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Effects of Plastics in Agriculture in the Jordan Valley: Utility, Impact, and Alternative Approaches
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Acronyms

BDM .................................................................................................................. Biodegradable mulch
EPA .................................................................................................................. Environmental Protection Agency
JOD .................................................................................................................... Jordanian dinar
PAE ................................................................................................................... Phthalate acid esters
PE ..................................................................................................................... Polyethylene
WUE .................................................................................................................. Water use efficiency
Executive Summary

The use of plastic mulch film in agricultural practices in the Jordan Valley provides numerous benefits when properly managed, however, improper use and disposal can lead to myriad unintended negative environmental, social, and economic impacts. Plastic use for agriculture began to proliferate Jordan in the early 1960s as a way to increase water use efficiency (WUE). Today, plastic mulch provides an opportunity for Jordanian farmers to increase crop production through the regulation of inconsistent growing climates due to extreme temperatures and inconsistent rainfall, particularly in arid regions. Plastic mulch increases soil temperature, keeps soil moist, and controls growth of weeds, contributing to an increase in usable farmland and water conservation efforts, higher crop yields, and potential for increased income-generation.

However, if not maintained and removed from the field(s) properly, degraded plastic, known as mulch residue, can infiltrate the soil or contaminate the surrounding environment. Mulch residue may impact soil structure, moisture retention, and microbial biomass, leading to decreased crop yields in the longer-term. For example, to increase efficiency, some farmers in Jordan use the same plastic mulch to grow two rounds of crops in one growing season; however, oftentimes, the mulch begins to lose its plasticity, break apart and degrade after the second use. Lingering plastic residue from practices like double-cropping may impact moisture and nutrient transport by physically blocking absorption of water and nutrients. Mulch residue could change soil properties in ways that impact the effectiveness of fertilizer or pesticides on crops and may result in leaching into groundwater supplies, negatively impacting human health. Another threat to human health is the potential for phthalates or other cancer-causing compounds to leach into the soil and groundwater, which could be absorbed by crops and enter the food supply. Additionally, deteriorated plastic may contaminate adjacent land or waterways like the Jordan River or Dead Sea, posing additional environmental and economic risks. Because the Jordan River is used extensively for irrigation, water containing microplastics may be used to irrigate fields and microscopic pieces of plastic could be returned to the fields and potentially enter the food supply. Additionally, in the Jordan Valley, many farmers rely on livestock, such as sheep or goats, as an additional source of income. Plastic residue can be easily ingested by livestock grazing in areas close to mulched fields, which can become impacted in the rumens (stomachs) and possibly cause death.

Another challenge presented by the use of plastic mulch film is awareness and access to proper disposal options. While recycling is the preferred method of disposal for plastic mulch, if this option is not available, landfiling is a better choice than incineration, open burning or illegal dumping. Currently, plastic mulch is typically burned on the farm site, illegally dumped, or left on fields to disintegrate. Open burning on-site releases a variety of harmful pollutants (e.g., hydrochloric acid, sulfur dioxide, furans, heavy metals, nitrous oxide, methane, and others) into the air and across the farmland, which can be detrimental to humans, livestock and other wildlife. Leaving the plastic mulch to degrade into the field or illegal dumping through burying or disposing of plastic mulch into waterways contributes to plastic pollution of the surrounding environment in the Jordan Valley. Complicating factors for proper disposal include the current solid waste management and recycling infrastructure and capacity in country. Additional challenges to recycling of plastic mulch in Jordan include soil/dirt/vegetative contamination of the plastic mulch, disintegration of plastic after multiple growing cycles, and lack of interest in use of recovered plastic mulch in a degraded condition.
Currently, it is not feasible or practical to collect, clean, transport, market and utilize recovered plastic mulch in the manufacture of new products in the Jordan Valley. However, environmentally preferable alternatives to plastic mulch film should be considered, including biodegradable mulch (BDM) that is designed to be tilled into soil after use, as well as cornstarch or paper-based alternatives which naturally break down over time. Other organic options include compost, flax-wool, and chopped leaf litter. Such environmentally friendly alternatives not only reduce the burden of collection and disposal at the end of the growing season but may also offer cost-savings in some instances and are generally safer for human health and the environment.

For BDM alternatives to be considered for adoption in Jordan, there must be additional steps taken to prove the performance and economic feasibility. While there currently is no local manufacturer of BDM in Jordan, there has been expressed interest by current manufacturers of plastic mulch to explore the possibility of producing BDM. Additionally, there has been expressed interest by the farming community to participate in pilot testing to compare the performance of BDM over plastic mulch due to the benefits to human health and the environment.

Alternatively, should BDM not prove to be a viable option for consideration, another option may include to explore the feasibility of formalized collection and incineration of plastic at a cement kiln in-country as an alternative fuel source.

It is imperative to increase general awareness of the effects of agricultural plastics in the Jordan Valley and the best practices in the selection, application, maintenance, removal and disposal of plastic mulch to lessen the negative impacts on the region. Additionally, further consideration of more environmentally friendly, biodegradable alternatives to plastic mulch requires ongoing discussion among key stakeholders, including the Ministry of Local Administration, Ministry of Environment, Ministry of Agriculture, representatives from local municipalities, the farming and manufacturing communities, and other non-governmental stakeholders, such as EcoPeace.
1. Introduction

Plastic mulch film and the use of plastics in agriculture (plasticulture) has aided farmers of the Jordan Valley by regulating an otherwise inconsistent growing climate through maintenance of the temperature and moisture of crop soil for the duration of the growing season and beyond. This report will define plastic mulch and its uses, assess impacts of the use of plastic mulch, highlight research findings regarding its use, and provide options and best practices for the use of plastic mulch or sustainable alternatives, when feasible, in Jordan.

1.1. Definition of Plastic Mulch Film

Plastic mulch is a sheeting of low- or high-density polyethylene (PE) (e.g., medium density PE, CAS number 9002-88-4), polyvinyl chloride (CAS number 9002-86-2), or polypropylene (CAS number 9003-07-0) used to cover the soil surface. As an agricultural practice, use of plastic mulch dates back to the 1950s, when it quickly replaced the paper mulch used at the time. The use of plastic mulch spread quickly due to its ability to increase crop production by regulating soil temperature, maintaining soil moisture, influencing soil microorganisms, and controlling weed growth (Espi et al., 2006; Hong et al., 2011; Kader et al., 2017; Miles et al., 2006). For these reasons, plastic mulch is used in the hot, dry climate of the Jordan Valley (Amayreh & Al-Abed, 2005).

1.2. The Life Cycle of Plastic Mulch

Selection

Plastic mulch can be used for a wide variety of fruits and vegetables and is best suited for row crops including tomatoes, peppers, melons, squash, and cucumbers. Maughan and Drost (2016) recommend considering mulch selection based on three key features: type, thickness, and color.

- **Type**: There are two types of plastic mulch, smooth and embossed. While smooth plastic will expand and contract as temperatures fluctuate, embossed plastic is easily stretched and is more resistant to wind and cracking.

- **Thickness**: The thickness of plastic mulch ranges from 0.007 to 0.125 mm (Ngouajio, 2011). The cost of the mulch increases as thickness increases. Thin plastics are appropriate for single season use, as this plastic is more likely to tear. Plastic thickness of around 0.03 mm is appropriate for most vegetable crops. However, when planning to reuse the mulch or double cropping, thicker plastic is recommended. See Table 1 for recommended mulch thicknesses by crop type and growing duration.

- **Color**: Black, white, and clear are the most common plastic mulch colors. The color selected will depend largely on the climate in which the growing will be done. Black is the most widely used and most affordable color of plastic mulch. Black mulch will perform best in temperate climates, clear is best for cooler regions, and white in tropical regions that require aphid control. Silver or reflective mulch can also be used for pest control and temperature control, as this type of mulch reflects heat to help keep soil cool, which helps when planting fall crops toward the end of the summer season (Cedar Circle Farm, n.d.).
Table 1. Selection of Plastic Mulch by Crop and Thickness

<table>
<thead>
<tr>
<th>Crops</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundnut</td>
<td>0.007</td>
</tr>
<tr>
<td>Fruits and vegetables: Short duration (3 to 4 month growing season)</td>
<td>0.025-0.03</td>
</tr>
<tr>
<td>Fruits and vegetables: Medium duration (10 to 12 month growing season) early stage of fruit crops: coffee, banana, papaya, sugarcane, cotton, etc.</td>
<td>0.04-0.05</td>
</tr>
<tr>
<td>Long duration crops (more than 12 months): fruit crops, plantation crops, etc.</td>
<td>0.07-0.1</td>
</tr>
<tr>
<td>Soil solarization (transparent film)</td>
<td>0.015-0.02</td>
</tr>
</tbody>
</table>

Adapted from Raman, 2017.

Application

Farmers in the Jordan Valley report having used plastic mulch since 1994 and typically apply mulch at a rate of 7-8kg/dunum. Plastic mulch is distributed by vendors in the Jordan Valley who specialize in agricultural products and can be purchased at stores that sell products for commercial agriculture. It is applied to the soil at the beginning of the growing season and may remain on the soil until the beginning of the next growing season or may be removed at the conclusion of the growing season. The former increases the likelihood that plastic residues will remain in the soil (Sanders, 2001). Plastic mulch may be applied in long strips by hand or mechanically on raised beds or flat ground. Mechanical application requires a tractor and attachments for laying down the mulch can cost several thousand dollars (or hundreds/thousands JOD) (Maughan & Drost, 2016) and therefore, is less feasible in some areas, such as the Jordan Valley. The ends of the mulch are typically anchored down to keep the plastic from shifting. This can be done using metal, U-shaped pins, rocks, irrigation pipes (Figure 1), or soil (Caines, 2018).

Maintenance

Many farmers choose to use plastic mulch because it reduces the emergence of weeds and retains moisture in the soil. When plants are starting out, a small amount of weeding may be needed to cut off competition in the holes created by the mulch-laying equipment (or by hand) (Figure 2). Otherwise, weeds may colonize the exposed circles of soil and take nutrients and water from crops. Often, plastic mulch is paired with drip irrigation tubes laid under the mulch (Figure 3). This system allows water to go directly to the roots of the plant while the mulch limits evapotranspiration.

Holes around the plants should be wide enough in diameter so that the plastic does not touch stems. In hot climates, black plastic will burn plants if too close. To keep plants from overheating, they can be started earlier in the season, so the foliage shades the plastic. In
addition, mulch can be covered with straw, wood chips, or another natural mulch to keep the temperature under the mulch from getting too high (Caines, 2018).

**Removal**

A variety of machines are available to remove plastic mulch from soil beds. These include equipment that lifts the mulch from the soil or rolls the mulch on a spool (Parish, Bracy, & McCoy, 2000). The majority of plastic mulch removal is often done by hand and is labor and time intensive (Figure 4) (McCraw and Motes, 1991). Agricultural laborers benefit if mulch is removed by hand – they are provided with income after the harvest. Farm managers and owners, however, are paying for labor after the growing season has ended. Farm managers may purchase a machine to remove or assist in the removal of mulch, but the costs of specialized equipment may or may not be more economically advantageous than labor costs associated with removal.

In some cases, mulch is left on the field until the following year's planting. In this case, the mulch disintegrates into smaller pieces (Figure 5), which are plowed beneath the topsoil, and new mulch is laid on top. This method may have broad repercussions on soil quality and is not recommended by horticulturists (Kasirajan & Ngouajio, 2012; Sanders, 2001). It is likely that plastic mulch pieces will be scattered by the wind which could pollute local landscapes and waterways. Additionally, the plastic remnants may be eaten by livestock grazing in the same area, leading to potential health repercussions for the animals and economic repercussions to herders (Hailat et al., 1998).

**Disposal Options**

While some areas have more opportunities than others for proper disposal, some do not have proper access to or are unaware of disposal options. Disposal of plastic mulch may be perceived as time-consuming and costly, ultimately resulting in plastic build-up in landfills or on-site burning (Hemphill, 1993).

Globally, the majority of plastic mulch is either recycled or disposed of in a landfill after it is collected (Kasirajan & Ngouajio, 2012). In Jordan, domestic waste is collected by public and private organizations and is transported to either a transfer station or a dumpsite (Figure 6). In some cases, waste is sent to transfer stations for consolidation and sorting before being sent to
dumpsites; otherwise waste goes directly to the
dumpsite. Dumpsites that likely serve the Jordan Valley
include Al Aghwar-Al Shamaaliyah, New Deir Allah, Al
Humra, Al Barakah, and Al Samard. Many transfer
stations serve these dumpsites including Al Aghwar-Al
Shamaaliyah, Al Shoneh-Al Wsta, Ajloun, and Al Salt
(Saidan et al., 2016). No large-scale incineration takes
place in Jordan at present – the closest incinerators
are across the border in Israel.

Waste from Amman is sent to the Al Ghabawi landfill,
managed by the Greater Amman Municipality. The
coastal city of Aqaba is the only other site with a public
organization managing solid waste – the Social
Economic Zone of Aqaba has contracted waste
management to the Lebanese company, Averda.

Lack of prioritization of waste disposal at the national
level has proved to be the primary challenge for
effective waste management in Jordan. In 2017,
recommendations were made for national objectives
and priorities for waste management at a national level
(Stathis, 2017). The recommendations were developed
under a project funded by the European Union titled “Support to the Implementation of the
National Strategy for the Solid Waste Management in Jordan.” The current plan will reduce the
number of open dumps from 22 down to 8 regional landfills, converting the 14 other sites to
transfer stations (Stathis, 2017). Nonetheless, local municipalities have no written procedures
for disposing of waste (Aljaradin, 2014). Other challenges include lack of a trained labor force
and outdated equipment.

Recycling is the environmentally preferred disposal
option. However, existing infrastructure may limit the
scalability of widespread agricultural recycling. At
present, formal and informal recycling takes place at
small scale and municipalities often lack funds to
update their waste disposal infrastructure (Yamin,
2018). Recycling at transfer stations is not a
widespread practice, but these stations may be
utilized in new or different ways if recycling becomes
more prevalent. A recycling center is under
construction outside Deir Allah but will mainly be for
sorting and recovery of locally generated and
collected municipal waste.

Challenges to recycling of plastic mulch in Jordan
include soil/dirt/vegetative contamination,
disintegration of plastic after multiple growing cycles,
lack of recycling infrastructure in general, and lack of
interest in use of recovered plastic mulch by
manufacturers. All recyclables must be clean of dirt
and grime; even a tiny amount of dirt can jam sorting
and processing systems (Kotrba, 2018). It was

Figure 4. Removing plastic mulch by hand
(Ruesch, 2019c).

Figure 5. Plastic mulch disintegrating in
farm field (Ruesch, 2019d).
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observed during field visits conducted in 2018-2019 that some farmers use the plastic mulch for two growing cycles prior to removal. The mulch begins to lose its plasticity, break apart and degrade after the second use. It was also observed to be contaminated with soil/rock/dead vegetation (which adheres to the material) and falls apart when removed by hand. Cleaning the mulch will require additional labor hours at the farm or recycling facility and is not currently standard practice. Farmers themselves may not be equipped to clean long strips of mulch, and this task may be more effectively completed at a recycling facility or transfer station. There are methods of cleaning recyclables prior to sorting, but some facilities may simply discard recyclables that are too soiled (Moore & Wszelaki, 2016).

Recyclables also need to be sorted by plastic type and sometimes color. In the U.S., there are six resin identification codes, and plastics of different codes cannot be mixed. In addition, dyes used to color plastics introduce another sorting variable. For example, black and white plastics of the same resin type must be processed separately. The required sorting introduces complications, but sorting could also be an opportunity for increased investments in labor at recycling facilities (Kotobra, 2018).

Some materials (including PE plastic) may not be recyclable, because no companies are interested in purchasing it for reuse; the process of repurposing may not be economically viable when compared to the initial price of the recyclable. During site visits with farmers in 2019, several mentioned that manufacturers of plastic mulch do accept the thicker (0.2 mm) plastic mulch and pay 200 JOD/ton. However, due to the degradation and contamination issues mentioned above, manufacturers are not interested in collecting the thinner plastic mulch. Some manufacturers reportedly tried incorporating recycling of plastic mulch into their processes but were not able to do so profitably. In 2018, China announced that they would no longer be accepting certain types of plastic and paper, including some PE products, like plastic bags (Brooks et al., 2018). Currently, only 5-10% of solid waste in Jordan is recycled, mostly by non-governmental organizations, corporations, and individuals. Agricultural plastic used to cover greenhouses (0.2 mm or thicker) is collected and sold to recycling factories located outside the Jordan Valley, but the demand for low-density PE has been declining (Kool, 2016; Saidan et al., 2016).

While recycling is the preferred method of disposal for plastic mulch, if this option is not available, landfilling is a better choice than incineration or open burning for reasons discussed in Section 2.3. With no large-scale incinerators operating in Jordan, incineration of plastic mulch may not be feasible. Building a waste-to-energy incinerator would improve the solid waste and energy infrastructure in Jordan, especially considering that the majority of Jordan’s energy is imported and that waste-to-energy options may enhance Jordan’s energy independence (Bloss & Pfisterer, 1989). Because waste management is largely public-funded and financial resources for such projects are limited, experts recommend public-private partnerships as a possible solution to limited project financing (Aljaradin, 2018). There is currently a waste-to-energy plant under consideration in the early planning stages (Nicolopoulos, 2016).
Most plastic mulch is either dumped on the roadside or burned on farms (Figures 7 and 8). This practice poses a myriad of health risks, discussed further in Section 2.3. Growers may also bury, dump, or dispose of plastic in waterways, contributing to plastic pollution of the environment (Moore & Wszelaki, 2016). This practice is illegal in Jordan, and violators are subject to fines (Abboud, 2018).

1.3. Utilization of Plastic Mulch Film in Agriculture in Jordan

The ability of agricultural plastics to retain water contributes to their use in the arid climate of the Jordan Valley. Plastic mulch film, plastic houses, and plastic tunneling are used to aid in year-round crop production while conserving water through soil moisture retention.

Agriculture in Jordan

The Jordanian Ministry of Agriculture (2011) describes the agriculture sector in Jordan as not only a source of food security and income, but also as a way of life. Agriculture in Jordan has suffered from major issues including scarcity of irrigation water, overuse of groundwater, and land fragmentation. The agriculture sector declined from 30% GDP in 1954 to 3% GDP in 2010 (Sidahmed et al., 2012). Additionally, between 1975 and 2007, urban areas expanded and total arable land area decreased (Sidahmed et al., 2012). With a growing population, farming remains important as a major source of food items. Jordan has been locally meeting their needs for poultry, eggs, 50% of milk and dairy, vegetables and fruit, but overall is a net food importing country, relying on imports of wheat, cereals, and fodder (FAO, 2011). In addition to local demand, fruits and vegetables are a significant share of the export market, with 17% of 2011 national exports being agricultural products worth about 795 million Jordanian dinar/dunum (JOD) (Sidahmed et al., 2012). These statistics demonstrate the need for effective farming practices in the agricultural sector of the Jordan Valley.

Plasticulture in Jordan

Over the past few decades, the Jordan Valley has relied heavily on the use of plastics and plastic mulches. Starting in the late 1960s, as an experiment initiated by the Ministry of
Agriculture of Jordan, use of plastic houses and tunnels through winter became imperative to ease the economic burden of a traditional agricultural off-season. In warmer months, use of plastic mulches and greenhouses raises soil and air temperatures and can increase fruit and vegetable output when demand for traditional summer produce, such as tomatoes, is high (Khour, 1979). Aside from use of greenhouses in the off-season, use of plastic mulch in the growing season ensures a high yield with minimal maintenance while crops are developing. The success of plastics in both the summer and winter months further embeds plasticulture in the Jordan Valley.

**Use of Plastics to Reduce Evaporation**

The Jordanian agricultural sector continues to face several challenges due to environmental conditions of the Jordan Valley. Successive drought years and irregular rainfall have solidified the need for sustainable water retention, which plastic mulch fulfills by regulating evaporation and maintaining consistent soil moisture and temperature. The ability to mitigate the uncertainty of temperature and rainfall using plastic mulch has encouraged economic growth in the Jordan Valley as well as in other arid and semi-arid parts of the world. (Espí et al., 2006; Manickam et al., 2010). Studies conducted in similar arid and semi-arid environments have shown 35% more soil water retention than soil without plastic mulch, while overall plant health and vitality increase (Olanson, 1999; Stelli et al., 2018).

2. **Assessment of the Impacts of Plastic Mulch Film Use**

Plastic mulch is used worldwide. According to Santelmann and colleagues (2012), farmers around the world have applied plastic mulch to as much as 300 million acres of farmland. Though there are clear economic benefits, but other factors should be evaluated.

Although the use of plastics in agriculture in the Jordan Valley has certainly aided in the increase of usable farmland, water conservation, and income-generation, it is important to also consider the environmental, economic, and social impacts of consistent plastic use.

2.1. **Environmental Impacts**

A wide variety of environmental effects should be considered when deciding to use plastic mulch for agriculture. Plastics allow for more efficient use of water, a scarce resource in the Jordan Valley, but can ultimately contribute to the leaching of pesticides and fertilizer into the groundwater. Build-ups of leftover plastic residue may ultimately hinder crop yields, soil structure, and overall crop quality over time. Aside from impacts on soil quality, air quality is also affected if plastic mulch is burned at the end of the growing season.

**Impacts on Soil Quality**

Weather, machinery, and general wear and tear can cause holes and rips in plastic mulches, which may lead to the infiltration of degraded mulch residue into the soil (Figure 9). Thicker mulch is less likely to rip as a result of daily wear and tear and is therefore less likely to produce large amounts of residue (Mahadeen, 2014). Although thicker films are less likely to leave residue, they are more
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expensive than thinner films; however, some thicker films can be reused and are recommended for double cropping (planting a second crop after the first is harvested). While thinner films are less expensive, they are more likely to contribute to plastic pollution of the soil (Maughan & Drost, 2016).

At the end of the growing season, remaining mulch may be plowed under and may or may not be collected before the next growing season. If this method is used, a piece of farm equipment with a rake-like attachment is needed to comb the plastic from the soil to ensure plastic from past crop seasons does not hinder nutrient and moisture transfer to the soil (Changrong, Wenqing, & Neil, 2014). Regardless of the collection method, large and small pieces of plastic remain in the soil, even if residue is collected mechanically. This is especially true of thinner mulches (less than 0.008 mm) that disintegrate more quickly than thicker mulches (0.04 to 0.125mm) (Liu et al., 2014).

Despite the efforts of farmers to collect the plastic after each season, the infiltration of mulch residue into the soil remains of primary concern to researchers (Liu et al., 2014). Plastic pollution of the soil can have wide-reaching impacts on soil structure, moisture retention, and microbial biomass (Song et al., 2003; Wang et al., 2003). While the use of plastic mulches may increase yields in the short-term, a build-up of plastic residues over time can lead to decreased crop yields in the long-term (Mamkagh et al., 2009).

Chinese researchers examined factors that influenced the amount of residual mulch in field sites in Xinjiang, China. Film thickness, number of consecutive years the plot has been covered in plastic mulch, and crop type all impacted the amount of plastic residue present in the soil. For example, fields that had been mulched with plastic for over 20 consecutive years had the most plastic residue and fields that had been mulched for 10-20, 5-10, and less than 5 years had decreasing amounts of mulch residue. The researchers also looked at the crop type’s impact on film residue in the soil. Cotton contributed the most to mulch residue, followed by maize, vegetables, and potatoes, although maize and cotton are not grown extensively in Jordan (Food and Agriculture Organization, 2008; Zhang et al., 2016).

Examining effects of plastic mulching over time, researchers found that 10 years of mulching left residues at a volume of 50-260 kg/ha (Yan et al., 2010). Researchers in China used two varieties of cotton (one with a taproot and the other with a shallow root system) to test how increasing gradients of mulch residue impacted crop yields. When plastic residues in the soil reached 2000 kg/ha (the highest amount tested), crop yields of both cotton varieties decreased by an average of 42%. The authors estimated that after 139 years of using plastic mulch with cotton, the decrease in crop yield would negate the increased crop yields associated with plastic mulching (Dong et al., 2015; Li et al., 2014).

Plastic mulch buildup occurs when mulch breaks down into pieces of various sizes and is not adequately removed from the soil. Researchers in Argentina surveyed a horticultural field for meso- and macroplastics and found that up 10% of the soil surface was comprised of plastic (Ramos et al., 2015). In places where thinner film is used, the amount of meso- and macroplastics in the soil may be higher (Lui et al., 2014). Also of concern to researchers is the degradation of meso- and macroplastics into microplastics, which are harder to measure and could have more widespread implications for human health. Measuring microplastics in soil is challenging for researchers, and new methods are being developed to do so (Steinmetz et al., 2016).

Soil scientists have identified several ways in which mulch residue may have lasting impacts on crop yields and soil structure. Plastic residue impacts moisture and nutrient transport by physically blocking water and nutrients from being absorbed by the roots. Mulch residue
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changes soil properties in the first layer of soil, but also has implications for deeper strata. In a study that compared soils with and without residual mulch, water content and saturated hydraulic conductivity (describes how water moves through a saturated media) were both decreased in soil with residual plastic (Jiang et al., 2017). Soil with high levels of residual plastic also exhibited preferential flow, or when water soaks into the soil through the ‘path of least resistance’ (through wormholes, cracks, around mulch pieces) in a rapid and uneven pattern. Any fertilizers, pesticides, or other substances applied to the soil surface travel quickly and deeply through the soil and may leach into groundwater (Peranginangin, 2003).

Relatedly, researchers determined that water infiltrates soil at an inconsistent rate in plots with residual plastic mulch. In their 2017 study, Jiang and colleagues (2017) noted that water infiltration of soils with large amounts of residual mulch were not evenly distributed around the root system. Their findings suggest that, if plastic film is present in the soil, crops with long, single taproots (e.g., cotton) may perform better than crops with fibrous, surface layer roots (e.g., wheat and corn). In addition to water infiltration, rates of seed emergence and crop yields may decrease when plastic residue in topsoil exceeds 200 kg/ha (Dong et al., 2013).

In addition to potentially inhibiting moisture and nutrient transport, plastic residues also release PAE. PAEs increase the flexibility of plastics and are freely mobile compounds. As such, PAEs can leach from plastics into surrounding environments (Balafas et al., 1999). A survey of Chinese soils found a correlation between phthalate contamination and plastic mulch use, with contamination levels exceeding allowable limits in other countries (Hu et al., 2003). In sites where plastic mulch was recycled or otherwise removed from the soil, PAE contamination was much lower, showing that proper film management can impact the amount of phthalates in the soil. PAEs are known to be carcinogenic when ingested in large amounts or over long periods of time (Kluwe, 1986; Thomas et al., 1984).

**Impacts of Plastic Residue on Soil Health**

High amounts of plastic residue may negatively impact soil health by:

- Decreasing plants’ absorption of water and nutrients
- Decreasing water content in deeper soil strata
- Contributing to uneven distribution of water in soil
- Allowing for deeper penetration of herbicides, pesticides, and fertilizers
- Increasing levels of phthalate acid esters (PAE)

**Impacts on Soil Microbial Biomass**

Research is inconclusive on the impacts of plastic mulching on soil microbial biomass. Soil microbial biomass is used as an indicator of the fertility of a soil (Li et al., 2004). Plastic mulches increase the moisture content and temperature of the soil, creating a condition which fosters increased crop yields and plants that grow more quickly and efficiently. However, this condition also promotes soil productivity and has the potential to lead to soil degradation, if not amended with fertilizer (Song et al., 2003). Researchers in Germany found that use of plastic mulches may lead to “less favorable soil conditions” due to changes in in the “microbial communities under the plastic film,” including decrease in beneficial fungi and bacteria (Buyer et al., 2010; Muñoz et al., 2017). Fungi under the mulched soil were more likely to produce mycotoxins, a stress condition of soil fungi that can be a safety concern for humans and livestock (Elmholt, 2008). Research in China, however, has shown that soil microbial biomass increased under plastic mulch (Li et al., 2004). More research may be needed to fully elucidate the influence of plastic mulch on soil microbial biomass.
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Increased Release of Greenhouse Gases

The earth’s soils store more carbon than the atmosphere and plants combined (Lal, 2010). Scientists have noted the potential for greater carbon emissions from the soil due to increased ambient temperature (Davidson & Janssens, 2006). Because plastic mulch increases the soil temperature, the combined effect of increased ambient temperature and increased soil temperature could result in increased emissions of greenhouse gases from the soil. This is particularly salient in warmer climates, where increases in soil and air temperatures will increase the rate of decomposition in the soil. At high temperatures, certain gases (e.g., nitrous oxide) can permeate plastic mulch, and as temperatures increase, the permeance of the film by nitrous oxide can increase exponentially (Nishimura et al., 2012).

Researchers examined emissions of nitrous oxide and methane from fields mulched with plastic. Plastic mulches serve as a physical barrier, limiting evapotranspiration, and thus, contributing to higher soil moisture. Soil moisture content, methane, and nitrous oxide emissions were positively correlated in the study. Overall, plastic film mulching increased the global warming potential (a measure to compare the warming impact of different gases) by 12-82% over no-mulching (Cuello et al., 2015; Environmental Protection Agency (EPA), 2018). Soils covered with plastic mulch and fertilized using biomass (barley and vetch) produced more nitrous oxide than mulched soils fertilized with chemicals.

Increased Water Use Efficiency

Jordan is facing a water shortage which is anticipated to get worse due to both population growth and an increase in the everyday needs for water (Philippe, 2003). In arid regions, use of plastic mulch increases WUE. Stanhill (1986) defines WUE as “the ratio of the volume of water used productively.” For example, reducing leaks in an irrigation system can improve WUE, while planting seeds too early or late may reduce WUE. Physical and chemical properties of the soil also affect WUE. Jordanian soils are sandy, loamy, and coarse, meaning the soil is made up of larger particles and water can move easily throughout the soil. However, sandy soils have limited porosity (less overall space between soil particles) and hold less water (Ball, 2011).

The soils of the Jordan Valley are primarily entisol and inceptisol (Lucke et al., 2013). Entisols are found in traditionally unstable environments such as floodplains, sand dunes, and steep slopes. They vary in their productivity potential – entisols found in floodplains are more fertile than those on slopes or dunes. Inceptisols are found in more mountainous regions and contain more clay, salt, and organic material. The productivity of inceptisols also varies depending on location and plant-related factors (United States Department of Agriculture, 2018).

Plastic mulch used in conjunction with drip irrigation has been shown to increase WUE and decrease the total amount of water applied to crops. The highest increases in WUE have been reported with drip irrigation and transparent plastic mulch, followed by drip irrigation with black plastic mulch, when compared to controls (Xie et al., 2005; Yaghi et al., 2013). Use of plastic mulch and drip irrigation increases WUE by decreasing the amount of water lost to evapotranspiration, improving soil water infiltration, and allowing moisture to permeate the soil more evenly (provided the soil has low amounts of plastic residue) (Gan et al., 2013; Li et al., 2004). In arid and semi-arid growing regions, use of plastic mulches could limit the amount of overall water used to irrigate crops.

Increasing WUE is important in a water-scarce nation like Jordan. The majority of precipitation occurs in winter months, and year-round stream flow is low due to high evaporation. However, due to high infiltration of water into the soil, groundwater reserves in Jordan have traditionally had a high rate of recharge (Mohsen, 2007). Water moves through the soil quickly and may
move even more quickly in soils containing residual plastic. As discussed previously, any pesticides, fertilizers, or chemicals applied to the soil surface will move more quickly and directly to groundwater reserves in soils with large amounts of mulch residue.

**Increased Runoff**

Studies have shown that use of plastic mulches increases the volume and velocity of runoff (Arnhold et al., 2013; Templeton, 2013; Wan & El-Swaify, 1999). Because plastic mulch is impermeable to rain, less water is absorbed by the soil and more water heads to waterways (Rice et al., 2007). In addition to plastic residues, runoff may include pesticides, fungicides, or fertilizers applied after the mulch has been laid (Durham, 2003). These chemicals can enter local water sources and have deleterious effects on aquatic ecological health (Arnold et al., 2004).

Runoff can be mitigated by the use of vegetative furrows (Rice et al., 2004) or changing the field’s topography (Arnhold et al., 2013). Plants in vegetative furrows reduce runoff by absorbing water and chemicals when it rains. Rye is commonly used for vegetative furrows, although planting vegetative furrows may be more costly than bare-soil furrows (Rice et al., 2007). Plastic mulch on concave fields in ridges and furrows has been shown to increase erosion significantly compared to unmulched, level ground, while a convex field with neither ridges and furrows nor mulching shows a small decrease in the amount of erosion, compared to the control (Arnhold et al., 2013). Because plastic mulch increases the amount of soil loss, convex field topography may mitigate the amount of soil loss compared to concave topography. Like vegetative furrows, altering topography to minimize erosion requires additional cost and labor.

**Plastic Pollution of Waterways**

While little research has been conducted on the impact of plastic *mulch* debris on waterways, research is abundant on the negative effects of plastic pollution on waterways. In rivers, large pieces of plastic debris gather at the shoreline and can be ingested by marine and land animals. Plastic mulch that is tilled into the soil after harvest, or otherwise not fully removed from the soil, may blow off fields into the Jordan River (Kool, 2016). Plastic breaks down quickly into small particles, called microplastics, which are smaller than a grain of rice. These microplastics absorb toxins in polluted waters, including pesticides which runoff into the Jordan River from nearby agricultural areas (Foderaro, 2016).

In addition to absorbing chemicals, plastic particles also leach chemicals into the water, including flame retardants, antimicrobials, and preservatives. These chemicals are known to influence hormone production in humans and animals. Researchers studying the effects of nanoplastics on oysters found that nanoplastic consumption was correlated with decreased fertilization success (Tallec et al., 2018).

The Jordan River flows into the Dead Sea, whose salt is believed to have therapeutic and cosmetic benefits. Researchers in China, however, have found that ocean and lake salts contain fragments of microplastics, including polyethylene (Yang et al., 2015). Polyethylene releases lead and chromium as it degrades, and the water of the Dead Sea has been found to contain elevated levels of chromium (Al Bawab et al., 2018; Nakashima et al., 2010). In fact, plastic pollution in the Dead Sea has prompted the campaign ‘One Dead Sea is Enough.’ The campaign, initiated by the Jordanian Ministry of the Environment, aims to raise awareness about marine plastic pollution (United Nations Environment Programme, 2018).

**2.2. Economic Impacts**
The Jordan Valley has experienced both positive and negative economic effects as a result of plastic mulch film application. Crops mulched with plastics have higher yields and allow farmers to grow in the off-season, resulting in a considerable net return that is enough to justify the labor and equipment costs for those who use it. Although often cost-effective, the use of plastics can negatively affect another economic resource in the Jordan Valley, livestock, as researchers often find plastics in the stomachs of goats and sheep.

**Increased Yields**

Applying plastic mulch is more expensive than using bare ground alone. However, the increased yields (especially when paired with drip irrigation) and decreased need for weeding have been found to offset the additional costs of mulching, which include materials for application and disposal and increased time and labor for laying and removing mulch (Arancibia & Motsenbocker, 2008). Case study 1 provides examples of extra costs that may be incurred in using plastic mulch, but also explains reasons why the additional cost is worth it for some farmers.

Specialized equipment can be used to expedite the application of plastic mulch, planting of crops and seeds, and collection of mulch. This includes equipment for preparing the shape of the bed, a mulch laying machine, a transplanting/seeding machine, and a mulch lifter. While none of these pieces of equipment are imperative for the use of plastic mulch, their use does cut down on labor costs. For example, removal of mulch at the end of the growing season is often done by hand and takes approximately eight hours per acre of land, or two hours per dunum, the Jordanian equivalent used to measure parcels (McCraw & Motes, 1991). A piece of equipment would lower labor costs, but whether the additional cost and maintenance of that equipment offset labor costs is dependent on each farm’s context. In addition, cost-effective maintenance of farm equipment requires easy access to a technician who can fix highly specialized equipment. In other words, equipment may only be a wise investment if someone is able to fix it when it breaks.

Despite the potential increase in total labor and equipment costs, use of plastic mulch may increase a farmer’s net return by 21 JOD/dunum. It should be noted, however, that some research indicates that drip irrigation on unmulched soil has a higher cost benefit ratio than drip irrigation used on mulched soil (Tiwari et al., 1998). Steinmetz and colleagues (2016) believe that the literature remains “incomplete and contradictory” regarding the cost-effectiveness of

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**Case Study 1. Farm Rite with Yinka**

Yinka Adesola (2017) is a farmer and agribusiness trainer in Nigeria. She uses plastic mulch on her farm because it allows her to plant earlier in the year. Weed management is much easier and she uses less water on her crops. Yinka uses drip irrigation in conjunction with plastic mulch and delivers fertilizers to her plants by mixing it with the water sent through the drip irrigation tubes. An advantage of using plastic mulch is that she uses less fertilizer because the water/fertilizer mix is less likely to leach from the beds when covered in plastic. Because Yinka lives in a hot climate, the mulch keeps the soil from crusting under the effects of the sun and heat. When harvest time approaches, the mulch keeps ripening fruits and vegetables from coming into contact with the soil, limiting rot.

Yinka’s primary complaints about plastic mulch are the various additional costs incurred compared to planting on bare ground. On her farm, these additional costs include equipment used to lay the mulch, the mulch itself, special transplanters designed for beds covered in plastic, and extra labor during installation and removal of the mulch.
plastic mulching. Additionally, plastic mulches may not be the most economical choice for all crops. Trees (e.g., olive) do not perform well enough under plastic mulch to justify the additional cost (Leclerc, 1997). Cold-weather crops grown in warm climates (e.g., spinach and lettuce) may be too hot under plastic mulch. As such, hot-weather crops (tomatoes, cucumbers, etc.) tend to grow better under plastic mulch than cold-weather crops (Figures 10 and 11). Natural, breathable mulches made from locally available materials may be more cost-effective than plastic (e.g., unprocessed bark from sawmills, paddy straw mulch) (Nath & Sarma, 1992; Ringe & Graves, 1990).

**Impacts on Livestock**

Goats and sheep are important economic resources for Jordanian farmers. As such, the health and productivity of ruminants are paramount to the financial wellbeing of many Jordanians. Researchers have noticed high levels of plastics in the rumens (stomachs) of goats and sheep. Veterinarians found plastics in the stomach linings of goats, and in some cases, plastics became impacted and/or caused the death of the animal. A study in Iran found that 27.5% of sheep and 24.3% of goats surveyed had foreign bodies in their digestive tracts, the majority of which were plastics. Perhaps more economically impactful, 40% of pregnant animals had foreign masses in their digestive tracts (Omidi et al., 2012). Ethiopian researchers found that the most frequently indigestible item found in the stomachs of ruminants were plastic bags (Mekuanint et al., 2017). Body weight and age were associated with the presence of foreign bodies in the rumen; older and underweight animals had the most foreign material in their stomachs (Fromsa & Mohammed, 2011). Use of plastic mulch may contribute to the presence of plastic in the rumens of goats, especially if goats are grazing in areas close to mulched fields or areas where there is high plastic mulch residue (Hailat et al., 1998). Drought and lack of grazing area may also contribute to ruminants’ ingestion of plastics.

2.3. Health and Social Impacts
The use of plastic mulches may present a variety of health and social impacts for the Jordan Valley, both positive and negative. For example, the burning of mulch has a negative impact on air quality, posing health risks to local communities. Overall, public perception of the use of plastics should be investigated to further gauge social impacts.

**Impacts on Community Health**

Plasticulture could have wide reaching negative impacts on human health. Leaching of chemicals used in plastics (PAEs, for example) may affect health outcomes in areas where mulch is widely used. Phthalates and other potentially carcinogenic and mutagenic compounds leaching into soil and water may be absorbed by crops and enter the food supply (Sun et al., 2015). Plastic residues in soil and irrigation of fields with water containing microplastics may contribute to phthalate contamination of agricultural soils (Figure 12). Using an alternative biodegradable mulch or recycling plastic mulch would decrease the amount of phthalates (attributable to degraded plastic mulch) in soil and water, and thereby risk to human health.

Burning plastic mulches as part of the disposal process can release carcinogenic substances into the air (Valavanidis et al., 2008). Plastic agricultural waste burned in an incinerator contributes to greenhouse gas emissions, but formal incineration releases fewer toxic chemicals than open burning. Incinerators are oxygen and temperature controlled, and plastics burn hotter and more efficiently, producing far less toxins than open burning (EPA, 2001; Kotrba, 2018).

Plastic mulch that is eliminated via open burning on agricultural fields poses threats to human health because the emissions produced by the plastic are uncontrolled. Open burning releases pollutants into the air and across the farmland, which is detrimental to humans, livestock and aquatic life in the surrounding areas (Biemiller, 2013; Hailat et al., 1998; Templeton, 2013). Open burning poses the most risk to those living closest to the burn site, including farmers and laborers who may not be wearing personal protective equipment. Additionally, open burning is inefficient because used plastic mulch is difficult to ignite and burns slowly due to moisture and vegetative material on the mulch surface (Linak et al., 1989). Inefficient and slow burning may prolong exposure to hazardous chemicals. Additionally, the temperature of the fire is not measured or maintained and may lead to incomplete combustion of hazardous components of plastic mulch. Any residual toxins from the burn may not be disposed of appropriately (Guendehou et al., 2006).
Effects of Agricultural Plastic in the Jordan Valley

Chemicals released from informal burning of plastic waste include hydrochloric acid, sulfur dioxide, dioxins, furans, heavy metals, and particulate matter (Biemiller, 2013). Perhaps the most harmful chemical released as a result of open burning of plastics are dioxins, which are carcinogenic and hormone disrupting. If burned on the agricultural site, dioxins can settle on crops and in waterways, ending up in the food supply (Figure 13) (EPA, 2016a).

Agricultural Labor Force in Jordan

With just under 15% of citizens living below the poverty line, farming remains economically important for 25% of Jordan’s poorest citizens, employing 124,000 people (Sidahmed et al., 2012; Assessment of the Agricultural Sector, 2012). The poor rely on family labor (22% of total operations) and depend on domestic gardens to meet their basic resource needs (Sidahmed et al., 2012). Households considered the poorest of the poor are those headed by women (Food and Nutrition Security, 2013).

Labor wages rose from 70 JOD/month in 2002 to 180 JOD/month in the mid-2000s (Naber & Molle, 2017). Due to rising wages, farmers of irrigated lands relied more on migrant labor, with 79,685 non-Jordanian men and 2,006 non-Jordanian women holding work permits in agriculture. Most of these permit holders were of Egyptian and Syrian nationality (Jordan Statistical Yearbook, 2018). Some migrant workers leave agricultural jobs to contribute to the growth of the capitol, similar to many Jordanian Nationals who have shifted away from working in agriculture in favor of leasing land or sharecropping, while growing numbers of young Jordanians are unwilling to work in agriculture (Sidahmed et al., 2012).

Potential Import Increase

The increased crop yields precipitated by the use of plastic mulch have led some farmers to plant cash crops rather than crops grown historically in their respective regions. For example, Chinese farmers are not growing as much wheat in Minqin County because wheat requires more water and is not compatible with plastic mulching (Ingman, Santelmann, & Tilt, 2015). If other areas of the country are not compensating for Minqin’s decrease in wheat production, China may need to import more wheat, which may affect the price of consumer goods. While no specific examples of Jordanian farmers switching crops were identified, it is plausible to assume that farmers in Jordan are motivated to maximize their yields by planting cash crops much like Chinese farmers.

Public Perception of Rural Space

More research is needed on how the public perceives rural space covered in plastic mulch (Steinmetz et al., 2016). Scientists have determined that humans find green landscapes most visually appealing and gray and black landscapes least visually appealing (Yao et al., 2011). Similarly, plastic mulches contribute to “aesthetic pollution” and may have cultural impacts on
3. Biodegradable Alternatives to Plastic Mulch

While the utilization of plastic mulch offers some benefits, the potential negative impacts of long-term use and disposal should not be minimized. While avoiding waste generation is the preferred first step in waste management, alternatives to plastic mulch should be pilot tested by smaller farmers in the agricultural sector (EPA, 2016b). Replacement mulches to be considered include biodegradable plastics, starch, paper, and wool, as these alternatives have undergone testing as substitutes to plastic mulch.

3.1. Alternatives to Plastic Mulch Film

Despite the utility of plastic mulch film, some researchers are raising the alarm about long-term consequences of plastic mulch use and the generation of waste (Liu et al., 2014; Steinmetz et al., 2016). Alternatives can typically be bought in high quantities at a discount, similar to traditional plastic mulches. These alternatives have been found to be beneficial to human health and the environment, improving the quality of the surrounding water, air, and soil, as well as being cost-effective. Some alternatives, such as wool, are already available to U.S. farmers and have proven effective in American agriculture. Case study 2 provides an example of why a farmer may choose to use biodegradable, organic mulches rather than plastic.

**Case Study 2. Plastic Mulch in Small Gardens**

Amy Grant and Teo Spengler (2018) are gardeners based in the United States. Teo appreciates that plants can be sowed and harvested earlier and produce higher yields by using plastic mulch. From an economic perspective, reduced evaporation of moisture from the beds has cut Teo’s water bills. Teo spends less time weeding and has seen a reduction in pests (that often eat or lay eggs on weeds).

Amy, on the other hand, sees many problems with the use of plastic mulch. First, it is more expensive than other mulches. She favors organic mulches (bark, leaves, manure, newspapers), which are cheaper, do not need to removed at the end of the growing season, and enrich the soil as they degrade. Second, Amy does not like the labor-intensive removal process and does not want to contribute to ever-increasing landfill waste.

**Biodegradable Options**

Alternatives to plastic mulch film have been investigated since the 1970s, but only recently have these alternatives been more heavily researched (Uzrad, 1978). The alternatives to conventional plastic mulch vary from inorganic mulches and organic mulches to biodegradable mulches (BDMs).

Inorganic mulches: Inorganic mulches can be natural or man-made. Aside from PE mulch, inorganic mulches also include crushed rock or gravel and marble chips, which are mainly used in areas where weed control is needed (Tyagi et al., 2018). Landscape fabric also allows for weed suppression and should be used in conjunction with other mulches (Chicago Botanical Garden, n.d.). Inorganic mulches other than plastic are typically utilized for landscape or household gardening rather than commercial agricultural farming use.
Organic mulches: Organic mulches reduce evaporation and maintain soil temperature. Organic mulches also add nutrients to the soil as they break down. These types of mulches can be purchased by the bag or cubic yard and should be applied soon after they are purchased (Chicago Botanic Garden, n.d.). Some organic mulches, such as grass clippings, hay and straw, compost, cotton stalks, and peat moss, improve soil structure as they break down and are tilled into the soil at the end of a season. Other organic mulches, such as barks, shells and hulls, wood chips, pine needles, and sawdust, take longer to degrade, and thus are convenient to use for perennial plants (Schumer, 2017; Tyagi et al., 2018). For instance, a study of organic mulches determined that pistachio shell mulch and wood chip mulch were found to be superior to other mulches in maintaining soil water content in olive trees (Farzi et al., 2017). Other organic alternatives include wool and flax-wool blends that repurpose unsalable or low-sale sheared wool. Wool alternatives have also been shown to maintain a high amount of moisture and insulation in the soil and to increase yields of various crops (O’Briant & Charlton-Perkins, 2012; Santelmann et al., 2012).

Biodegradable film mulches: Biodegradable film mulches decompose into carbon dioxide, water, and cell biomass over time and are tilled into the soil at the end of the growing season, as is done with organic mulches. These films are often made from plant starches, such as corn, wheat, or paper, making them a bit more fragile than plastic mulch. These mulches require more care during the laying process to limit waste of the product. It is important to lay full beds with edges well covered so that once moistened, edges may stick together and maintain an even layer of coverage that will not be blown or swept away from the bed over time (Dentzman & Hayes, 2019; DuPont et al., 2016). Like many organic mulches, BDMs not only alleviate the burden of disposal at the end of a season, but also provide nutrients to the soil.

Although BDMs were introduced to the agricultural sector in the 1980s, adoption of BDMs has been minimal. Kasirajan and Ngouajio (2012) note that, aside from the cost of BDMs, the initial biodegradable options on the market during this time were not truly biodegradable. These two factors likely contributed to the lack of adoption of BDMs. However, in recent years, many researchers have noted advancements in degradation, crop yield, enhanced soil environment, and affordability of paper- and starch-based BDMs (Miles et al., 2006; O’Briant & Charlton-Perkins, 2012; Santelmann et al., 2012; Scopel et al., 2016; Zhang et al., 2008). Of note, researchers found the brand Mater-Bi BDM mulch (http://materbi.com/en/solutions/agriculture/) successful for growing tomato crops in a northeastern Spanish climate. Using Mater-Bi, PE mulch, paper mulch, and bare soil as a control, researchers found that crop growth was similar for both the biodegradable and the PE mulch, with growth being higher overall than the paper and control treatments. The Mater-Bi was also high in fruit weight and number of fruit per plant, and was successful in regard to weed control. The authors concluded that Mater-Bi is suitable for warmer climates (Martin-Closas et al., 2006).

Aside from paper and starch, other biodegradable options have been developed, including “upcycling” plastic mulch and turning it into biodegradable plastic and polymer sprays (Adhikari, 2015; Babu, O’Connor, & Seeram, 2013). These alternatives have been shown to be effective alternatives to PE mulch, with the polymer spray being used to minimize soil evaporation in a semi-arid climate. The polymer required 28% less irrigation water than the control; however, the development and testing of the biodegradability of these options are ongoing. No results were found regarding cases of upcycling or BDM spray use in Jordan or the surrounding region.

Sintim and Flury (2017) posit that for BDMs to be a competitive alternative to PE mulch, BDMs must possess the following attributes:
- Maintain a conducive microclimate for plant growth,
- Be flexible to allow mechanical installation,
- Remain intact during the majority of the cropping season,
- Undergo complete degradation after soil incorporation or composting,
- Have no adverse impact on the environment, and
- Be economical.

Goldberger and colleagues (2015) conducted interviews with key stakeholders including specialty crop growers, agricultural extension agents, agricultural input suppliers, and mulch manufacturers regarding perceived bridges and barriers to BDM adoption. Their findings mirrored many of Sintim and Flury’s (2017) proposed BDM attributes. Barriers to adoption of BDMs include:
- insufficient knowledge and lack of information regarding BDMs, resulting in respondents feeling they would not know how to use BDMs, high cost concern, unpredictable BDM break down (too quickly or not quickly enough), and skepticism that BDMs would not be completely biodegradable.
- Bridges to the adoption of BDMs included reduced waste, environmental benefits that would give stakeholders a smaller footprint, and a strong interest in further learning about BDMs. During a field visit in 2019, representatives from the Jordan Ministry of Environment and several farms in the Jordan Valley stated that any BDM should biodegrade within 24 months to be considered viable for use.

Cost of alternatives: When available, biodegradable mulch options vary greatly in cost and typically cost more than PE mulch. However, while BDMs may appear to cost more than plastic, the increased cost of biodegradable options may be less than the removal and disposal of plastic mulches (Anderson et al., 1996; Waterer, 2010). Season-end activities are greatly reduced through the use of biodegradable mulches because no removal or disposal is needed, which helps to offset the short-term economic impact of transitioning to BDM (Velandia, et al., 2018). Additionally, like plastic mulches, natural mulches lessen weed management and the need for herbicides and other chemicals (Duppong et al., 2004). Table 2 presents common length, width, and thickness options for plastic and paper BDM and PE mulch and, as well as the approximate cost of each.

In the case of other alternatives, such as wool and flax-wool mulch, farmers could benefit from the local sheep industry in Jordan. Resources already available to farmers may be more cost-effective than plastic. The farmers in Case study 3, for example, use scrap wool sheered from the farm’s sheep as an effective alternative to plastic mulch. However, during field visits in 2019, several farmers indicated higher-end markets for sheep wool (Figure 14).
### Table 2. Size of Mulch Rolls Commonly Used in Crop Production, Purchase Price, and Suitability for Machine Laying

<table>
<thead>
<tr>
<th></th>
<th>Plastic BDM</th>
<th>Paper BDM</th>
<th>PE mulch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available roll length</td>
<td>Up to 6,000 ft</td>
<td>Up to 750 ft</td>
<td>Up to 4,000 ft</td>
</tr>
<tr>
<td>Available roll width</td>
<td>3-5 ft</td>
<td>2-4 ft</td>
<td>3-5 ft</td>
</tr>
<tr>
<td>Roll thickness</td>
<td>0.5-1.5 mil</td>
<td>9.0 mil</td>
<td>0.5-1.5 mil</td>
</tr>
<tr>
<td>Purchase cost (per 1,000 ft)</td>
<td>$46-$190</td>
<td>$160-$390</td>
<td>$25-$65</td>
</tr>
<tr>
<td>Weight (per 1,000 ft)*</td>
<td>15-35 lb</td>
<td>90 lb</td>
<td>9-29 lb</td>
</tr>
<tr>
<td>Machine application</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Note: * Refers to the weight of mulch only, does not include the weight of the cardboard tube used to roll the mulch. A standard cardboard tube of 3-inch diameter and 4-ft length weighs approximately 2.5 lb. From Ghimire et al., 2018.

### 4. Best Practices in the Use of Plastic Mulch and Biodegradable Alternatives

When feasible, the adoption of biodegradable alternatives to plastic mulch should be utilized if the BDM is, indeed, proven to be safely biodegradable. If suitable alternatives are not accessible or are cost-prohibitive, there are best practices that farmers can take to lessen the potential for negative impacts of improper use and disposal of plastic mulch. This section highlights recommendations for best practices in the utilization of plastic mulch and biodegradable alternatives.

#### 4.1 Best Practices in the Use of Plastic Mulch

Plastic mulch is a cost-effective option to increase crop yields. However, users of plastic mulch should be mindful of best practices to mitigate detrimental environmental, economic, and social effects of plastic mulch use. Such impacts can be mitigated through the use of the following best practices for plastic mulch use:

**Selection Phase**

- Whenever possible, select biodegradable alternatives, such as films made from plant starches, such as corn and wheat, paper, or organic mulches.
Choose a thicker mulch to limit the likelihood of tears or degradation of the plastic, which could result in buildup of mulch residue in soil or cause contamination of surrounding landscape and waterways.

- Thicknesses of 0.04 mm – 0.125 mm are recommended. (If plastic mulch thickness is measured in mils, 0.6 mils – 2.0 mils is recommended (Ngouajio, 2011)).

- If planning to use plastic mulch for double cropping, opt for a thicker mulch that will have a higher likelihood of withstanding two growing seasons.

**Application Phase**

- Site crop plantings in ways to minimize runoff, noting that mulch applied on convex fields will produce less runoff than plastic mulch on concave fields.
  
  - For example, if a farmer grows wheat and tomatoes, the tomatoes (which grow well under plastic mulching) should be planted on the convex field, while wheat (not amenable to mulching) should be placed on the concave field. Such an approach to siting would mitigate the amount of runoff attributable to plastic mulch use.

- Increased duration of use on the same land (e.g., >20 years) results in a larger cumulative level of mulch residue, decreasing soil quality and likely impacting crop yields more significantly than fields using plastic mulch for less time.

**Maintenance Phase**

- Routinely inspect plastic mulch for signs of wear and tear and address any signs of deterioration quickly to minimize plastic infiltration into the soil or contamination of surrounding areas and waterways.

- Allow for separation from mulched areas and livestock grazing areas to minimize likelihood of livestock ingesting plastic debris.

**Removal Phase**

- If the film is not specifically designed for multiple growing season use, be sure to remove the film promptly at the end of the growing season either mechanically or by hand. Do not wait for the start of the next season to remove. Removal at the end of the growing season reduces likelihood of further deterioration and mulch residue build up, as well as contamination of surrounding areas and waterways.
• Use caution if using machinery to remove plastic mulch to minimize potential for mulch residue buildup. Visually inspect and remove by-hand any remaining mulch pieces after mechanical removal.

**Disposal Phase**

• Whenever possible, opt for recycling or upcycling plastic mulch film at a local facility. Depending on the services available, an agricultural recycling program that includes onsite pickup may be available.

• If recycling is not an option, identify locations for formal incineration or other waste disposal opportunities. **Do not** burn plastic mulch residue at the farm site, bury, or otherwise illegally dispose of plastic mulch film.

4.2 Best Practices in the Application of Biodegradable Alternatives

Biodegradable alternatives will also increase crop yields and offer a low-maintenance solution after application. It is also important to be mindful of best practices of these biodegradable options as they can be more costly than traditional PE mulch or present other challenges in application and maintenance.

Recommendations for the consideration and utilization of biodegradable mulch alternatives include the following:

• When comparing cost of PE and BDM, calculate cost as accurately as possible by accounting for the amount of plastic to be removed, the labor hours and other resources needed to remove and dispose of PE mulch, including labor hours and/or machinery, transportation costs and landfill disposal fees. Calculate cost of BDM by price per roll and labor hours to remove drip tape and to till into the soil at the end of the season (Chen et al., 2018; Velandia et al., 2018).

• Understand the myriad co-benefits to environmental, economic, social and health factors that BDM can offer over PE mulch.

• Understand any implications associated with reducing season-end activities and allowing workers to leave the farm early. When overlapping production or harvest, workers can perform money-making activities or be sent home early (Velandia et al., 2018).

• Avoid excess tension when laying BDM (DuPont, 2016).

• Do not reuse BDM for a second season – till residue back into the soil to gain the added benefits of the organic materials.

5. **Practical Considerations in Selecting Alternative Approaches in Jordan**

To fully understand the context of the use of plastic mulch in Jordan, it is important to understand the financial, human, and technological resources that are required and commonly involved in agricultural production and waste management in Jordan.

The limitations associated with the recovery, collection and recycling of plastic mulch are discussed in Section 1.2 - Disposal Options. The aforementioned degradation and contamination issues directly correlated with observations and evidence from field reconnaissance conducted in 2018 and 2019. For these reasons, it is not considered feasible
from a practical or economic standpoint to collect, clean, transport, market, or utilize recovered plastic mulch in the manufacture of new product(s). It was reported during field visits with plastic film manufacturers in 2019 that several manufacturers attempted to utilize recycled plastic mulch but were unable to do so profitably (EcoPeace, 2019). These manufacturers indicated that in order for plastic film recycling to be feasible, collection, cleaning (two washing stations) and compaction would need to take place in the Jordan Valley prior to shipment to Amman (EcoPeace, 2019).

As stated in Section 4, the adoption of biodegradable alternatives to plastic mulch should be pursued if shown to perform and prove economically feasible. If suitable alternatives are not accessible or are cost-prohibitive, Section 4 highlights recommendations for best practices in the utilization of plastic mulch and biodegradable alternatives, which can serve to lessen the potential for negative impacts of improper use and disposal of plastic mulch.

Several farmers interviewed during a field visit in 2019 expressed interest in utilization of biodegradable plastic mulch. The farmers were not aware that this product existed and did not believe it was available locally. They were aware of the negative air, soil, water and health impacts of burning PE mulch and were receptive of a more environmentally friendly alternative. In addition, they recognized that the potentially higher cost of the BDM product may offset their costs to collect and burn the PE mulch. However, in order for biodegradable film alternatives to be considered for adoption, it was emphasized the following criteria must be met:

- BDMs should be proven to be safely biodegradable in terms of impacts on human health, crops and the environment;
- BDMs must be proven in local fields to perform the same as PE mulch; and
- BDMs should improve farming practice, increase crop yield, and increase profit if possible.

Two farmers stated that they would be willing to try BDM and compare it to PE mulch in a controlled demonstration. Additionally, in interviews with the Jordan Ministry of Agriculture, a research facility located in Deir Allah has the capacity to monitor a pilot project to demonstrate the application and performance of BDMs. It was further recommended by the Ministry that workshops be held at the beginning, mid-term, and end of the pilot to share information on the application, crop behavior, and actual degradability of the BDM product in local field conditions.

An important aspect of the feasibility of the utilization of BDMs is the availability and cost of the product in Jordan. It would be important to have a local manufacturer of BDM to avoid transport/import costs associated with a foreign product. In addition, local manufacturers and suppliers would not be receptive to a competing product for the PE mulches currently made and distributed in Jordan. During field visits with plastic film manufacturers in 2019, one entity expressed a willingness to produce BDM, but only if there was a contract in place to guarantee sale to an end user. Therefore, a further recommendation is to identify current manufacturers of PE mulches in Jordan to determine if the operators are willing and able to attempt making the BDM product. Biodegradable plastic resin product formulations are standard and could be experimented with at a local manufacturer. However, it would first be important to have an inventory of manufacturers and to discuss with them their willingness to attempt a biodegradable formulation.

Another potential option discussed was to collect the plastics and incinerate them as an alternative to recycling or land disposal. The Jordan Ministry of Environment indicated that there is a cement kiln in-country that might be approached to determine if plastic mulch could be utilized as an alternative fuel. The operators of the cement kiln could be approached to
determine if it would be feasible to introduce the plastic mulch in loose or baled form, and further, if the current operating permit/conditions would allow use of alternative fuel.

Any of the options in this Section will require participation and coordination with the Ministry of Local Administration, Ministry of Environment, Ministry of Agriculture, the municipality, and local farmers. The pilot could be facilitated by a non-governmental organization such as EcoPeace.

6. Environmental Justice Considerations

Though many Jordanians work in agriculture, 41-52% of agricultural labor in Jordan is done by migrant workers (Azzeh, 2017). Migrant workers sign contracts to work in Jordan for one year and are often sponsored by the farm itself (International Labor Organization, 2018). Female participation in the agriculture sector is higher than in other sectors of the economy.

Farmers have expressed frustration with the state of the agriculture sector in Jordan. Restricted access to migrant labor and severe water scarcities are among their main concerns. A study by the World Bank (2018), however, found opportunities for growth in the Jordanian agriculture sector. The report found that modernizing growing techniques and enhancing refrigeration would significantly increase the amount of agricultural exports. If modern growing techniques were to be adopted (e.g., water-saving methodologies) farms would be more productive and income may increase.

Some farmers have purchased equipment to boost productivity and have seen profits increase. As the government limits the number of permits provided to migrant workers, mechanization of farm work may create higher paying jobs for domestic laborers. In order for greater mechanization to be feasible, farmers must have access to lines of credit and loans to invest in machinery. Additionally, training on new machines must be available, although some farmers have expressed unwillingness to train their workforce because migrant workers rarely stay with the same employer for more than a year (Razzaz, 2017).
7. References


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