavares et al., 2017) and disinfectant by-products (Okoya et al., 2020).

Regarding its use as a biosorbent of metals, the seeds, husks, and pods were found to reduce lead concentrations by greater than 96% (Tavares et al., 2017). Another study compared *M. oleifera* pods to babassu coconut activated carbon for diclofenac removal. The *M. oleifera* pods compared favorably as a low-cost alternative with an adsorption capacity of 60.8 mg/g compared to activated carbon's adsorption capacity of 71.2 mg/g (Viotti et al., 2019).

Although *M. oleifera*'s water purification properties have been heavily studied, there is still a lack of large-scale case studies. Saleem and Bachmann (2019), in their review of plant-based coagulants, found only two semi- or full-scale plant operations in Malawi and Nigeria. Life cycle assessments may help facilitate their adoption, especially if the results suggest that a transition to plant-based coagulants is more profitable and environmentally responsible. Amante et al. (2016) performed a life cycle assessment comparing the crude *M. oleifera* seed extract and alum and found that energy consumption from the production of alum was 40% greater and GHG emissions 80% greater when compared to the crude *M. oleifera* extract usage. A multi-product lifecycle assessment that includes coagulant production and *M. oleifera* oil may help communicate the FEWL benefits of seed usage. Extraction of *M. oleifera* oil has not been shown to affect the protein content of *M. oleifera* seeds or their coagulation activity (Magalhães et al., 2021).

4.5. *M. oleifera* for biodiesel production

Biofuels have been proposed as a part of a diversified, renewable, low-carbon energy source. However, biofuel feedstock growth often comes into conflict with other types of land uses, such as food production. As a result, biofuels should be produced in a way that does not compromise food security (HLPE, 2013). This could be achieved by

growing biofuel feedstocks on marginal lands (i.e., lands with poor soil quality, degraded soil; (Garg et al., 2011; Mudywa et al., 2013)). *M. oleifera* offers a multipurpose, fast-growing, drought-resistant tree that has been gaining attention as a biofuel feedstock (Azad et al., 2015; Rashid et al., 2008). *M. oleifera* seeds have favorably high oil contents as high as 42% (Nadeem and Imran, 2016). The oleic acid content of *M. oleifera* oil is the highest compared to soybean, rapeseed, palm oil, and sunflower oil (da Silva et al., 2010; Rashid et al., 2008). A byproduct of the *M. oleifera* oil extraction process, the *M. oleifera* seed cake, contains the MOCP. This presents a unique opportunity to jointly produce natural water treatment materials and renewable energy.

The CETANE number is used to rate the quality of combustion of diesel fuels. *M. oleifera* methyl-esters (MOME) meet the criteria of biodiesel standards in both the U.S. (ASTM D6571) and Europe (EN1424) (Saini et al., 2016). MOME also has the highest biodiesel CETANE number (Rashid et al., 2008). Additionally, MOME offers a biofuel with high oxidation stability, in contrast to many other biofuels. Antioxidants added from *M. oleifera* leaf extracts can also be used to increase the oxidation stability of many biofuels and have been shown to be more effective than a synthetic alternative (Fernandes et al., 2015; Rashid et al., 2008).

MOME derived from *M. oleifera* seeds produced *M. oleifera* oils that met all the EN 1424 and ASTM 6751 biodiesel specifications (Rashid et al., 2011). Similarly, MOME from *M. oleifera* seeds in Brazil had properties within the acceptable ranges for biodiesel except for kinematic viscosity, which at 5.4 mm²/s was above the EN 1424 standard of 5.0 mm²/s (da Silva et al., 2010). While there may be an increase in nitrous oxide emissions, a reduction in overall engine emissions has been observed when using MOME (Mofijur et al., 2014; Rahman et al., 2014). Results from a “cradle to gate” life cycle analysis (partial life cycle from resource extraction to the facility gate) of 1000 L *M. oleifera* biodiesel production estimated the removal of 14,085 kg CO₂ equivalent from the atmosphere, an environmental benefit (Biswas, 2008). The net reduction in atmospheric emissions results from the inclusion of an estimated 15,000 kg/yr CO₂ equivalent sequestered by the plants.

M. oleifera provides a promising biofuel feedstock (Azad et al., 2015). However, the effects of the genetic variability of different seeds located in different geographic areas may impact the biofuel quality as seen by the different properties from the Pakistan variety (Rashid et al., 2011) and the Brazil variety (da Silva et al., 2010). Different transesterification methods may also affect the quality of the biofuel, and techniques that optimize the biofuel quality need to be considered (Rashid et al., 2011). One unique feature of *M. oleifera* biofuel production is the seed cake byproduct which contains the MOCP. This synergy between water purification and clean energy production is an area that needs to be explored further. A life cycle sustainability assessment which consists of a social life cycle assessment, life cycle cost assessment, and life cycle environmental assessment, would provide further insight into the advantages of the additional uses of *M. oleifera* coproducts produced in conjunction with biodiesel production in comparison to other biofuel feedstocks. Zortea et al. (2018) performed a life cycle sustainability analysis for soybean, and it will be insightful if something similar is done for *M. oleifera*. A comparative assessment between the use of waste cooking oil and *M. oleifera* oil would be beneficial as well, since *M. oleifera* oil has additional, competing uses in cosmetics, industrial processes, and foods.

5. Effect of tree density and tradeoff of different uses

As a multifunctional tree, the purpose of *M. oleifera* cultivation should be considered for maximal leaf or seed production, depending on the desired application (Fig. 2). Many studies have found that higher *M. oleifera* planting densities are generally associated with higher leaf production (Foidl et al., 2001; Goss, 2012; Mendieta-Araica et al., 2013; Patricio et al., 2017). However, the stem diameter, an indicator of tree growth and survival (Haase, 2008), decreases as planting density increases (Goss, 2012). Therefore, the need for farming inputs such as

water and fertilizer increases as planting density increases to produce and maintain high yields.

Optimal planting densities of approximately 1 million trees/ha are recommended for *M. oleifera* leaf production (Amaglo et al., 2006; Saini et al., 2016). In a study conducted in Ghana, Amaglo et al. (2006) found that a spacing of 5 cm × 15 cm (1.33 million trees/ha) was optimal when compared to spacings of 5 cm × 5 cm (4 million trees/ha) and 5 cm × 10 cm (2 million trees/ha) because it had the lowest loss of plants after successive cuttings. Foidl et al. (2001) tested planting densities from as low as 95,000 plants/ha to up to 16 million plants/ha in Nicaragua and found that 1 million plants/ha produced the optimal yield when considering many factors such as plant loss after the 1st cutting, cost of seeds, and cost of soil preparation. For this planting density, Foidl et al. (2001) reported harvests of 78 metric tons/ha of fresh *M. oleifera* leaves (13.26 metric tons/ha of dried *M. oleifera* leaves). At such high planting densities, fertilizer and irrigation inputs were increased to maintain high yields. This practice calls into question the sustainability of an industrial *M. oleifera* plantation over time due to the increased water demands and the need for higher amounts of synthetic fertilizer to sustain high yields at high tree densities. Profits from increased yields have the potential to offset the costs of additional inputs.

Few studies have been performed on the effect of plant density on seed production for *M. oleifera*. Ayerza (2011) found that *M. oleifera* seed production is dependent on environmental factors such as climate and soil conditions. The optimal tree density recommended for pod harvest is 1666 trees/ha, with a recommended tree to tree spacing of 1.2 m and 5 m between rows (Saini et al., 2016). In South Africa, planting densities of 1250, 1667, 2500, and 5000 trees/ha were compared over two harvesting seasons, and it was found that seed yields and oil yields increased as planting density increased (Bopape-mabapa, 2019). At 1667 trees per hectare, a total of 191 kg/ha of seed and 4843 kg/ha of oil was produced, while at 5000 trees/ha, a total of 290 kg/ha of seed and 7550 kg/ha of oil was produced after one year.

Deciding the area of land and the number of trees required is critical to meeting the *M. oleifera* leaf or seed production objectives for the desired application. This presents a fundamental tradeoff that *M. oleifera* growers encounter. A cost-benefit analysis would help inform their decision.

All parts of the *M. oleifera* plant have the potential to be consumed for food or medicinal use, as can be seen in Fig. 2. The roots can be used as a food source or for medicinal use, while the bark can be used as medicine, wood, a blue dye, or for its tannins. In addition to its consumption as food, *M. oleifera* leaves can be used as animal fodder or a biostimulant. The most versatile of the parts of the *M. oleifera* tree are the pods. Fig. 2 shows that these pods and their components can be used as a food, fuel, or water purifier. The *M. oleifera* seeds have applications that can affect all four FEWL components. Since *M. oleifera* is typically grown for its leaves and pods, they are the focus of the systems analysis in this study and are shown in bold in Fig. 2.

Although Fig. 2 shows the multiple uses of the different parts of the tree, the linear presentation does not capture tradeoffs that arise from these applications. Consequently, the interrelations among these different applications can be overlooked. For example, the tradeoff between leaf yields and seed yields is not included in this flow diagram. Hence the subsequent tradeoffs among the different uses of the leaves and seeds are not considered. The lack of inclusion of the different FEWL nexus interactions among different uses of the *M. oleifera* tree is a significant shortcoming in Fig. 2. The system thinking principles and tools presented in the following section demonstrate the utility of a systems approach that incorporates tradeoffs and synergies to address such shortcomings.

6. Systems approach to analyzing the *M. oleifera* FEWL nexus

6.1. Systems thinking tools and archetypes

Systems thinking is a holistic approach that focuses on how constituent parts interrelate (Meadows, 2009). A CLD provides a qualitative

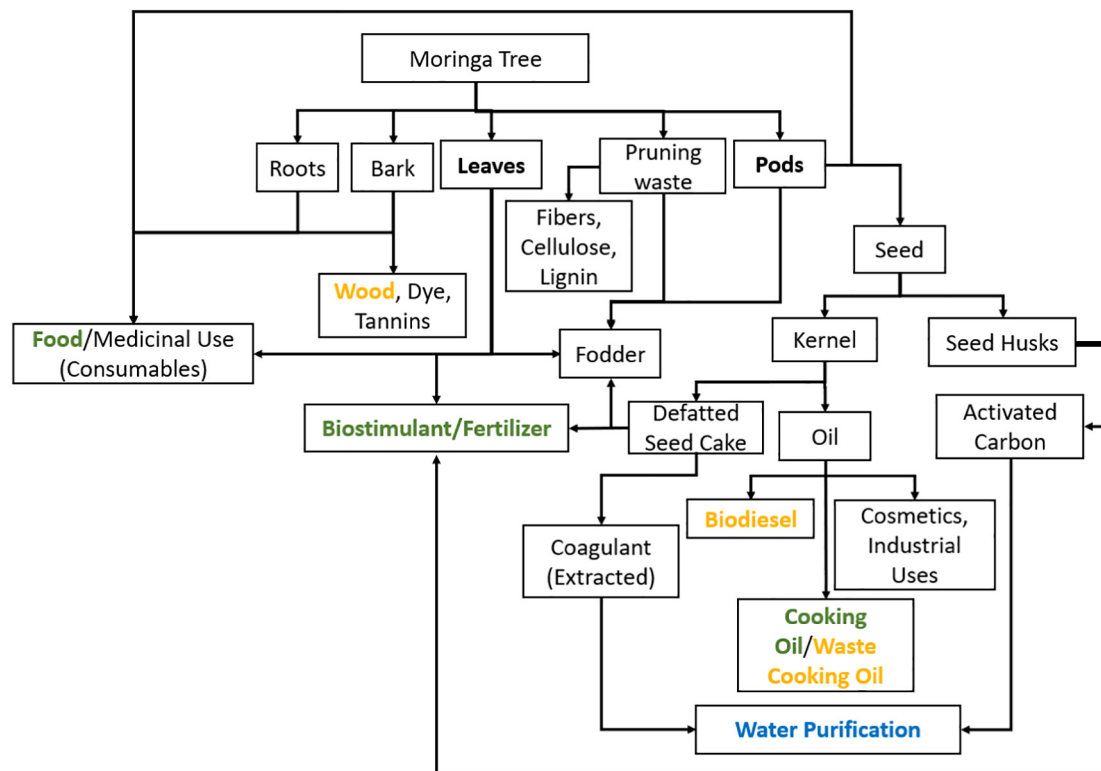


Fig. 2. Flow diagram of the many uses of the *M. oleifera* tree and its byproducts. *M. oleifera* leaves and pods (bold) have the most products and are the focus of the systems approach in this study. Food (green), energy (orange), and water (blue) related applications are indicated as well. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

systems thinking tool for understanding the relationships among a system's components and their interactions with each other. Interactions between a system's constituents can be captured by causal links. When causal links connect and close, they form feedback loops. Feedback loops are the drivers of a system's behavior. They are also the source of nonlinearity in systems modeling. Since feedback loops drive system behavior, similar feedback loop structures produce similar system behaviors. As a result, there are commonly reoccurring combinations of reinforcing and balancing feedback loops that provide characteristic behaviors called archetypes (Braun, 2002; Meadows, 2009). These archetypes are useful system thinking tools because systems with similar archetypes call for similar strategies to address unwanted behavior. Some systems archetypes include "Limits to Growth," "Tragedy of the Commons," "Fixes that Fail," "Success to the Successful," and others. This study will focus on applying the "Success to the Successful" archetype to characterize *M. oleifera* multifunctionality. Although other archetypes could potentially be applied to this system, "Success to the Successful" was selected due to its applicability for characterizing competition between a shared resource.

The "Success to the Successful" archetype represents a system that can occur when two reinforcing loops interact (Fig. 3). The two reinforcing loops compete for a common resource. As one of the two parties becomes more successful, it receives more of the shared resource and continues to be successful at the expense of the other party. In this figure, the success of party A leads to an increase in the allocation of resources to A compared to party B, which leads to more resources for A and increased success. By increasing the allocation of resources to party A instead of party B, the reinforcing loop that represents party B's success diminishes continuously.

Some potential strategies to address unwanted system behavior for this archetype include identifying shared resources and balancing their distribution or potentially linking the entities for a mutually beneficial outcome. In some cases, policies that limit the success of the dominant party may be necessary. Similarly, a policy that balances both

parties' advantages and disadvantages can help balance these two loops. Ultimately, an equalizing strategy needs to be implemented to prevent this system from operating uninhibited and potentially becoming unstable.

6.2. Causal loop diagram (CLD) for *M. oleifera* leaf and seed production

Depending on the initial goal of either producing seeds or producing leaves, an informed decision on the desired product output and tree density need to be made. By selecting a tree density, either leaf production or seed production will be prioritized. This choice will have implications on byproducts further up in the value chain. The many applications of *M. oleifera* products reviewed in this paper are mapped, and their complex interrelations are displayed in Fig. 4. This complexity is captured with a CLD in the context of the impact of *M. oleifera* byproducts on supplying FEWL services and the effect this has on livelihood (Biggs et al., 2015). In doing so, a holistic approach is utilized to characterize the multifunctionality of *M. oleifera*.

The CLD shown in Fig. 4 conceptualizes the implications of *M. oleifera* production on FEWL. The "Success to the Successful" systems archetype is adopted to characterize the competition for resources that arise when growing *M. oleifera* for either its leaves or seeds. This is represented with two reinforcing loops where the success of one leads to the failure in the other. *Intent to Grow Leaves Instead of Seeds* is the variable that links the two reinforcing loops. Key FEWL loops and livelihood loops are labeled and numbered. All loops in Fig. 4 are reinforcing loops. The potential benefits in health, income, and, subsequently, livelihood from growing *M. oleifera* for either its leaves or seeds are captured by the CLD.

In Fig. 4, *Tree Density*, *Land Available*, and *Water and Fertilizer Needs* are treated as exogenous variables. Higher *Tree Density* values and *Water and Fertilizer Needs* are associated with higher *Leaf Production*, so a positive causal link is used to relate the *Tree Density* and *Intent to Grow Leaves Instead of Seeds* variables. *Land Available* can be negatively linked to the *Tree Density*. Changes in the *Intent to Grow Leaves Instead*

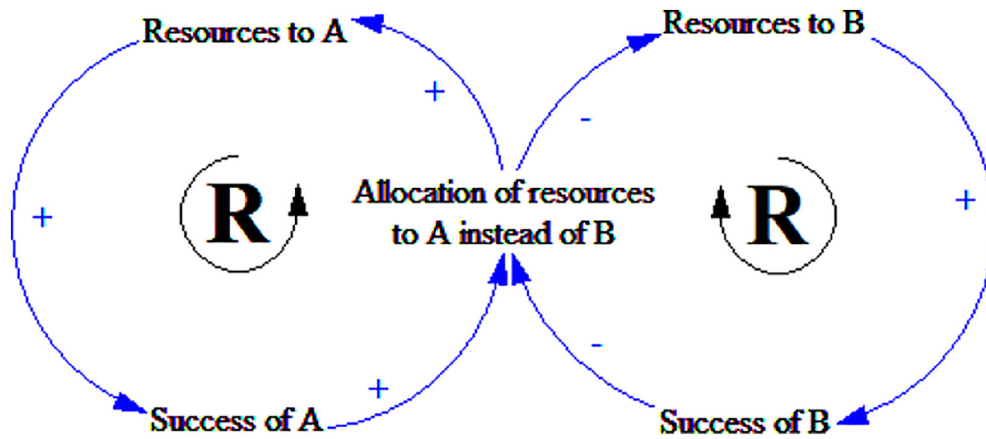


Fig. 3. The “Success to the Successful” archetype depicting two reinforcing loops interacting and competing for the allocation of resources, which is determined by the success of one of the parties at the expense of the other.

of Seeds variable will result in changes in the same direction for the *Moringa Foliage Production* variable. As a result, a positive causal link is used to connect the two variables. The positive relationship between the *Intent to Grow Leaves Instead of Seeds* and *Moringa Foliage Production* is carried over to the *Food Production* variable with another positive causal link. Assuming market conditions are favorable, successful Food

Production results in the continued desire to produce more food. A positive relationship is created with the *Intent to Produce Leaves Instead of Seeds*, thus completing the upper loop of the CLD and forming one of the main reinforcing loops, **Food Loop 1**. However, as *Intent to Grow Leaves Instead of Seeds* increases, the impact will be negative on all the *M. oleifera* seed byproducts such as *M. oleifera* oil and the *M. oleifera*

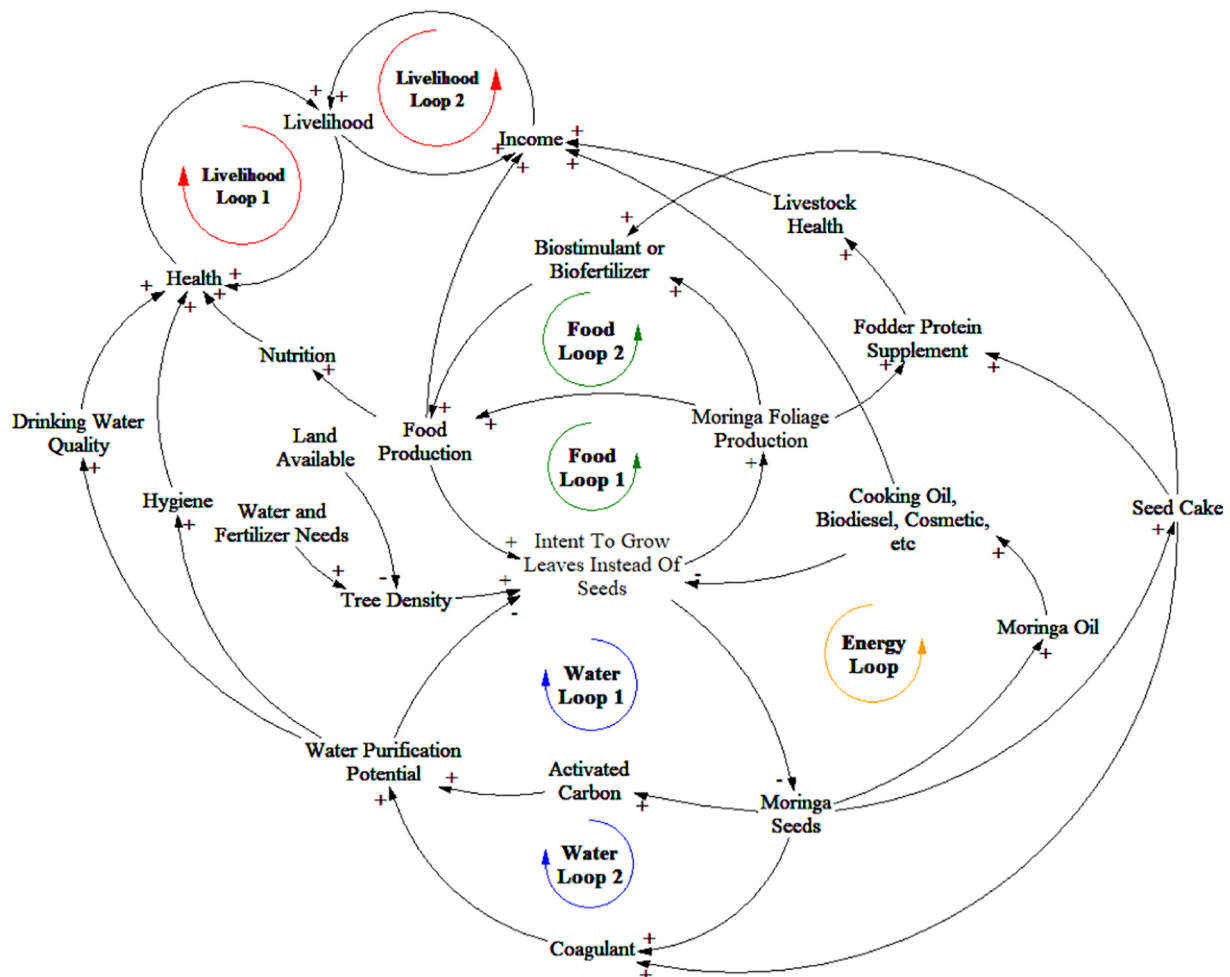


Fig. 4. A CLD of the interrelationships between the different applications of *M. oleifera* byproducts. Potential contributions to livelihood (**Livelihood Loop 1** and **Livelihood Loop 2**) as well as the different contributions to food (**Food Loop 1** and **Food Loop 2**), water (**Water Loop 1** and **Water Loop 2**), and energy (**Energy Loop**) related sectors are considered.

coagulant used for water purification. Due to the nature of the “Success to the Successful” archetype, this dominating effect is cascading, and stakeholders should be aware of the different means that can be used to improve their livelihoods by way of *M. oleifera* seed production.

When *M. oleifera* is used as food for humans, its high nutritional content is effective in combatting malnutrition and improving health. As a result, there is a positive relationship between *Food Production* and *Nutrition* and between *Nutrition* and *Health*. *Health* is positively linked to *Livelihood* because poor health deteriorates livelihood. In turn, an improvement in *Livelihood* allows for access to more resources and education. This creates a positive relationship with *Health*, forming a reinforcing loop that has been labeled **Livelihood Loop 1**. Another way to improve livelihood through *Food Production* is to sell the produced *M. oleifera* leaves in the market as nutritional supplements or teas. The potential to sell *M. oleifera* leaves in the market forms a positive causal link between *Food Production* and *Income*. Consequently, since increases in income can be followed by improvements in livelihoods and vice versa, the **Livelihood Loop 2** reinforcing loop is formed between *Income* and *Livelihood*.

M. oleifera leaves can also be used as a *Biostimulant/Fertilizer*, in the form of a foliar spray or fertilizer, to enhance other crops' growth and increase *Food Production* through another positive causal link instead of being directly used for human consumption. The result is the formation of the **Food Loop 2** reinforcing loop.

M. oleifera foliage can also be redirected and used as a fodder protein supplement. If *M. oleifera* leaves are used as a fodder supplement, then livestock health and energy may improve due to the high protein and nutrient content in *M. oleifera* (Cohen-Zinder et al., 2016). Hence, a positive causal link is used to connect *Fodder Protein Supplement* and *Improved Livestock Health*. Healthier livestock sells higher in markets, so a positive link is formed between *Improved Livestock Health* and *Income*. Income then can be used to improve one's *Livelihood*, forming a positive relationship between the two variables. A better *Livelihood* can also lead to more opportunities to secure income and the creation of generational wealth, contributing to the reinforcing **Livelihood Loop 2**.

On the other hand, if the intent is to produce seeds, then a lower tree density (on the order of 10^3 /ha) relative to foliage production tree density requirements (on the order of 10^6 trees/ha) should be followed before operations begin. As depicted by the negative causal link connecting the two variables, decreases in *Intent to Grow Leaves Instead of Seeds* result in increases in the production of *Moringa Seeds*. *Moringa Seeds* production is positively correlated with its byproducts, the *Coagulant*, *Activated Carbon*, *Seed Cake*, and *Moringa Oil* variables. Both the *Coagulant* and *Activated Carbon* seed byproducts have practical applications in water purification, and they are both positively linked with the *Water Purification Potential* variable. As positive results are realized with the seed's water purification applications, the *Intent to Grow Leaves Instead of Seeds* is negatively affected, forming reinforcing loops **Water Loop 1** and **Water Loop 2**.

Improvements in drinking water quality and hygiene will result if the water purification potential of the *Coagulant* and *Activated Carbon* is realized. This relationship is represented with positive causal links that connect the *Water Purification Potential* to *Drinking Water Quality* and *Hygiene* variables. Improvements in drinking water quality and hygiene will positively impact public health, so both the *Drinking Water Quality* and *Hygiene* variables are connected to *Health* with positive causal links. The positive contributions to the *Health* variable will then contribute to the reinforcing **Livelihood Loop 1**.

Moringa Oil also forms a reinforcing loop with its positive relationship with the variable representing value-added *M. oleifera* oil products, *Cooking Oil*, *Biodiesel*, *Cosmetic Oils*, etc. The production of value-added *M. oleifera* products is negatively related to the *Intent to Grow Leaves Instead of Seeds* variable forming the reinforcing **Energy Loop**.

Since the production of *Cooking Oil*, *Biodiesel*, *Cosmetic Oils*, etc. could create employment and entrepreneurial opportunities, a positive relationship is formed between *Cooking Oil*, *Biodiesel*, *Cosmetic Oils*, etc.

and *Income*. This relationship strengthens the **Livelihood Loop 2** reinforcing loop.

7. Discussion

The conceptualization of the interconnections between FEWL and *M. oleifera* biomass is captured with systems thinking tools like the CLD presented in Fig. 4. One key advantage of this approach, compared to the use of traditional value webs and value chains, is the ability to draw on existing archetype structures to identify synergies, tradeoffs, and appropriate interventions. Additionally, the conceptualization of the FEWL nexus with systems thinking tools facilitates this integration. Because qualitative mapping (or CLD) is a precursor to system dynamics modeling, there is also the potential to include the entire *M. oleifera* value web in a system dynamics model (Dizyee et al., 2020). Similar methods can be adopted for other multifunctional crops.

Many tradeoffs and synergies exist in the production of highly multifunctional crops like *M. oleifera*. It is to the advantage of any stakeholder to understand the interrelations between the various products of a multifunctional crop. As indicated in Fig. 4, the most visible tradeoff in *M. oleifera* production is between the leaf and seed yields. If the goal is to maximize food production and address food insecurity, then growing *M. oleifera* trees with a high density to increase leaf production is advantageous (Mendieta-Araica et al., 2013; Patricio et al., 2017).

M. oleifera leaves have many applications and can adjust to market demands and provide some security against market volatility. In addition to being grown directly for human consumption, *M. oleifera* leaves can also augment food supply with their uses as fodder or fertilizer (See Fig. 2). Furthermore, in smallholder farming communities, where livestock themselves are multifunctional (Weiler et al., 2014), the benefit of using *M. oleifera* to increase the nutritional quality of fodder is further amplified. Another alternative allows for *M. oleifera* leaf extracts to be used as effective biostimulants to grow other multifunctional crops with the potential to improve yields by 20–35% (Foidl et al., 2001). The utilization of *M. oleifera* leaves as biostimulants and fertilizers offers opportunities to progress towards food security and livelihood improvements. However, when using *M. oleifera* in fertilizer or animal feed, the opportunity cost incurred from the tradeoff of direct leaf production may be high from an economic perspective. An appropriate cost-benefit analysis should be carried out by relevant stakeholders in order to ensure desired profitability. The potential to improve livelihood through leaf production can ultimately be achieved through improvements in health by consuming the leaves directly or using the leaves to enhance the growth of other crops and income from selling the leaves or healthier livestock.

However, caution should be taken to choose an appropriate tree planting density for the desired yield and accessible agricultural inputs. If access to fertilizers or the capacity to irrigate the trees are limited, the yields will underperform. Consequently, livelihood improvements may not be as significant as expected. Similarly, if a high tree planting density is selected to maximize leaf yields, tradeoffs can arise with water security. Potential leaching of nutrients from synthetic fertilizers into groundwater or surface water, greater irrigation water demand, and an increase in the greenhouse gas emissions of fertilizer production and application are embedded in the life cycle of intensive *M. oleifera* leaf production.

The goal to maximize leaf production occurs at the expense of seed production. Seed yield per tree begins to diminish beyond a threshold tree density, so lower tree densities are recommended to enhance seed production relative to leaf production (Foidl et al., 2001). Increases in seeds produced will increase water purification capacity based on activated carbon and coagulant production. The result is direct progress towards water security. Furthermore, valuable oil can be extracted from the seeds before the coagulant is extracted. *M. oleifera* oil can be used as cooking oil, for cosmetic products, and as a lubricant, in addition to its prospects as a biodiesel feedstock.

The synergy created by the coproduction of *M. oleifera* seed products creates opportunities for positive nexus linkages. An intervention for

systems characterized by the “Success to the Successful” archetype involves balancing the competing loops to address undesired system behavior. In the context of the FEWL nexus, this balance is essential. If the coagulant extracted seed cake is an effective fertilizer, then a synergistic FEWL relationship can be created through *M. oleifera* seed production. Converting *M. oleifera* oil to biofuel, using the coagulant and activated carbon for water treatment, and applying the residual seed cake in fertilizer can contribute to each component of the FEWL nexus and subsequently result in livelihood improvements.

The application of a systems archetype to the FEWL nexus offers an approach that captures the complexity of a multifunctional system while providing established intervention strategies for mitigating unwanted system behavior. The inclusion of livelihoods in this nexus approach shows that while there is a competition between *M. oleifera* leaf and seed production, the overarching goal of improving livelihoods through *M. oleifera* cultivation is shared. Local resource security in the FEWL nexus, as well as market forces, will determine which approach should be preferred for livelihood improvement and management of multifunctionality.

8. Conclusion and future research

8.1. Conclusions

The multifunctionality of the *M. oleifera* tree has been reviewed and qualitatively analyzed using a systems approach. A CLD has been constructed to map various applications and identify the interactions (positive and negative) among the different relationships in its production and uses. Whether grown for its leaves or its seeds, *M. oleifera* has the potential to contribute to multiple, interrelated societal objectives through its contributions to food security, water security, sustainable energy security, and livelihood improvements. Notable improvements in the livelihoods of rural communities are possible through increases in rural incomes from selling *M. oleifera* leaf or seed products. Similarly, through proper stakeholder education on *M. oleifera*'s various uses, improvements in rural livelihoods, and public health through household water treatment and improved nutrition.

Coproduction of multiple byproducts of a multifunctional crop could benefit from a systems approach. Adopting a systems approach can help capitalize on multifunctional crop production by identifying opportunities for coproduction. Additionally, the interrelations between social, economic, and environmental impacts can be considered, allowing for optimal management of a multifunctional crop. Thus, this study concludes that multifunctional crop producers could benefit from applying a systems approach and qualitative systems thinking tools such as CLDs (as used in this paper) to gain a holistic understanding of their products. This will allow them to consider the implications of their decisions on the FEWL nexus. Multifunctional crop production value chain actors may seek to explore similar approaches to improve social and economic benefits while reducing the environmental impact of a product.

8.2. Future research

There is a maximum tree density threshold beyond which *M. oleifera* tree seed yields begin to diminish. Bopape-mabapa (2019) found that higher *M. oleifera* tree densities resulted in better seed and oil yields. However, the threshold where seed yields begin to diminish was not explored. Although it would vary depending on environmental and climatic conditions, it would be interesting to see the effect of increasing tree density on seed yield per tree and seed yield per acre. Many studies have been done relating leaf yields and tree density. Despite leaf yields per tree decreases beyond a certain tree density, yield per acre can continue to increase, so higher yields may still be obtained. Studies to determine optimum tree density for seed production would have an impact on stakeholder decision-making. It would inform whether it is more profitable to grow *M. oleifera* trees for their seeds or their leaves. In addition to studying

how tree density affects seed yields, *M. oleifera* seed and leaf yields on marginal lands is an area that needs to be researched further. This has particular relevance to the feasibility of *M. oleifera* as a biofuel feedstock.

It has been found that increasing plant density can result in higher leaf yields (Mabapa et al., 2017). Additionally, applying fertilizer has also been shown to potentially increase yields by over a factor of two (Motis and Reader, 2019). However, to the authors' knowledge, water and fertilizer inputs have not yet been researched for different planting densities of *M. oleifera*. Amaglo et al. (2006) observed that leaf yields are larger for higher plant densities, but that competition for nutrients in the soil increases as well. As a result, the optimal amount of fertilizer for different *M. oleifera* planting densities remains a knowledge gap.

The phytochemicals found in *M. oleifera* vary depending on their local environmental conditions as well as how the trees are maintained. An improved understanding of the processes that govern the *M. oleifera* intraspecies variation in phytochemistry may help improve biomass production, quality of biofuels, nutritional quality, and the MOCP water purification performance. All components of the *M. oleifera*'s FEWL nexus are affected by its phytochemistry.

Research into the effect of the extraction of the MOCP on the quality of the seed cake as an animal feed or fertilizer would be beneficial. This would be important to determine how animals that are fed with *M. oleifera* seed cake without the MOCP respond, how growth is affected, how the nutritional quality is altered, and identifying the appropriate dosages. In vitro and in vivo studies on how MOCP deficient seed cake may affect livestock feed nutrition and enteric fermentation have not been done yet. Similarly, experimenting with MOCP deficient seed cake as fertilizer and observing how crop yields and soil quality are affected remains unexplored. Studies on the MOCP deficient seed cake are necessary in order to take full advantage of the synergy between *M. oleifera* oil production, MOCP for water purification, and MOCP deficient seed cake.

A quantitative analysis of the information depicted in the CLD could help communicate these results and inform decision-makers. For instance, an environmental life cycle assessment of *M. oleifera* leaf production and couples the production of *M. oleifera* biodiesel, water purification, and seed cake used as fertilizer would help put into perspective how environmentally burdensome these practices are. Additionally, a life cycle sustainability assessment that quantifies the environmental burden, social impact, and economic costs of the competing loops of *M. oleifera* leaf and seed production could be performed to assess the total impact of an *M. oleifera* plantation on livelihoods.

Another quantitative study would be a systems dynamics model of the *M. oleifera* value chain by converting the CLD to a stock and flow diagram. With the relevant data from an *M. oleifera* growing community, such a model could provide further insight into the benefits, challenges, and opportunities of *M. oleifera* production. Interventions that capitalize on the synergy between coproduction of multiple *M. oleifera* products, shifting local market demands, and seasonal changes in production would all be quantified and assessed. Furthermore, developing a system dynamics model that characterizes the relationship between biomass production and biodiversity loss would provide insight into an important environmental tradeoff to consider in multifunctional agriculture. Other modeling approaches, such as agent-based modeling, should be considered as well for capturing the complexities that arise from multifunctionality in agriculture.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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