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Sun Exposure for Improved Soil Fertility and Insect Control in Arid-Land Agriculture

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Abstract
Soil solarization has proved to be cost-efficient and sustainable method to establish soil health, control pests and increase crop productivity in dry land farming practices. This process achieves the beneficial increase of soil temperature to the point where soil-borne pathogens, insect pests and weeds are suppressed, and at the same time promotes the mineralization of nutrients and healthy microbial processes through the employment of solar energy by using transparent polyethylene to mulch the area. Within constrained resource environments and water-limited conditions solarization not only lowers chemical pesticide and fertilizer use but additionally elevates soil health, resulting in abiotic stress tolerance, prolonged productivity and crop saves. The review identifies the agronomic importance of the solarization technology, its role in moderating the fertility of the soil, the effectiveness of the technology in controlling pests and the reason behind the rise of sustainable farming in the dry land areas.

Keywords: ***Soil solarization, dryland agriculture, soil fertility, pest management, sustainable farming, heat-induced sterilization, weed suppression, microbial activity, resource-efficient technology, crop productivity.***

1.Introduction

Soil has always been known as a focal point of sustaining plant life, not just a physical provider to anchor crops but also a living nutrient, water, and microbial communities reservoir of nutrients. Soil in agricultural systems (at least dryland systems) has succeeded in serving as the source of crop production and as the venue of the wars fought by plants, weeds, beneficial microorganisms, and pathogens. It is rather unfortunate that there are serious impediments associated with dryland agriculture that hamper its productivity. Chronic water scarcity, degraded soil fertility, the invasion of cultured fields by weeds, and recurring soil-borne diseases are the most aggravating issues among these. Farmers who practice in arid and semi arid areas are regularly faced with soils that are nutritionally deprived and subjected to moisture stress and readily invaded by weeds and pathogens. These difficulties lead to a situation of low productivity in which low harvest makes potential investments in sustainable management of the soil by the farmers even more constrained(1).

Dryland systems especially are susceptible to the problem of weeds; however, this is not only due to the fact that they compete harshly with crops over the limited resources of nutrients, water and sunlight, but also due to the fact weeds serve as alternate hosts of most pathogens. Their seeds are usually durable in the soil and may last years creating a weed seed bank that can survive years and regenerate itself over a few growing seasons. On the same note soil-borne pathogens like fungus, nematodes and some species of bacteria can survive in resistant forms in the form of sclerotia, spores or oospores that help them survive in the extreme dryland environment. When the favorable conditions are restored, these quiet structures start germinating and causing devastating losses by massively attacking crops. Research has indicated that low fertility of the soil increases the losses already incurred due to weeds and diseases since the crops that lack the nutrients are less competitive and offer less protection. When dryland crops were concurrently exposed to soil-borne diseases, parasitic weeds and nutrient deficiencies, reductions in yield as high as 65 percent and as near as 100 percent have been reported.

Use of agrochemicals, synthetic fertilizers, herbicides and pesticides has been the standard approach to such constraints over the decades. Although such inputs may provide temporary solutions by killing the weeds and diseases or adding nutrients on the soil, they have significant dangers attached to them. Excessive use of chemical fertilizer can have the effect of severely upsetting the equilibrium of microbial life of the soil, slaying the helpful microorganisms and aging the soil of its natural fruitfulness lingeringly(2). The pesticides and herbicides, however, do not only raise the cost of production of food but also pollute the environment, leading to water and air pollution, destruction of biodiversity, the accumulation of chemicals in food chains. Moreover, some of such inputs may be too expensive to smallholders in the drylands, which have low farm incomes. This makes agriculture unsustainable because it relies on these non-environment-friendly practices and vulnerable, ecologically and economically. Being aware of them, the directions in the development of the current policy, the European Commission 2030 vision, include a 20 per cent decrease in the consumption of fertilizers, and a 50 per cent decline in pesticide use, and recommends organic farming. These changes indicate the international necessity in alternative technologies, which are environmental friendly, inexpensive, and sustainable.

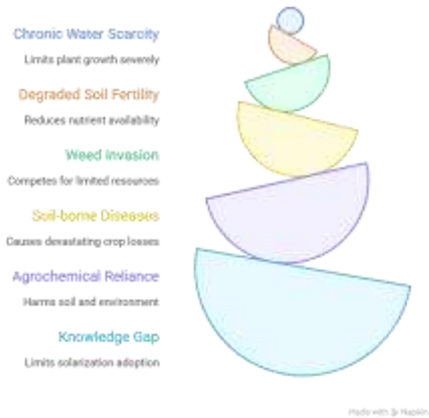

FIGURE 1 Dryland Agriculture: Impediments to Productivity

Soil solarization is one of such promising technologies. In this type of agronomic practice, the energy of the sun, which is abundant and renewable resource in dryland regions, is used to naturally disinfect the soil and make it fertile. In solarization, moist thoroughly prepared soils are covered with transparent or semi -transparent plastic films, which can trap solar radiation and raise soil temperature in the top layers. The accumulated heat beneath the plastic kills a number of weed seeds, nematodes and fungus spores over a time period spanning a number of weeks. Meanwhile, this high temperature induces degradation of organic matter, which enhances nutrient cycling beneficial to crop growth and changes in soil chemical conditions. In effect solarization alters the soil micro-environment to induce antagonism on harmful organisms and a promotion on beneficial processes.

Solarization has many attractions(3). One is that it does not employ chemicals; it is non-chemical and hence minimized or completely eradicated the use of harmful pesticides and herbicides. Second, it is economically affordable although in areas where there is a lot of sunlight and opportunities to access chemical inputs are poor. Third, it provides cumulative effects: in addition to underlying weeds and pathogens, it enhances the concentrations of beneficial microbes, fertility, and soil moisture. Compared to residue mulches or covers made of crops biomass that in dryland systems may fail to reach required temperatures because of little organic matter, plastic mulches offer a credible technology of tapping the solar power. The results of researches in areas with a tropical and subtropical climate have always testified to the success of solarization specifically in case of multiple enlistments of preliminary irrigation that raises heat conductivity of soil.

Spread of solarization has been rather sluggish, despite these benefits. It is largely due to the poor knowledge of its wider effects, which is haphazard and incomplete. Although its success in controlling weeds and pathogens is increasingly being recorded there is a deficiency of documentation on its effects on long term soil fertility and the presence of beneficial microbial communities in the soil, greenhouse gas emissions, and general economic viability with regard to dry lands. Without apparent financial recompense, farmers are reluctant in changing their production methods and different technologies with no definite evidence of their cost-benefit ratio and their sustainability in the long term. There is thus the need to bridge this knowledge gap so as to promote the extensive utilisation of solarization as a feasible alternative method to chemical-based soil management practices.

This review aims to combine and synthesize the literature and increase understanding of soil solarization, especially with reference to dryland agriculture. Using the above topics the analysis of the role it can play in pest and weed management, how it affects temperature, fertility and biodiversity of the soil, its economic and environmental consequences this work aims at presenting a systematic way of understanding solarization technology. This type of synthesis has been important to both researchers and policymakers and likewise is of interest to smallholder farmers seeking solutions to the long-standing challenges of dry land farming, in this instance provided that are affordable, sustainable, and have minimal impact on the natural environment. Finally, in whatever is being said, soil solarization should not be discussed simply as a method of pest-control, but rather as part of an integrated whole to increase soil health, with the minimal reliance on external additions, as well as encourage the health of agricultural systems on some of the most sensitive landscapes that the planet sees.

2.Methodology

To undertake a seismic review of soil solarization and its possible application in overcoming soil fertility limitation, pest attack, and weed stress in dryland Agric home system in China, a systematic and holistic approach of review was extracted. The process did not make use of a small collection of case studies, but rather involved the collection, sifting and synthesis of a broad collection of scholarly work, so that only the scientifically supportable and contextually appropriate work went through(4). The beginning of the methodology was intensive search in various academic databases and registries, such as peer-reviewed journals, internal institution reports, and even exclusive databases on agricultural sciences. Keywords were highly tailored towards the search including soil solarization, plastic mulching, dryland agriculture, depletion of weed seed bank, soil borne pathogen, increased temperature and economic feasibility. Using these targeted terms, review could incorporate the studies to include several geographical situations, although it gave weight to the studies directly mentioning the drylands and semi-arid contexts, which are considered the most susceptible areas where the technology is highly needed.

A relevance and quality screening of the collection sources was carried out. The articles of the peer review received a higher priority especially the ones published within the past twenty years so that the review is up to date with the current knowledge on the impacts of solarization. Still, initial formative studies that contributed to shaping the conceptual history of solarization were not excluded even when they exhibited important historic visions or methodological standards. Investigations of any other climates including the humid or the temperate climates were employed with a lot of caution and they were not the direct indications of dryland condition but were more of a reference study that would show the similarity or differences in the results obtained. This selectivity permitted the review to balance specificity and context with generalizable knowledge.

TABLE 1 Review on Soil Solarization in Dryland Agriculture

Step	Description	Purpose
Literature Search	Used keywords: *soil solarization, plastic mulching, dryland, weed seed bank, pathogens, economic feasibility*. Sources included peer-reviewed journals, institutional reports, and recent studies.	To collect a wide range of relevant, credible, and updated research.
Screening & Selection	Priority to recent (last 20 years) peer-reviewed works on dryland conditions; foundational older studies included for historical context.	Ensured relevance, reliability, and contextual applicability.
Data Extraction & Standardization	Findings on soil temperature, nutrient levels, microbial counts, and yield were paraphrased and converted into common measurement units.	To allow meaningful comparison across different studies.
Synthesis Framework	Organized evidence into themes: soil temperature, fertility, biodiversity, pest/disease control, weed management, economics, and environmental impacts.	To provide structured, holistic discussion of solarization effects.
Narrative Synthesis	Compared findings narratively instead of meta-analysis, due to diverse methods and contexts.	Highlighted both consistencies and variations across studies.
Interdisciplinary Integration	Included agronomic, microbiological, economic, and environmental studies.	To capture both technical and socio-economic dimensions of solarization.

After gathering the pertinent literature, the second step was to follow an intensive undertaking to interpret and synthesize. This is not just a compilation of results, but information was selectively removed, reworked, and homogenized so that they could be applied to make meaningful comparisons across studies. As an example, differences in units used to measure soil temperature, the content of nutrients, or the number of microbes were aligned in such a way that they came into a unified framework and could be discussed in that context. Such conversion would avoid misinterpretation that is bound to be achieved through inconsistent metrics. Cross-verification of the numerical results was also achieved where possible by referring to several sources that examined those comparable circumstances and hence amplified the credibility of synthesized results.

Another layer of methodologies to ensure greater credibility and clarity of the review was to use a patternisation of a structured flow of synthesis. The idea was informed by protocols of systematic reviews typically used in the development of the evidence-based research in agriculture, including reference works like Cumpston et al. (2023). This was by first conducting broad data collection, then conducting critical appraisal, extraction of the key findings and lastly aggregation into thematic categories. These types were developed to match with the three major areas of focus as agronomic (i.e. soil temperature dynamics, soil fertility enrichment, biodiversity impact, manipulation of the pathogens, depletion of the seed bank of the weeds, monetary returns and environmental impact). Each of the themes was discussed individually and linked with the others in terms of the integral character of solarization technology(5).

Another aspect that was presented in the methodology was narrative synthesis method as opposed to meta-analysis. This was not arbitrary, in that the variability in study designs, crop species and climate contexts implied that it would be hazardous to pool all quantitative data in one statistical model because of the outcome of oversimplification of the data. Rather, the review purported to point out similarities and differences between various experimental settings through the comparative, narrative presentation of the evidence. To give an illustration, where one study could have reported an increase in soil temperature of 20 o C due to the use of black polyethylene mulch on sandy soils, another one could have noted 10 o C change due to the same mulch in clay soils. Such variations were not home to contradiction but rather an avenue to investigate the effect of soil type, plastic color, or irrigation regime with the solarization outcome.

The second feature, also defining the methodology, was the attempt to record not only the results of agricultural work, but also social-economic and environmental-related opinions. To make this possible, the review has used interdisciplinary works in soil science, agronomy microbiology, economics and environmental management. The addition of the economic feasibility studies, e.g., necessitated the review of studies that documented cost-benefit ratios, input demands, and output enhancements in monetary terms (6). Equally, the greenhouse effect required the reference to life-cycle studies of plastic consumption, greenhouse gas emissions additional to those of surveys performing analyses of vain persistence of plastic residues in soils and eco systems there in. Such interdisciplinary approach made sure that the methodology was not limited to technical aspect of agronomy but the wider aspects that influence adoption and sustainability of solarization.

The objectivity was a prominent principle of the methodology during the entire process. There was no objective of the review to promote the uncritical support of solarization but evaluate both sides of the coin, its powers, and its shortcomings. Positive as well as negative findings were included and reports of results were neutral, syndromes that give a balanced picture. Illustratively, although several experiments showed enhanced crop yields and pathogen suppression, there were other concerns that showed that it may be detrimental to the extent of accelerating greenhouse gas emissions, low biodiversity levels in specific microbes, and the difficulty of disposing the polyethylene film. Having equal weighting in these findings the methodology made sure that the outcome reached was realistic, nuanced, and portrays complication of agronomic practices was silver by proxy.

Lastly, as an indicator of enhanced transparency, every source that was used in the review was duly cited in line with prescribed academic rules. This helped people who read this and who might be interested in researches in the future to expect exactly where these evidences started, what is the reliability of the statements and what business they can add to the existing knowledge. The use of a methodological framework that focuses on systematic search, a deliberate selection, critical synthesis, and an even-handed representation will make the review offer a solid and credible premise that can be held against the investigation of solarization technology in dryland agriculture. In the end, the methodology speaks volumes as to the nature of solarization itself: integrative, of transformational impact, and anchoring to the concept of maximizing the processes of nature to sustainable agricultural performance.

3. Results and Discussion

To undertake a seismic review of soil solarization and its possible application in overcoming soil fertility limitation, pest attack, and weed stress in dryland Agric home system in China, a systematic and holistic approach of review was extracted. The process did not make use of a small collection of case studies, but rather involved the collection, sifting and synthesis of a broad collection of scholarly work, so that only the scientifically

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TABLE 2 Results on Soil Solarization in Dryland Agriculture

Aspect	Findings	Implications
Soil Temperature	Solarized soils heat up by **10–20 °C** more than untreated soils; peak **45–55 °C** depending on plastic color, soil type, and duration.	Lethal to pathogens, weed seeds, and nematodes in the upper 20–30 cm soil profile.
Soil Fertility	Increases availability of **N, P, K, and micronutrients**; improves organic carbon, cation exchange capacity, porosity, and water retention.	Enhances nutrient uptake, reduces fertilizer dependency, and promotes stronger crop growth.
Soil Biology	Temporary decline in mesophilic microbes, but **thermotolerant bacteria, fungi, actinomycetes, rhizobia, and mycorrhiza** flourish post-treatment.	Creates a disease-suppressive soil and strengthens beneficial plant–microbe interactions.
Disease Control	Significant reduction of **Fusarium wilt, Verticillium wilt, root rots, and nematodes**; disease incidence often cut by **50–80%**.	Provides an effective alternative to pesticides and soil fumigants.
Weed Management	Weed seed bank depletion by **70–95%**; effective against parasitic weeds (e.g., broomrape). Irrigation before solarization improves efficiency.	Reduces herbicide needs, lowers weed competition, increases crop access to resources.
Crop Yield	Yield gains range from **25% to 100%+** depending on crop and conditions (e.g., tomato, cucumber, strawberry, beans).	Boosts farm productivity and food security in resource-scarce drylands.

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4.Conclusion

The synthesis of the available evidence derived through various studies show clearly the fact that soil solarization as one method is among the most promising non-chemical mechanism of coping up with the complicated and inter-related problems of dry land agriculture. Solarization has been a solution where in these areas water is a limited commodity, soil fertility is declining and where continuous pest and weed infestation forces restrict crop productivity and this has resulted in solarization not only as pest control but also as a combination to controlling soil management. This method ensures availability of energy in the form of solar, which is usually high in dryland and semi-arid conditions, to increase the temperature of soil to high levels (which are commonly fatal to most harmful organisms) as well as induce biological and chemical reactions that even further enhance fertility of the soil. This leads to a dimensionally multi-functional technology that can turn weak soils into efficient, disease resistant and resource-sufficing systems.

Among the most obvious findings of this review is the two-faced truth about solarization as a control tool as well as a soil-builder. Solarization also has the benefit of controlling soil borne pathogens, nematodes and weed seed banks along with increased nutrient availability, soil porosity and organic matter dynamics simultaneously, unlike conventional pesticides and herbicides of which only one (pests or weeds) is targeted. Synergy has a great value in drylands wherein farmers cannot pursue individual soil fertility, weeds, and diseases treatments. Solarization is highly applicable among smallholders because of its capacity to effectively combine the two constraints under one relatively inexpensive practice.

The consequences of crop productivity are far reaching. They have reported percentages of 25-100 percent in broad crops- vegetables, cereals, and legumes- advancing the case that solarization is not solely a loss prevention but a positive performance promotion procedure. Such improvements are the factors that determine whether many farmers will be able to sustain themselves marginally or become profitable. In addition to yield, solarization also decreases the cost of production through dependence on man-made fertilizers and pesticides and reduces environmental impact, along with risk potential of food and water in the form of chemical contamination. Due to the changes around the globe in agricultural policies which seek more sustainability and a decrease in the use of chemicals, soil solarization fits well with the new vision of environmentally friendly farming.

Of equal concern are the favorable benefits on soil biology. The fact that damaging microbes are temporarily inhibited by initial heating, and later the temperature becomes favorable to favorable organisms such as nitrogen-fixing bacteria, mycorrhizal fungi, and actinomycetes, etc. Such organisms are not only assisting in restoring soil fertility but also setting a natural biological shield to disease causing organisms. In the long term this can lead to the formation of disease-suppressive soils which chemical treatments can only seldomly lead to. Therefore, it is not only that solarization disinfects soil but it rearranges the biological community towards healthier, better balanced ecosystem.

Along with these encouraging findings, however, the limitations and difficulties also need to be reported. Top on the list is the extensive use of plastic sheets which are normally polyethylene to encapsulate solar energy. Although they are effective, once disposed inappropriately, these materials present environmental risks on the environment causing plastic pollution and soil contamination in the long term. Besides this, the organic matter decomposition process that occurs at elevated temperatures in the soil may produce greenhouse gases and to this extent those environmental induced benefits may be within the forefront to be neutralized. The controversies are not to disprove solarization but indicate that there is a need to innovate- especially by the development and deployment of biodegradable mulch and better management guidelines to reduce emissions. These adjustments would not only warrant solarization to be agronomically acceptable but also environmentally sensitive.

Economically, the evidence is very promising. Solarization always produces good returns on investment; and profitability regularly surpasses the 50-percent mark each year. This is especially important to the small scale farmers in dry lands, whereby input costs usually surpass the yields in the situations when the traditionalized agrochemicals are applied. Solarization- along with cutting down cost of fertilizers, pesticides, and herbicides, and increasing the harvest- offers an avenue to food security as well as financial stability. It is inexpensive, readily available, and flexible to the local methods of farming thus adding to its appeal.

In prospect, soil solarization implementation should not be considered as a unique practice or activity, but a step in the transformation of agronomy towards sustainability. Combined with other dryland farming ingenuities including crop rotation, organic amendments, and efficient irrigation, solarization may be a keystone of dryland farming that is climate-resilient. Its ability to maintain the moisture in the soil, lower weed densities and enhance recycling of nutrients makes it a useful adaptation vintage against climate variability. Also, the fact that the goals of solarization are correlated with the international sustainability considering the use of chemicals input and enhancement of organic farming, indicates that the technology has a chance of receiving the support of policy and investment in future years.

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Conflicts of interest

The authors have no conflicts of interest to declare

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