Creating Novel Soil Amendments Using Class A Biosolids

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Abstract

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By blending Class A biosolids with organic and inorganic materials, thirteen unique soil amendments were created with a goal of developing a product able to access a wider market than unblended Class A biosolids. A set of criteria were developed to assess if the developed blends could be successful general-purpose soil amendments used in a wide range of applications. These criteria included public acceptability of product odor and appearance, efficacy in improving plant growth, and ability to meet existing industry specifications for soil amendments. Several blends met all the criteria established for a successful soil amendment product.

The final properties of the blends depended on the initial properties and mixing ratios of the feedstocks and biosolids as well as biological and chemical processes blends underwent during a month long curing period. Certain properties were found to affect plant growth and odor. Blends with rates of CO_2 flux from microbial respiration higher than 8 mg CO_2-C g OM^{-1} day^{-1} or with a pH above 10 were both malodorous and performed poorly in plant growth trials. The five blends which performed best in the plant growth trials had C:N ratios within the range of 10:1-25:1, blends with electrical conductivity (EC_5) greater than 6 dS m^{-1} performed poorly in plant growth trials and there appeared to be an ideal range for NH_4^+ levels, above and below which plant growth was reduced.

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1. Introduction

The San Francisco Public Utilities Commission (SFPUC) is in the process of transitioning to Class A biosolids production at its Oceanside Treatment Plant. This represents an opportunity to pursue new options for the use of this material. Although Class A biosolids are effective as a substitute for synthetic fertilizer in agriculture, they are difficult to use for other applications such as a manufactured topsoil or an amendment for a home gardener. High moisture content, potential for odor and low C:N ratio all limit the potential for broader use. By blending Class A cake with organic and mineral feedstocks it is possible to create novel soil amendment products that resolve these issues.

The county where the majority of SFPUC biosolids are used in agriculture limits application of biosolids to the 6 month dry season that occurs between April 15th and October 15th in the San Francisco Bay Area (Solano County 2003). During the 6 month wet season, more than 90% of the SFPUC's biosolids are sent to landfills (Internal SFPUC records). To continue the practice of landfilling with class A biosolids is a failure to capitalize on the increased value of the material. Furthermore, sending biosolids to landfills is a source of methane, a waste of valuable soil nutrients and a lost opportunity to sequester carbon in soils (Peters and Rowley 2009; Tian et al. 2005; Tian et al. 2015; Brown et al. 2011)

The goal of this project was to create novel soil amendment products with class A biosolids that can access new markets which unblended biosolids cannot. These products were created by blending class A biosolids with a variety of other organic and mineral feedstocks. This approach has already been successful for the cities of Tacoma, WA and Alexandria, VA. The Class A biosolids soil amendments that this project created have the potential to be used in applications where compost is also used. Therefore, commonly held quality standards for compost were used to help guide what properties the biosolids soil amendments should have. In addition to meeting industry standards, the biosolids soil amendment products had to be publicly acceptable in terms of odor and appearance. Lastly, the product needed to work well in its intended role as a soil amendment by improving the growth of plants. Based on these three goals – meeting industry standards, acceptable odor and appearance, and ability to improve plant growth – a set of criteria were developed. Novel biosolids products were created using SFPUC biosolids and locally sourced feedstocks. These biosolids products were then evaluated to determine if they met the criteria for a successful soil amendment and to understand what factors were important in meeting these criteria.

2. Literature Review

Human waste has long been recognized as a valuable resource for the maintenance of soil fertility. Sewer systems in ancient Greece delivered human waste and storm water to outlying farmland for use as fertilizer as early as the 5th century BC (Semple 1931, Feo et al. 2014). The first written references to the use of human waste as a soil amendment appear by the 3rd century BC in Chinese texts (Yang 2006). Human waste continues to be recycled for agricultural and horticultural uses today, with the vast majority of wastes in the US converted at wastewater treatment plants into biosolids (US Census 2013).

Biosolids are the nutrient rich solids recovered from the wastewater treatment process. They are known to be effective for applications in agriculture (Ozores-hampton and Peach 2002; Barbarick et al. 2012; McFarland et al. 2010; Sharma et al. 2017), silviculture (Henry et al. 1994), horticulture (Hummel et al. 2010; Ticknor et al. 1985) and restoration (Brown et al. 2003; R. N. Brown and Gorres 2011). Biosolids can be used as is or they can be blended with other materials to create a product which is better suited for certain end uses than biosolids alone.

There are multiple ways that biosolids are blended with other materials to make a novel product. The resulting biosolids products can be organized into three categories: compost, non-composted soil amendments, and manufactured topsoil. Compost typically entails mixing biosolids with other organic materials and subjecting the resulting blend to the biological transformation of the composting process (California Code of Regulations 1989). Non-composted soil amendments are a mixture of biosolids with predominantly organic materials which do not undergo a composting process. An example of this type of product is TAGRO mix, a blend of sawdust, biosolids and sand produced by the city of Tacoma. These non-composted biosolids soil amendments are referred to as blended amendments. Manufactured topsoils mimic natural topsoils and are a mixture of inorganic material, often mineral soil, with biosolids and other materials added as sources of organic matter. Manufactured topsoils can also be created by mixing biosolids compost with inorganic mineral soil. The distinction between these three categories is not always clear. For example, a material that is created with equal parts biosolids, mineral soil, and sawdust could be seen as a manufactured topsoil, or a blended soil amendment. The purpose of organizing biosolids products into these three categories is to compare materials with similar compositions and end use goals. Therefore, materials in this literature review are categorized based on the predominant feedstock blended with biosolids and the intentions of the producers.

2.1 Manufactured topsoils

Whereas blended amendments and compost are used to amend existing soil, manufactured topsoils are used in places where existing soil is insufficient in depth or quality or when there is no existing soil whatsoever. Examples of this are mine reclamation or the construction of fields in athletic facilities. Naturally occurring topsoils can be taken from existing landscapes (Etten et. al 2012), however this strips these landscapes of organic matter rich soil. When manufactured topsoils incorporate biosolids as a source of organic matter, they can make use of inorganic mineral sediment which does not work well as a topsoil on its own. This could include low quality sub soils or sands from mining operations (Stokowski 1988; Carpenter and Fernandez 2000), dredgings (Sheehan et al. 2013; Sturgis et al. 2001), fly and bottom ash (Belyaeva and Haynes 2009; Brodie and Biermann 1996; Jarrett et al. 1994), foundry sand (De Koff et al. 2010), treated coal mine waste and steel slag (Firpo et al. 2015), and of course, topsoil or sand from a borrow pit (Ray et al. 2015; Persyn et al. 2004; Birt et al. 2007). Soil formation is an extremely slow process, the mean rate of soil formation in coastal Oregon and California for example, is estimated to be only .144 mm year^{-1} (Stockmann et. al 2014). Using global soil formation rates, it is estimated that 15 cm of soil removed for the purpose of topsoil mining takes approximately 1,875 years to replace (Brown et. al 2014). The practice of manufacturing topsoils leaves existing soils intact (or at least leaves larger areas untouched if topsoil is in fact used as an ingredient) and is preferable to stripping soils off of farmland or natural areas given the slow rate of soil formation.

General specifications for topsoil can include requirements for particle size, pH, organic matter content, C:N ratio, EC, and nutrient content. ASTM standard D5268, Topsoil Used for Landscaping Purposes, is relatively simple with a required organic matter content range of 2 to 20%, a pH range of 5 to 7, and requirements for particle size (ASTM 2013). The national British standard for topsoil, BS 3882:2015, has similar acceptable ranges for organic matter of 3 to 20% and a pH range of 5.5 to 8.5 for multipurpose topsoils (BSI 2015). Other than histosols, naturally occurring soils do not contain levels above 20% organic matter and agricultural soils generally contain from 1 to 6 % organic matter (Bowman and Petersen 2004). Therefore, it is most likely that soils stripped from existing fields do not have more than 6% organic matter. By manufacturing topsoils with biosolids however, it is possible to achieve higher levels of organic matter. Furthermore, by using biosolids as a source of organic matter, it is possible to create topsoils using mineral materials which are devoid of organic matter.

One of the earliest specifications for manufactured topsoil which used biosolids as a source of organic matter was the Texas Department of Transportation's criteria for Compost Manufactured Topsoil which is still used in the current specification (TxDOT 2014). The specification states that the manufactured topsoil must be 75% topsoil and 25% compost by volume. The compost used can be a Class A biosolids compost and must meet certain ranges for pH, EC, organic matter, CO_2 evolution, fecal coliform, particle size and heavy metals. The only requirements for the topsoil portion used in these blends is that it is free of contaminants and is within a pH range of 5.5 to 8.5. While the ratio between compost and topsoil is prescribed in the specifications and these ingredients must meet the above-mentioned criteria, the TxDOT specifications contain no specific requirements for the final manufactured topsoil product in terms of pH, particle size, or other criteria.

Various ratios between mineral soil and biosolids/biosolids compost can be used to create manufactured topsoils with different properties. For example, there are 6 different blend ratios used to by a single landscape supply company in Austin, Texas to make products targeted towards different end uses. These blends incorporate different ratios of sand, loam, decomposed granite, and compost. Certain blends use Dillo Dirt, the biosolids compost produced by the city of Austin (Austin Landscape Supplies 2017).

The process for creating topsoil blends is physical, not biological. Mineral material is screened to a certain size and is mixed with biosolids or biosolids compost. No curing is necessary when blending mineral soil with already stable biosolids or biosolids compost as little biological change occurs due to this mixing, unlike when mixing biosolids with other organic materials. When creating a manufactured topsoil by blending 80% biosolids compost with 20% topsoil, or 20% of a fly ash and sand mix, microbial biomass and microbial respiration either remained unchanged or decreased compared to the unblended compost (Belyaeva et al. 2012). In situations where the mineral component of a manufactured topsoil does not contribute greatly to the final pH, EC, or organic matter content of the product, the main considerations for the final properties of a manufactured topsoil are the ratio and quality of biosolids/biosolids compost added and the particle size of the topsoil.

A common use of manufactured topsoils is to replace topsoil which has been removed or degraded due to large construction projects. King County, Washington, specifies a manufactured topsoil for this purpose in landscaping and construction projects. The material is made of native topsoil blended with compost to increase the final organic matter content to 15 – 30%. The use of biosolids compost as a source of organic matter is actively encouraged in the specification (King County 2016).

One project which investigated using lime stabilized biosolids blended with screened mine overburden had issues with excessive alkalinity. It was only possible to grow alkaline resistant grass in the topsoil blend when it had a pH of 8-9.5. Curing the manufactured topsoil over 4 months was found to reduce pH from 12.8 to 7.8 however, further reduction in pH from 7.8 to 6.5 using sulfur was recommended (Stokowski 1988). Obtaining the proper pH range is critical for a successful soil amendment. This can be achieved by adding additional materials to topsoil mixtures. In Brazil, manufactured topsoils were created with treated coal mine waste, steel slag, and biosolids which were treated to the equivalent of Class A standards. Coal mine waste alone as well as 85% coal waste mixed with 15% biosolids had pH ranges below 4.5. However, mixtures of 80% coal waste, 12% biosolids, and 8% steel slag had a pH of 7. In this mixture where the presence of steel slag increased pH to acceptable levels and biosolids provided essential plant nutrients, sorghum growth was significantly better than a control topsoil, as well as topsoil blends without steel slag (Firpo et al. 2015).

Similar to the amelioration of excessive acidity or alkalinity, C:N ratios which are too low can be improved by adding additional materials to mixtures. Paper sludge, a product comparable to biosolids, was evaluated as an ingredient in mixtures with sand and flume grit to make manufactured topsoils.

When used for mine reclamation, paper sludge topsoils all greatly outperformed an imported topsoil in terms of grass growth and poplar tree diameter. This same study showed paper sludge mixed with sand at a 1:1 ratio had the highest yield of grass, which is unsurprising given it also had the highest concentration of NO_3^-. In poplar plantations however, this high NO_3^- concentration favored dense weed growth which contributed to lower height and drought stress in poplars. The mixes with higher ratios of paper sludge also had higher rates of initial nitrate leaching, however adding high carbon content flume grit to mixes raised C:N ratios in the topsoils and minimized nitrate leaching (Carpenter and Fernandez 2000). This study points to the benefits and challenges of working with an un composted digestate product like paper sludge or biosolids. Elevated levels of soluble nitrogen can improve plant growth, but they can also result in nutrient leaching and the invasion of weedy species, a phenomenon which has been widely reported (Seabloom 2015). But as the Carpenter study showed, increasing the C:N ratio of the final product by adding a high C:N ratio material can ameliorate these issues.

Certain mineral components may not be of a high enough quality to produce manufactured topsoils with. Dredged material from the New York, New Jersey Harbor area was mixed with varying ratios of biosolids, but germination and plant growth were poor for many of the treatments and was always significantly lower than in a fertile control. This was potentially the result of reduced sulfur compounds or salinity. In addition, the dredged harbor material had a dioxin Toxic Equivalency of 517 ppt TCDD and lead concentration of 617 ppm, which is above the EPA 503 pollutant concentration limits for metals although below the 503 pollutant ceiling limits. Adding biosolids to the dredgings dropped the dioxin TEQ to 182 ppt TCDD and the lead to 219 ppm. Nevertheless, the authors of the study recommended that this material only be used as cover for highly contaminated superfund sites, landfill cover, and mine reclamation due to levels of organic contaminants in the dredged material (Sturgis et al. 2001).

It is also important for the source of organic matter in manufactured topsoils to be a quality product. Excessively alkaline biosolids, as with Stokowski 1988, or immature compost, can mean a manufactured topsoil is better off with lower amounts of the organic component added. A study evaluating decontaminated river sediment mixed with compost found that biomass in grass was highest in a 75% sediment + 25% compost mix and lower in a 50% river sediment + 50% compost mix. Germination decreased with increasing rates of compost in the topsoil mixture, raising the question of the quality of the compost. No EC values were given for the compost although the reported Solvita maturity index indicated the compost was immature or “raw” compost (Smith-Sebasto et. al 2012). It is conceivable that with higher quality compost, biomass production would have been better at higher proportions of compost mixed with the river sediment and germination would not have suffered.

There are also targeted or specialized uses for manufactured soils. For example, manufactured soils are often used for storm water bioretention systems. Uses of manufactured topsoils which require high rates of infiltration require a larger particle size in the topsoil component. Specifications for manufactured topsoils designed for bioretention call for a high percentage of sand for this reason. The Wisconsin Department of Natural Resources standards for bioretention media call for 70 to 85% sand and 15 to 30% compost by volume (WDNR 2014). Certain specifications for bioretention soil mixes include the use of biosolids compost, such as DC Water’s specification made with 10-20% sandy loam or loamy sand topsoil, 20-30% biosolids compost, and 50-60% sand (Ray et al. 2015). The hydraulic conductivity of a bioretention mix is inversely correlated with the percentage of mineral particles smaller than 75 ųm and it is recommended that sands or topsoils with more than 5 percent by weight passing through a 75 ųm screen not be used in bioretention mixes (Hinman 2009). The amount of compost used in a bioretention mix can also impact hydraulic conductivity. A study which evaluated the impact of adding compost to sand at ratios of 0%, 10%, 30%, and 50% found that hydraulic conductivity decreased with each increase in the percentage of compost. However, the purpose of a bioretention system is to remove pollutants, and the study also found that retention of cadmium, copper and zinc increased with each increasing ratios of compost (Paus et al. 2014) Higher ratios of compost in bioretention systems can also lead to increased leaching of nitrogen and phosphorus (Hatt et. al 2009). Designers of bioretention systems must decide whether infiltration, pollutant retention, or concerns about nutrient leaching are the main priorities for their system and create a manufactured topsoil recipe for bioretention systems accordingly.

Erosion control is another potential use for these topsoil products. While manufactured topsoils have been shown to excel in bioretention systems and in places where natural topsoil has been removed, they do not perform as well at erosion control. Erosion control compost made of 67% composted dairy manure and 33% wood chips was more effective at reducing runoff and erosion than manufactured topsoils. However, these manufactured topsoils were more effective than imported topsoil alone. Manufactured topsoil made with 25% composted dairy manure and 75% sand experienced less runoff and erosion than sandy topsoil alone. The same was true for a manufactured topsoil made of 25% compost and 75% loam compared to a loamy topsoil (Hansen et al. 2009). Similar findings were reported in a study where a 5 cm application of erosion control compost (50% composted dairy manure and 50% wood chips) outperformed an equal application rate of manufactured topsoil and imported topsoil (Birt et. al 2007). In a study comparing a biosolids compost and a yard waste compost to imported topsoil for erosion control, yard waste and biosolids compost outperformed the imported topsoil. Interestingly, there was significantly less runoff and erosion in the yard waste compost compared to the biosolids compost. This was attributed to larger particle size of the yard waste compost which translated to a faster infiltration rate (Persyn et al. 2004). The above-mentioned study by Hansen in 2009 also found that particle size was an important consideration for erosion control as sand based topsoil outperformed loam based topsoil and compost manufactured topsoil with sand outperformed a similar product made with loam. The larger particle size of sand is more resistant to erosion than the finer silt sized particles in a loam.

A study comparing runoff from manufactured topsoil made of biosolids compost, chicken manure compost, dairy manure compost, and feedlot manure, found the manufactured topsoil with biosolids compost had the lowest rate of runoff. Additionally, the composted biosolids was the only compost product of the four composts that met all the specifications laid out by TxDOT for compost quality. The biosolids compost had much higher organic matter which is one possible reason for its superior performance. As is often found with biosolids, the concentration of potassium was relatively low compared to the other composts (Kirchhoff et al. 2004).

In certain situations, the addition of biosolids can decrease porosity and pH below ideal levels. The addition of biosolids to green waste alone and to green waste and topsoil was found to increase bulk density as the biosolids greatly reduced the amount of macropores and mesopores in the material although microporosity did increase. The addition of topsoil to the biosolids + yard waste mixtures was beneficial in that it increased mesoporosity and water holding capacity. Although both the biosolids and greenwaste had a pH of 7.2, when the two materials were mixed 3:1, green waste:biosolids, pH dropped to 5.6, and at a 1:1 ratio pH dropped to 5.3. This drop in pH was attributed to nitrification (Belyaeva et. al 2012) and shows that even in a product which does not undergo intentional composting, biological activity can change the final properties.

There is a history of commercially produced manufactured topsoils that were made using biosolids. For example, topsoils made with the biosolids compost All-Gro (produced by Synagro at various locations), were used in high profile location such as Central Park in New York (Cole 1997) and Ecoloam (produced in Pennsylvania by Horsehead Industries), a mixture of biosolids and fly ash (Jarrett et al. 1994) which was most notably used to reclaim 1070 acres of a superfund site in Pennsylvania. N-

Viro Soil is produced in numerous locations in Canada and the US using a process which mixes biosolids with high alkalinity material such as cement kiln dust at high heat to produce a pathogen free product with relatively low moisture content (Logan and Harrisson 1995, City of Galion 2017). Early reports on N-Viro Soil describe a pH range of 11-12, but that alkalinity due to $Ca(OH)_2$ was rapidly neutralized in soil. Even at application rates of 500 metric tons/ha of N-Viro soil, soil pH only rose from 7.35 to 7.4 compared to an increase to 7.7 when using an equivalent amount of $CaCO_3$ (Burnham and Logan 1993). Other studies using N-Viro Soil have reported a pH of 9.2 (Wang et al. 2003) and 7.9 (Yao et al. 2007). Given that much of Eastern Canada is acidic soil which requires liming for most agricultural operations (Blatt et al. 2008), the high pH of N-Viro Soil is an advantage there where much of it is produced. Across the United States, both large companies such as Casella Organics, listed on NASDAQ as CWST, and smaller operations such as Austin Landscape Supplies, are engaged in the production of manufactured topsoils using biosolids as a source of organic matter.

2.2 Blended amendments

While manufactured topsoils entail blending biosolids with predominantly mineral material to act more as a replacement for topsoil, soil amendments are meant to improve existing soils and are primarily organic. A report by Beecher (2007) estimated 7.18 million dry tons of biosolids were produced annually in the US and approximately 55%, or 3.95 million dry tons were used as soil amendments. As only 471,000 dry tons of biosolids were composted in 2007 (Beecher 2007), and non-composted blended biosolids soil amendments comprise a relatively small market share, it can be safely assumed that the majority of biosolids used as soil amendments are not blended with other materials before application. The majority of these materials are used as an alternative to synthetic fertilizers to meet the N needs of agronomic crops. For a broader range of end uses including landscaping and home gardening it would likely be necessary to blend the biosolids with other materials. The purpose of blending biosolids with other organic materials is to alter some aspect of the biosolids which was not desirable for the end user. This could be related to the efficacy of the product in promoting plant growth. For example C:N ratio, pH or EC might not be ideal in the biosolids for certain end uses, but by adding another material such as sawdust, parameters can be brought closer to ideal ranges. Certain undesirable aspects of biosolids might have nothing to do with their actual efficacy as a product but rather their ease of use and the experience of the user. Excessively high moisture content might make transportation and application difficult. Excessive odors could limit the use of biosolids near population centers or in non-agricultural settings. Composting, heat dried pellets, and blending biosolids with other organic materials are ways to improve the user experience. Composting and heat dried pellets can create Class A material, although simply blending biosolids with other organic materials without composting cannot.

Biosolids with under 2,000,000 MPN fecal coliform per dry gram are considered Class B, while biosolids with under 1,000 MPN fecal coliform or 3 Salmonella per dry gram are considered Class A. When there is a high potential for public exposure, access to land is restricted for one year after Class B biosolids application. This restriction only lasts 30 days where potential for public exposure is low (EPA 1993). Class A biosolids are not subject to federal restrictions on use. Although an estimated 1,532,000 dry tons of biosolids were treated to Class A standards, only 613,000 dry tons were known to be beneficially reused in 2007. Of this, an estimated 471,000 dry tons was composted, although it is possible some portion of this tonnage includes the feedstock used to make the compost (Beecher 2007). Much of the remaining Class A material is in the form of heat dried pellets, such as the city of Milwaukee's Milorganite, with an annual production of approximately 42,000 dry tons per year (Leblanc 2009), or SoundGro from Pierce County, WA with an annual production of 2,300 dry tons per year (Pierce County 2010). An annual report from Synagro says 310,000 dry tons of heat dried pellets were produced in 2006, of which Synagro managed roughly a third. (Synagro 2006).

Relatively little Class A product is commercially marketed in the form of a non-composted blended amendment. The "household name" Class A biosolids products which are distributed to the general public include brands like All-Gro, Granulite, Milorganite, Dillo Dirt, OceanGro, PocoNite, Bay State Fertilizer, GroCo, ORGRO, EKO Compost, and MetroGro. All of these products are either composted biosolids or heat- dried pellets. An exception to this trend is the city of Tacoma's TAGRO line of products. TAGRO creates three products using Class A biosolids. A general purpose soil amendment called TAGRO Mix is made from 40% biosolids, 40% sawdust, and 20% sand by volume. A potting soil blend, TAGRO Potting Soil, is made from 8% biosolids, 61% aged bark, and 31% sawdust by volume. These percentages for TAGRO Potting Soil are derived from a blending recipe of 3 parts of a 2:1 bark:sawdust mixture with ¾ parts biosolids. TAGRO topsoil is made from 24% biosolids, 24% sawdust, 12% sand and 40% aged bark by volume. All of the biosolids produced by Tacoma, a total of 3,064 dry tons per year, are locally sold and distributed as soil amendments (Personal communication Dan Thompson, 2/15/2018). Alexandria Renew in Alexandria, VA uses a portion of its Class A biosolids, approximately 5,000 wet tons a year, to make a non-composted blended biosolids soil amendment called George's Old Town Blend. The product is produced and marketed by Culpepper Recycling. Biosolids and yard waste fines are mixed together in windrows and allowed to cure. Piles are monitored and turned to ensure temperatures do not cross the threshold into temperatures which would entail a composting permit. (Personal communication Allen Guilliams 10/27/17). DC Water in Washington D.C., is currently attempting to market Class A biosolids cake to the general public without composting, blending, or pelletization. The product is the result of the CAMBI thermal hydrolysis process and is marketed under the brand Bloom. Annual production is approximately 50,000 dry tons per year (Personal communication William Brower 1/2/2018).

A study by Alvarez-Campos and Evanylo (2016) examined the nutrient dynamics of several of these blended amendments and other Class A biosolids products which are distributed to the public. The study compared Livingston's Blend compost from Spotsylvania, PA, OceanGro heat dried pellets from Ocean County, NJ, TAGRO Mix and TAGRO Potting Soil, George's Old Town Blend, and DC Water's Bloom blended with mulch and also blended with sawdust and sand. Properties of these products are shown in Table 1 below. Although the pH of TAGRO Mix was measured as 9, brochures for TAGRO Mix list a pH of 7.9.

Table 1. Properties of Selected Class A biosolids Products. Modified from Alvarez-Campos and Evanylo 2016. Biosolids content for Bloom treatments from Alvarez-Campos and Evanylo. 2016 Biosolids content for George's Old Town Blend from personal communication with Allen Guilliams 10/27/17. Biosolids content for Tagro products from Tagro. All other information from Alvarez-Campos and Evanylo 2016.

Biosolids Product	Bloom + Mulch	Bloom + Sawdust + Sand	TAGRO Potting	TAGRO Mix	George's Old Town Blend	OceanGro Pellets	Livingston's Blend Compost
pH	6.52	6.07	7.77	9	7.44	7.3	7.98
TS (%)	67	70	67	63	59	95	61
TKN (mg/kg)	26900	22300	10000	9800	17200	49100	23100
NH_4^+ - N (mg/kg)	3600	2800	2600	3100	6200	5700	7800
C:N	14.4	11.1	26.5	18.4	18.5	7.8	15.8
Biosolids content (volume)	43%	43%	8%	40%	50%-33%	100%	-

The Class A products were used to grow soybeans at an application rate of 75 mg plant available nitrogen/kg soil and compared with an inorganic fertilizer application of this same rate. Biomass of soybeans in every biosolids product was significantly greater than the fertilizer control. When soybeans were grown in 100% of the Bloom and TAGRO products however, growth decreased. Soybeans grown in 100% Bloom + Mulch, Bloom + Sawdust + Sand and TAGRO Mix all performed similar to the fertilizer control. Plants grown in 100% Tagro Potting Soil however performed similar to biosolids products applied at the rate of 75 mg PAN/kg soil. Water was not allowed to drain freely from the pots, potentially creating artifacts in the observed results. The electrical conductivity of the Bloom products was measured at above 6 dS/m while both TAGRO products were above 3 dS/m. These EC levels could explain why soybeans grew poorly when the biosolids products comprised 100% of the growing medium. Interestingly however, soybeans grown in TAGRO Potting Soil, which had a slightly higher EC than TAGRO Mix, did not experience the same reduction in biomass. Organic N was approximately 40%

in heat dried pellets, 20% - 7% in blended products, and 15% in the compost (Alvarez-Campos et al. 2016). This could possibly be due to the fact that, until they are watered, there is little biological activity in heat- dried pellets that would allow for mineralization of N in organic matter.

While EC levels of a blended amendment play an important role in determining plant health, pH and N content are also critical parameters. Higher nitrogen content in biosolids of blended amendments along with the addition of material to adjust the pH of acidic soils has been shown to be important for restoration of contaminated mine soils. Biosolids blends with 4.4-5.3% N outperformed biosolids blends with 2.8% N at various application rates when restoring a mine site contaminated with Zn, Pb and Cd. It was found that the difference in biomass yields between the treatments was possibly due to plants suffering P deficiency in the high Zn and Pb soil and not solely a lack of N in the low N biosolids blends. The addition to the blends of wood ash from a biomass power plant increased pH which played a critical role in improving biomass yield. Different ratios of high N biosolids, ash, and log yard waste however, did not appear to be a significant factor affecting biomass yield (Brown et al. 2003).

While adding high pH materials to a blended amendment can help precipitate inorganic contaminants in soil, the addition of materials with readily decomposable C and reduced sulfur compounds have been shown to help limit solubility of inorganic contaminants within biosolids themselves. Biosolids + sawdust blends (2:1 ratio by weight) were shown to yield lower biomass than biosolids alone, but the concentration of Cd in grass grown using the sawdust blend was roughly half that of grass grown using only biosolids. (The total mass of biosolids was the same in both treatments.) The study authors thought decomposition of the sawdust in the blend likely increased sorption of Zn and Cd, however this does not explain why other plant uptake of other divalent cations was unaffected (Esperschütz et al. 2016). The addition of lignite to biosolids at a 1:1 ratio was found to reduce Cd uptake in plants by 30% without affecting biomass yield, most likely due to the affinity of Cd to reduced sulfur compounds in the lignite (Simmler et al. 2013).

Nitrogen dynamics of organic amendments can negatively impact groundwater through NO_3^- leaching as well as disrupt native plant ecology by encouraging invasive species(Sullivan et al. 2006; Jurado-Guerra et al. 2013). One advantage of creating blended biosolids amendments is the possibility to avoid these problems by adding materials which increase the final C:N ratio of the blend. Biochar, with its high C:N ratio can dramatically alter N dynamics. Addition of biosolids significantly increased pasture biomass yields over non-amended controls, but amendment with a blend of 0.9:2, biosolids : biochar, returned biomass yields down to the levels of the non-amended controls. What is interesting about this however, is that although the yields of biochar+biosolids and control soils were statistically similar, NO_3^- leaching was less in the biochar+biosolids amended soils than even the non-amended control soils. Heavier applications of biosolids at a ratio of 1.8:2 biosolids:biochar resulted in significantly more biomass yield than controls although NO_3^- leaching was statistically similar. While the mechanism for reduced leaching was not clear, the study authors doubted it was due to sorption as the biochar had low CEC to bind NH_4^+, but rather that the biochar inhibited N mineralization (Knowles et al. 2011). This study points to the advantages and challenges of blending organic materials with biosolids. It is possible to push parameters to either side of their ideal levels by blending too much or too little of a certain feedstock. In this instance, high proportions of biochar limited growth, while lower proportions improved growth. There are also tradeoffs when creating blended amendments and the end goals of the user dictate where the compromise will be. In the case of the Knowles study, there is the option of increased biomass yield and similar NO_3^- leaching compared to control soils, unimproved biomass yield and decreased leaching compared to control soils, or vastly increased biomass yield along with NO_3^- leaching significantly greater than the control soils.

In agreement with Knowles' findings, a study using biochar + biosolids as well as sawdust + biosolids blends found that NO_3^- was not chemically sorbed by the biochar or sawdust additions. However, NH_4^+ was chemically sorbed by biochar additions, and dry sawdust effectively eliminated NH_4^+ leaching and reduced NO_3^- leaching by over 40%. It was posited that the sawdust not only increased N immobilization, but also physically trapped NO_3^- leachate by increasing the water holding capacity of the blends (Paramashivam et al. 2016). Daniels et al. (2001), also found that sawdust + biosolids blends reduced NO_3^- leaching. Biosolids + lignite blends, similar to the biosolids + biochar blends mentioned previously, reduced NH_4^+ leaching in the Daniels study, but lignite had no effect on NO_3^- leaching and decreased plant growth compared to biosolids alone.

In addition to the use of blended amendments for application to soils, these mixtures of biosolids and organic materials can be used as a growing media in nurseries. Peat mixtures with fertilizer applied through fertigation are the industry standard. Hummel et al. (2010) investigated the use of TAGRO, GroCo (a sawdust and biosolids compost), and dairy manure products for use as a potting soil to grow Chrysanthemums and found that TAGRO based products yielded similar dry biomass as a peat control when all treatments were fertilized with additional inorganic N every other day. The GroCo based products did not perform as well due to lower water holding capacity although the addition of fir bark to GroCo increased the proportion of particles less than 42 mm which improved water holding capacity. Dairy manure based products had excessively high EC_5 levels and had to be leached prior to use. At lower N application rates, TAGRO based products outperformed the peat based control in terms of biomass, appearance, and flower number. Given the labor and accuracy required to apply inorganic N fertilizer every other day and the fact that TAGRO based products appeared to supply a substantial amount of their own N, using a TAGRO based potting soil appears superior to a peat + inorganic N combination in a nursery setting. In a separate study that looked at peppers and marigolds grown in different biosolids based potting soils, composted biosolids + bark, TAGRO potting, and a control peat mix all yielded comparable biomass. In comparison, GroCo, with its high C:N ratio of 29:1 performed poorly (Hummel et al. 2014). The potential immobilization of N with GroCo would be a serious problem as levels of inorganic N in compost used as potting soil have been shown to have a significant correlation with plant growth (Clark and Cavigelli 2013). Increases in available N in potting soils must be balanced against other considerations though. Additions of high N sources such as spent mushroom compost to yard waste compost used as a potting soil improved growth of rye grass, although increasing levels of mushroom compost could also increase EC which could eventually cause a decrease in growth response (Benito et al. 2005). As with parameters in other blended biosolids products, there are ideal levels when blends are used as potting soils. While a feedstock might help the blend achieve those levels at one mixing ratio, this same feedstock can push the levels below or above ideal ranges at different mixing ratios. For example, doubling the amount of composted biosolids mixed with bark, peat moss or sawdust to create a potting soil increases plant growth along with pH, EC, and pore space (Ticknor et al. 1985). While potting soils made of 50% biosolids by volume worked better than rates of 25% biosolids in this study, even higher rates would potentially cause problems due to high EC.

2.3 Biosolids compost

The primary distinction between a blended soil amendment and compost is that the compost has gone through a regulated time and temperature process to destroy pathogens that also stabilize the final product. During composting, microbial activity is managed to encourage decomposition/stabilization and high temperatures. Even without such management, decomposition/stabilization occurs over time in a material that is a mixture of biosolids and other organic materials. When blended soil amendments are created with similar feedstocks used in the creation of biosolids compost, the material experiences a period of elevated temperature due to microbial activity. Biosolids composting undergoes a process which optimizes conditions with the goal of intentionally raising the temperature above 55 C to meet pathogen reduction requirements. While regulations vary by state, in California, any organic waste management process where a mixture of organic material experiences temperatures above 50 C requires a composting permit (California Code of Regulations 1989. A more thorough definition of compost is that it should only refer to a material which was intentionally managed as a compost and met all PFRP time and temperature requirements. However, given that blended soil amendments and compost can undergo similar microbial decomposition, that blended soil amendments and compost seek to affect similar improvements in soil health and plant growth, it makes sense to examine research on biosolids compost when investigating the use of blended biosolids soil amendments.

Biosolids composting is a common method employed to bring biosolids to Class A standards. Biosolids composted in windrows are deemed a Class A material when the material surpasses 55 C for at least 15 days with the windrow turned 5 times during this period. When using aerated static pile or in-vessel composting systems, material which surpasses 55 C for at least 3 days is deemed a Class A material (EPA 2002).

In 1999, the US EPA estimated that 12% of biosolids were treated to Class A standards. This includes composting as well as other methods (EPA 1999). A National survey conducted in 2007 estimated that 23% of biosolids produced were Class A. At least 471,000 dry tons of biosolids were composted to Class A standards, representing 6.5% of total biosolids production (Beecher 2007). In 2010 the quantity of biosolids composted was estimated slightly higher at 562,000 dry tons a year, representing 7.8% of national biosolids production. A survey connected with this report counted 258 biosolids compositing facilities in the US (Beecher and Goldstein 2010). A later survey in 2014 counted 238 compost facilities processing biosolids, accounting for 5% of all composting facilities in the US (Platt et al. 2014).

Biosolids compost can be created by mixing biosolids with carbonaceous materials such as yard trimmings or wood chips (Pill and Goldberger 2009), sawdust (Zasoski et. al 1983), bark, processed wood pallets, agricultural waste such as corn stalks, (Doublet et al. 2011), rice straw (Martínez et. al 2009, Roca-perez et al. 2004), and sugarcane stalks (Jayasinghe et al. 2010). Biosolids can also be composted without the use of additional feedstocks, although this is much less common.

The composting process entails the decomposition of organic matter. Organic matter in the context of composting can be categorized into different pools based on solubility: organic matter soluble in hot water, organic matter soluble in neutral detergent, and hemicellulose, cellulose, and lignin like materials (Van Soest 1963, Van Soest and Wine 1967). Organic matter soluble in neutral detergent can further be divided into material with rapid degradability and material with slow degradability. Organic matter soluble in neutral detergent or water which is readily degradable is rapidly consumed by microbial biomass while hemicellulose and cellulose like compounds are consumed at a much slower rate. As dead microbial biomass accumulates, the pool of organic matter soluble in neutral detergent with slow degradability increases (Zhang et al. 2012). In this manner a more stable material is created through the decomposition of organic matter.

2.4 Market Potential

Markets for biosolids products include agriculture, commercial and residential landscaping, nursery production, mine reclamation, community gardens, topsoil production and roadside erosion control. The size of these markets can be estimated by looking at the amount of product (largely non biosolids based) currently used to supply market needs. Spent foundry sand used for horticultural purposes totals 220,949 tons (EPA 2014b), while the American Foundry Society refers to USDA estimates that more than 50 million cubic yards of sand are used for horticultural purposes (AFS 2017). Considering uses such as potting soils where sand makes up as little 10% by volume (Robbins and Evans

2011) or manufactured topsoils where they can make up as much as 50%, this could mean a market for finished horticultural soil amendment products between 100 and 500 million cubic yards. In 1994, North Carolina used 2 million cubic yards of potting and landscaping soils (Franciosi et al. 1998). Assuming a similar per capita use of these products across the entire US, this equates to a current national market of 90 million cubic yards of potting and landscaping soils. In 2014, the US consumed 1,521,000 US tons of peat with a projected consumption of 1,620,000 US tons for 2015. Horticultural uses represented 91% of this peat consumption (Apodaca 2016). In 2001, 118,580,000 cubic yards of bark were used for horticultural purposes such as potting soils and soil amendments (Lu et al. 2006).

The potential demand for compost in 1992 was estimated at 1040 million cubic yards (Slivka et al. 1992) although it is important to recognize that this estimate is 26 years old and was made before the potential for urban markets for these products was fully realized. The market segmentation of this demand is described in Table 2 and the majority of this potential demand is in agriculture. Assuming a reduction in volume of 42% during composting (CARB 2016), California produced approximately 3.4 million wet tons (roughly 6.8 million cubic yards) of compost in 2016 (CalRecycle 2016, CalRecycle 2016b). It could be argued that the compost market in California is more mature than in other parts of the country. If California's compost production is extrapolated across the entire US on a per capita basis, this equates to a market of 28 million wet tons of compost (approximately 56 million cubic yards). According to the US EPA, 23 million tons of yard and food waste were recovered for composting nationally (EPA 2014a). Using a reduction of 42% during composting, this represents 13.35 million wet tons of compost created nationally (26.7 million cubic yards). Based on the current market for compost in California, there could be demand for an additional 36.1 million cubic yards of compost nationally, given proper market development. Although compost, peat and bark are not the same product as biosolids, biosolids soil amendments can be produced which perform similar roles as these materials.

The largest single purchaser of compost in the US is the Texas Department of Transportation, which has used more than 4.2 million cubic yards of compost for roadside erosion control from 2001 to 2015 (Internal TxDOT data). Purchasing data for TxDOT, Caltrans (California) and WSDOT (Washington), shows that the three agencies combined used an average 473,000 cubic yards of compost annually from 2010 to 2015 (Internal TxDOT, Caltrans, WSDOT data). Extrapolating this nationally on a per capita basis, state DOT compost use could consume approximately 2,054,000 cubic yards.

In 2011, 12,840,000 tons of inorganic N were applied as fertilizer to US cropland (USDA 2013). Assuming an average N concentration of 5% by dry weight in biosolids, it would take 256,840,000 dry tons of biosolids to replace domestic inorganic N use. Slivka et al. 1992 corroborates the magnitude of this quantity with their estimate of a potential agricultural demand of 447,500,000 wet tons of compost. The US only produces 7,180,000 dry tons of biosolids (Beecher 2007), therefore replacing just a small portion of inorganic fertilizer use with biosolids would easily absorb all biosolids produced in the US. This raises important questions about our reliance on inorganic fertilizer and the lack of alternatives to replace the quantity currently used should its supply be threatened. Sequestration of carbon from compost (Ryals and Silver 2013) and biosolids use (Tian et al. 2005; Tian et al. 2015; S. Brown et al. 2011) are a promising tool for reducing atmospheric CO_2 concentrations which could represent an additional demand for these products. In addition, recycling nutrients rather than using energy to create synthetic fertilizers results in significant CO_2 reduction. It has been estimated that between 3-4 kg CO_2 are released for each kg N that is fixed for fertilizer (Brown et al. 2010).

Table 2. Estimates of potential markets for soil amendment products. Estimates are not exclusive of each other. Slivka et al. 1992 is an estimate of potential demand, not actual use. The values for State DOT use, Compost use, and Potting and landscape soil use actual values from certain geographic locations extrapolated to the entire US. Peat use and Bark use represent estimates of actual use across the US.

Market	**Potential annual US demand for soil amendment (million cubic yards)**	**Source**
Landscaping	2.0	Slivka et al. 1992
Topsoil	3.7	Slivka et al. 1992
Bagged products	8.0	Slivka et al. 1992
Landfill final cover	0.6	Slivka et al. 1992
Mine reclamation	0.2	Slivka et al. 1992
Nurseries	4.9	Slivka et al. 1992
Silviculture	104	Slivka et al. 1992
Agriculture	895	Slivka et al. 1992
State DOT use	2.1	Internal DOT data from 2010 to 2015 extrapolated to entire US
Compost use	56	CalRecycle 2016, California production extrapolated to entire US
Potting and landscape soil	90	Franciosi et al. 1998, North Carolina use extrapolated to entire US
Peat use	6.9	Apodaca 2016 converted to cubic yards assuming bulk density of 0.25 g/cm^3 for peat
Bark use	118	Lu et al. 2006

It is clear from the disparity between compost use in California and the rest of the country that there is room for greatly expanded use of class A biosolids soil amendment products and compost. The caveat to this is whether local ordinances and public misconception of biosolids products will limit their use. Lack of understanding can often lead to fear. Education and outreach are a key component to any expanded use of biosolids products. Additionally, biosolids on their own are often unsuitable for compost or potting soil markets. In order to enter these markets, biosolids products must be formulated to meet the quality parameters end users require in their soil amendment products.

2.5 Quality parameters for soil amendments

While it is clear that there are many potential end uses for biosolids based soil products, not all products are suitable for each use. There are many measurements that can be used to evaluate whether a soil amendment or soil blend is effective for a targeted end use. Phytotoxicity, electrical conductivity (EC), pH, CO_2 flux, and the percent organic matter are basic indicators of soil amendment quality which are found in most specifications for compost and are required analytes for the US Composting Council's Seal of Testing Assurance (STA) program (Caltrans 2015, AASHTO 2010, USCC 2017). Although not found in many specifications, the C:N ratio of a soil amendment is another important indicator of soil amendment quality.

Depending on the specific end use of a soil amendment, the ideal parameters can vary. In examples from previously mentioned studies, a higher C:N ratio soil amendment is preferable when restoring native habitat in order to reduce the occurrence of invasive weeds, and coarser grained materials with higher amounts of organic matter are more effective for erosion control. Although there are a range of different goals for soil amendments in their various end uses, virtually all end uses require a product that improves plant growth. Therefore, general quality parameters for soil amendments can be determined based on select parameters that have been associated with plant growth responses. In many cases, these variables have ranges which have been shown to increase yield and ranges which are shown to be phytotoxic. These measures typically include standard agronomic tests (EC and pH and available nutrients). In addition, they frequently include measures of stability. Organic matter based soil amendments, by their very nature are biologically active. This is especially true with soil amendments produced with biosolids, which are the dewatered microbial biomass that has actively digested wastewater influent. Certain indicators of soil amendment quality are attempts to directly measure this biological activity: CO_2 respiration or O_2 uptake(Wichuk and Mccartney 2010; Herrera et al. 2009), nitrogen transformations (USCC 2002; Brewer and Sullivan 2003), dissolved organic carbon (DOC) concentration(Zmora-Nahum et al. 2005; Wu et al. 2000), and volatile organic acid production (VOA, also referred to as volatile fatty acids or VFA) (Wichuk and Mccartney 2010; Zubillaga and Lavado 2006;

Brinton and Tränkner 1999). Biological activity also modifies EC, pH, C:N ratio, and percent organic matter.

For some variables the phytotoxic threshold is well defined. Electrical conductivity is an example of this. Measures of EC in this document note the measurement dilution in the subscript if it is available in cited articles. As many crops are grown in soils with elevated EC, tolerance to elevated salts is well understood for numerous plant species. The phytotoxic threshold for different measurements varies between plant species. For example artichokes (*Cynara Scolymus*) have a threshold as high as 4.9 dS/m EC_e before decrease in yield occurs, whereas carrots (*Daucus carota*) experience yield decreases beginning at an EC_e of 1.0 dS/m (Morales and Urrestarazu 2013). In biosolids amended semi-arid soils, yield of prairie switchgrass (*Panicum virgatum*) was found to increase linearly with soil EC_e up to 0.4 dS/m at which point yields started to decline when EC_e increased further. If irrigation is more frequent and evaporative stresses are lower, this threshold could be higher (Rodgers and Anderson 1995). Epstein (1997) suggests that EC levels in excess of 5 dS/m may lead to phytotoxicity. A general standard is that soil amendments should not raise the EC_e of soil above 2.5 dS/m and when salinity is comprised of soluble nutrients as opposed to sodium, an EC_e of up to 4 dS/m can be acceptable for amendments which are incorporated into soils. (Hartin and Crohn 2007). There is distinction between the EC performance thresholds for growth versus seedling germination, an important consideration for potting soils. Elevated EC has been a concern for composts produced from a range of feedstocks (Bustamante et al. 2008; Sánchez-Monedero et al. 2004; Ribeiro et al. 2009; Zubillaga and Lavado 2006; Ribeiro et al. 2000)

One examination of biosolids compost found EC was the most important factor in determining germination success, while organic acids, phenolic compounds and ammonia were not found to affect germination in this particular compost (Zubillaga and Lavado 2006). Germination success in this study could not be explained solely by EC however and there could be negative synergistic affects between pH, concentration of DOC and phytotoxic organic compounds. Studies of potting soil using compost also point to the importance of EC in determining phytotoxicity. Using more than 30% municipal compost in potting soil mixes decreased plant growth due to EC above 10 dS/m and high pH which affected nutrient availability (Herrera et al. 2009). Several other studies have also found that when using compost with a high EC, the ideal compost content in potting media is 30%. This was the case when using composts of EC_e of 13 and 8 dS/m (Sánchez-Monedero et al. 2004) compost of EC_2 8.3 dS/m (Kahn et al. 2005), compost of EC 3.43 dS/m (Spiers and Fietje 2008), and mushroom waste compost (Medina et al. 2009). A study of composted biosolids mixed with peat found that plant yield peaked at 30% biosolids compost + peat by volume and decreased with increasing proportions of biosolids compost, most likely due to increasing EC (Jayasinghe et al. 2010). Pill and Goldberger (2009) also found that greater than 30% by volume of biosolids compost decreased plant yield even though EC of the compost was only 1.56 at planting and 0.28 after 6 weeks, suggesting that other variables were possibly at play. When the EC of compost is lower, higher ratios of compost in potting soils are more effective. A study comparing growth of water spinach (*Ipomoea aquatica*) in mixtures of EC 0.22 dS/m compost with coconut coir as well as coconut coir and inorganic fertilizer showed highest biomass yields in 100% compost and 90% compost + 10% coconut coir (Jayasinghe 2014). Potting media created with EC 0.56 dS/m compost + peat also had higher yields when proportions of compost made up 70-90% of the blend (Benito et al. 2005). Therefore, the proportion of compost in a potting soil is not as important as the EC of the compost in predicting phytotoxicity. Yield response to compost in growth media also depends on plant species. Tomatoes (*Solanum lycopersicum*) , cucumber (*Cucumis sativus*), and gerbera daisy (Gerbera jamesonii) yielded higher in 50% biosolids compost + 50% peat while strawberries (*Fragaria vesca*) yielded higher in 100% peat when compost had an EC 1.8 dS/m (Pinamonti et al. 1997).

The standard remedy for elevated EC is irrigation in excess with low conductivity water. EC dropped significantly in biosolids compost used as a potting soil in greenhouse trials, probably from the simple mechanism of leaching from irrigation (Pill and Goldberger 2009). However, in some instances, other mechanisms have been attributed to decreases in EC. A decrease in EC over 40 days in active municipal compost to half its initial value was attributed to cations binding with stable organic complexes (Avnimelech 1996). In biosolids compost, researchers have found slight decreases in EC over 30 days (Wu et al. 2000) and substantial decreases in EC over 188 days in paper pulp sludge compost (Sesay et al. 1997). However increases in EC of biosolids compost during composting has also been reported (Zubillaga and Lavado 2006; Martínez et al. 2009; Banegas et al. 2007; Fang et al. 1998). Exact values for EC changes are in Table 3. Both Martinez et al. and Fang et al. attributed EC increases to the loss of material to respiration and a subsequent concentration of salt content. Although ammonia volatilization reduces ammonium content throughout the composting process (Zubillaga and Lavado 2006), it is possible that mineralization of organic N at rates greater than volatilization could contribute to increases in EC. EC increases have also been closely correlated with CO_2 evolution meaning EC rises could be due to mineralization or to production of VOAs, which in their dissociated form could increase EC (Aslam et al. 2008). In addition to washing of salts via rainfall or irrigation, the final EC of a biosolids soil amendment therefore varies depending on the interaction of initial EC of material, and the factors which dictate biological activity around carbon loss, organic acid production, ammonia volatilization, ammonification, nitrification. The EC of many of the biosolids composts mentioned in Table 3. was at some point above or near the phytotoxicity threshold of cress (*Lepidum sativum*) of 2.45 dS/m (Sesay et al. 1997).

Table 3. Changes in EC over time in biosolids composts. Mixing ratios and type of EC measurement dilution were not available for all studies.

Measure	Initial EC, dS/m	Final EC, dS/m	Time	Material	Ratio	Source
EC_{10}	4.8	1.8	30 d	Biosolids, food and yard waste, manure, wood chips	-	Wu et al. 2000
EC_{10}	1.8	1.6	30 d	Biosolids, yard waste	-	Wu et al. 2000
EC_{10}	1.3	1.4	35 d	Biosolids, sawdust	-	Wu et al. 2000
-	4.04	2.40	188 d	Paper pulp sludge, chicken litter, yard waste	8:2:1 v/v/v	Sesay et al. 1997
EC_{10}	2.1	2.62	90 d	Biosolids, pine sawdust	1:1 v/v	Zubillaga and Lavado 2006
EC_5	3.34	3.67	90 d	Biosolids, shredded rice straw	2.6:1 w/w	Martinez et al. 2009
EC_5	2.95	3.80	90 d	Biosolids, non shredded rice straw	2.6:1 w/w	Martinez et al. 2009
EC_5	5.68	5.96	90 d	Biosolids, sawdust	1:1 v/v	Banegas et al. 2007
EC_5	2.71	4.27	90 d	Biosolids, sawdust	1:3 v/v	Banegas et al. 2007
EC_5	2.02	3.2	90 d	Aerobically digested biosolids, sawdust	1:1 v/v	Banegas et al. 2007
EC_5	1.23	2.22	90 d	Aerobically digested biosolids, sawdust	1:3 v/v	Banegas et al. 2007
EC_5	1.03	1.80	100 d	Biosolids, sawdust	1:2 w/w wet	Fang et al. 1998
EC_5	1.11	2.06	100 d	Biosolids, sawdust, fly ash	(1:2 w/w wet bio+saw) + fly ash at 10% w/w dry	Fang et al. 1998
EC_5	1.32	2.11	100 d	Biosolids, sawdust, fly ash	(1:2 w/w wet bio+saw) + fly ash at 25% w/w dry	Fang et al. 1998
EC_5	1.36	2.51	100 d	Biosolids, sawdust, lagoon ash	(1:2 w/w wet bio+saw) + lagoon ash at 10% w/w dry	Fang et al. 1998
EC_5	1.62	3.22	100 d	Biosolids, sawdust, lagoon ash	(1:2 w/w we bio+saw) + lagoon ash at 25% w/w dry	Fang et al. 1998

While much focus has been given to EC as a quality indicator for compost due to its high potential for phytotoxicity, there are other informative indicators. As composts and other organic soil amendments consist of potentially degradable materials, their degree of stabilization can be a factor in plant response. For example, CO_2 evolution, while not phytotoxic in itself, is a sign of active decomposition and is correlated with phytotoxicity. It decreases over time as compost becomes more stable. (Wu et al. 2000; Aslam and Vandergheynst 2008b; Aslam et al. 2008; Cooperband et al. 2003; Brewer and Sullivan 2003; Banegas et al. 2007). While decreases in DOC, decreases in O_2 uptake, and increases in CEC have also been shown to be indicators of compost stabilization (Wu et al. 2000; Brewer and Sullivan 2003; Wichuk and Mccartney 2010; Butler et al. 2001), CO_2 evolution has become the standard measurement for assessing stability in the US compost industry. The US Composting Council has defined compost with CO_2 evolution higher than 8 mg CO_2-C gOM^{-1} day^{-1} as unstable material with a high potential for phytotoxic volatile organic acid (VOA) production (USCC 2002). The concentration in compost of VOAs decreases over time as they are degraded and is negatively correlated with plant growth (Avnimelech 1996; Himanen and Hänninen 2011). The rate at which VOAs are produced is highest during initial composting and appears to be dictated by a complex interaction between pH, concentration of labile carbon and porosity (Brinton and Tränkner 1999). Brinton and Tränkner also point out that high rates of VOA production can coincide with oxygen depletion which is also phytotoxic. Levels of VOAs above 1,000 mmoles dry g^{-1} are deemed problematic in compost (USCC 2002). Decrease in pH of biosolids compost via the production of organic acids, nitrification, and ammonia volatilization is common (Pill and Goldberger 2009; Banegas et al. 2007; Martínez et al. 2009; Fang et al. 1998) while increase in pH via degradation of organic acids was found in some biosolids compost (Wu et al. 2000) and in yard waste compost (Brewer and Sullivan 2003). This increase may have been related to anaerobic conditions during the composting process. Ideal levels of pH in soil amendments are the commonly accepted range at which most plants grow: 5.5-8.

Excessive concentrations of ammonium can be phytotoxic (Britto and Kronzucker 2002) and this could be a common pathway for phytotoxicity given the relatively large concentrations of ammonium found in biosolids soil amendments. Quality standards for compost indicate concentrations above 500 mg/kg ammonium as immature with levels below 75 mg/kg as ideal. These same standards also view the conversion of ammonium to nitrate as a sign of stability and levels above 3:1 ammonium : nitrate are deemed immature (USCC 2002). Given the high concentrations of organic N in biosolids, relatively high rates of organic N mineralization and low levels of nitrate, these standards are perhaps unrealistic for biosolids products.

The carbon: nitrogen (C:N) ratio can also be a predictive factor for poor plant growth. High C:N ratios typically indicate insufficient N and the potential for microbial immobilization of N. Low C:N ratios typically indicate high total N and can be associated with excessive levels of ammonium, as well as very active decomposition and the production of phytotoxic VOAs. The C:N ratio of compost decreases over time with C loss due to CO_2 evolution (Martínez 2009) or, at very low ratios and high pH, C:N increases through N loss pathways such as volatilization. An ideal C:N ratio in a finished compost has been calculated as 11 to 13 (Jimnez and Garcia 1989) while common specifications for compost accept a range of 10:1 – 25:1 (Caltrans 2015, Crohn 2016).

2.6 Odor and aesthetics

Offensive odors in anaerobically digested biosolids are most associated with the nitrogen compounds ammonia and trimethyl amine and the reduced sulfur compounds dimethyl sulfide, dimethyl disulfide, methane ethiol and carbon disulfide(Rosenfeld 1999; Higgins et al. 2006; Higgins et al. 2008). Volatile nitrogen based aromatic compounds such as skatole and indole have also been shown to contribute to offensive odors in biosolids (Chen 2006). However, emissions of reduced sulfur compounds from biosolids have been observed to be an order of magnitude higher than emissions of indole and skatole (as well as other aromatic compounds such as p-cresol and butyric acid). Emissions of reduced sulfur compounds also occur more quickly after digestion, and are associated with more intense odors than these emissions of indole and skatole from biosolids (Kacker 2011).

Rosenfeld et al. (2001), found that ammonia represented 98.1 to 99.9% of total N compounds released to air from biosolids while trimethyl amine comprised 0.1 to 1.9%. Other amines were not found to represent a significant flux of N to air. Humans can detect trimethyl amine at levels reported as low as 0.4ppb (Adams and Witherspoon 2003) to 0.046 ppb (Rosenfeld 1999) and ammonia at 17,000 ppb (Adams and Witherspoon 2003) to 7.2ppb (Ruth 1986). While the threshold for ammonia detection is higher than trimethyl amine, the sheer quantity of ammonium in biosolids which can volatilize as ammonia makes this a major source of offensive odor in biosolids. For a biosolids containing 5.2% total N, an average of 3.8% of this was found to volatilize as ammonia after application to agricultural land. The majority of these emissions occurred within the initial days after application and increasing temperature increases the rate of volatilization (Harmel et al. 1997). Other studies reported 15.6% of initial N of lost over 28 days during biosolids composting (Tubail et al. 2008), and an average of 23% of total N lost in biosolids with 4-6% total N, with the majority of losses in the first month (Robinson and Polglase 2000). A later study by Robinson showed losses of 12% of total N applied, with lower losses in the second study attributed to cold and wet climactic conditions unfavorable to volatilization (Robinson and Röper 2003). In addition to warm temperatures, alkaline conditions favor the deprotonation of ammonium to ammonia.

Humans have exceptionally low detection thresholds for reduced sulfur compounds: 0.026 ppb for dimethyl sulfide, 0.98 ppb for dimethyl sulfide, and 7.7 ppb for carbon disulfide (Ruth 1986). Carbon disulfide and DMS arise from both aerobic and anaerobic decomposition of S containing proteins (Higgins 2006) while DMDS is commonly produced from general decomposition of S containing compounds (Rosenfeld 1999). Methanogenesis is important in decreasing the production of the odorous reduced sulfur compounds produced during anaerobic digestion. When methanogens are inhibited, either by high levels of salinity or methanogen selective inhibitors, methane production decreases and methane thiol, dimethyl sulfide and dimethyl disulfide production increases (Muserref 2006; Chen et al. 2005). Methanogens were not found to be critical in the degradation of aromatic compounds such as indole and skatole as methanogen inhibition did not affect the emission of these compounds (Chen et al. 2004). Levels of carbon disulfide have been tested for in the solids of SFPUC biosolids, with 5 test results showing a range of 80 ppb, 0.60 ppb, and three non-detects (SFPUC data 2016, 2017). While it is not possible to infer the emissions of odorous carbon disulfide based on concentrations found in the solids several weeks after dewatering, this data suggests that some level of carbon disulfide emissions may be found in SFPUC biosolids.

Volatile aromatic compounds such as toluene, ethylbenzene, styrene, p-cresol, indole, and skatole are similar to odorous nitrogen and sulfur compounds in that they have very low detection thresholds, as low as 0.065 ppb for skatole and 0.13 ppb for indole (O'Neill and Phillips 1992) and are very offensive odors qualitatively. These compounds are produced through the decomposition of amino acids. In gas samples from biosolids produced by two different temperature phased anaerobic digesters, the aromatic compounds in the first biosolids were non-detectable except for a peak toluene concentration of 0.16 ppm, while the second biosolids contained peak concentrations of 0.91 ppm toluene, 0.09 ppm ethylbenzene, 1.07 ppm p-cresol, 0.13 ppm indole, and 0.17 ppm skatole (Chen et al. 2006). In analysis of solids, SFPUC biosolids were non-detect for ethylbenzene, 1.8 ppm p-cresol, and a mean of 0.025 ppm toluene (SFPUC data 2016,2017). Given that the detection threshold for toluene is 2.9 ppm (Amoore and Hautala 1983), it appears that toluene does not have the ability to be a source of odor over long periods of time in SFPUC biosolids. It is important to note that the concentrations found in the solids of SFPUC biosolids represent only a portion of initial concentrations as some amount of these compounds may have volatilized before testing was conducted. Many observers have noted that after initial fluxes of odor compounds, production of odor decreases with time (Rosenfeld 1999, Chen et al. 2006, Higgins et al. 2008).

Certain compounds which can be present in biosolids and have offensive odors have not been found to be major sources of offensive odor overall. Hydrogen sulfide for example, does not volatilize under aerobic conditions (Banwart and Bremner 1976). Methyl mercaptan and ethyl mercaptan, compounds with offensive odors and low detection thresholds, were not found in emissions from aerobic biosolids (Rosenfeld 1999), most likely because these compounds are readily oxidized into

DMDS (Hwang et al. 1994). Ketones such as acetone and methyl ethyl ketone are present in biosolids although their detection threshold is relatively high at 460 ppb for Acetone (Ruth 1986) and 737 ppb for methyl ethyl ketone (Rosenfeld 1999). Biosolids from San Francisco had an average concentration, in solids, of 1,337 ppb acetone and 1,250 ppb methyl ethyl ketone (SFPUC data 2016), which is not much higher than the detection threshold. Additionally, these ketones break down relatively quickly. Acetone has a half-life of 1 to 7 days in soil (Howard et al. 1991).

Control of odor in biosolids can be accomplished through sorption of odorous compounds, the degradation of those compounds, and preventing these compounds from forming in the first place. Materials with high surface areas and reactive surfaces are important for the sorption of odors. Materials with high rates of biological activity are better at degrading odorous compounds. Aerobic conditions, proper pH and proper temperature are important for preventing the production of odors.

Aeration is important for reducing the formation of reduced nitrogen and sulfur compounds. High rates of microbial activity in compost are strongly correlated with increased odor production, largely due to the fact that high rates of oxygen uptake in biofilms around organic matter creates anaerobic conditions (D'Imporzano et al. 2008). This phenomenon would be no different in biosolids and therefore, even when biosolids appear to be under aerobic conditions, anaerobic conditions can exist in microsites which can produce offensive odors. Anything which increases anaerobic conditions in a biosolids product such as a loss of porosity, enclosure in a sealed container, or submersion in water would result in offensive odors from the increase in the production of reduced sulfur and nitrogen compounds. As noted earlier, the volatilization of ammonia is increased at higher pH and higher temperatures. Therefore, keeping biosolids products at neutral or slightly acidic pH levels as well as preventing exposures to high temperatures reduces ammonia volatilization odors. Although the rate of mineralization of organic N to ammonium in biosolids is highest within the initial days after application, some level of mineralization continues for extended periods of time (Kumar et al. 2007), meaning there will continuously be some quantity of ammonium which could potentially volatilize into ammonia. Even when blending biosolids with high C:N ratio materials, aggregates of low C:N ratio biosolids persist and continue to be a source of N mineralization.

Sorption of odorous compounds is possible using materials with high surface area and porosity. However in some cases, reactivity of surfaces is more important than surface area and porosity. A study comparing zeolite, activated carbon, and MOF (metallic organic frameworks), showed that although MOF had a surface area of 1781 m^2g^{-1} compared to 954 m^2g^{-1} for activated carbon and 18.4 m^2g^{-1} for zeolite. Despite lower surface area, the activated carbon consistently outperformed MOF in sorbing a variety of aromatic organic odor compounds from pig manure. MOF performed well at sorbing odors from small volumes of gas, but activated carbon outperformed MOF and Zeolite in cleaning larger volumes of gas. The difference in performance between MOF and activated carbon is possibly due to differences in the quantity of oxygen groups on the surface of these materials (Ahmed et al. 2016). Higher surface areas and micro-porosity in bamboo char was found to be more effective at sorbing toluene, benzene, indole and skatole from spiked gas. However, a bamboo char with lower surface area and less micro-porosity but a higher concentration of acidic functional groups was considerably more effective at reducing ammonia concentrations, sorbing 95% of the ammonia introduced (Asada et al. 2002). In Rosenfeld's extensive 1999 study, the different considerations necessary for reducing ammonia odors compared to amines and reduced S compounds are also apparent. His work shows that surface area in activated carbon or wood ash is the most important factor in decreasing emissions of trimethyl amine and reduced S compounds as well as ketones. Activated carbon with a surface area of 520 m^2g^{-1} was most effective at reducing the emission of odors when mixed with biosolids at a 1:1 ratio by weight. This was followed by wood ash with a surface area of 85 m^2g^{-1}, an ash with surface area of 74 m^2g^{-1}, one of 25 m^2g^{-1}, and lastly an ash of 2 m^2g^{-1} which was only slightly less odorous than biosolids alone although the difference was significant. Emissions of ammonia however were higher with ash and activated carbon treatments as the ash had pH ranges of 11-12 and the activated carbon pH of 9.5 (Rosenfeld 1999). Interestingly, higher levels of Fe concentration in biosolids were shown to decrease the bio-availability of certain proteins for decomposition, which could result in a decrease in odor production (Higgins et al. 2008)

While sorption offers an important mechanism for reducing emissions of odor compounds, high levels of biological activity can actually degrade odor compounds. A study investigating the efficacy of various odor control strategies in biosolids evaluated covering materials with blankets of finished compost, incorporating finished compost, misting, odor neutralizing agents and hydrogen peroxide. Compost blankets reduced initial ammonia emissions by more than 25% and sulfur compound emissions were reduced by an order of magnitude with a 5cm blanket and were undetectable with blankets of greater thickness. After the first hour, there were no significant emissions of sulfur compounds in any of the compost blanket treatments over the next 95 hours suggesting that reduced sulfur compounds were initially sorbed in the compost blanket and eventually degraded. Incorporation of compost was also effective at decreasing reduced sulfur compound emissions and decreasing ammonia emissions during the initial 24 hours. The success of compost treatments in reducing odors was attributed to sorption, increased biological activity which oxidizes sulfur compounds, and in the case of the incorporated compost, increased aeration. While hydrogen peroxide released oxygen and was found to inhibit the production of reduced sulfur compounds initially, this effect eventually wore off and the release of oxygen was found to greatly increase ammonia production. Misting and odor neutralizing agents were not found to be effective at reducing odor (Buyuksonmez et al. 2012). Another investigation into odor reduction with activated carbon, biofilters, and ozonation found similar results in that activated carbon was very effective at removing emissions of reduced sulfur compounds but less so for reduced nitrogen compounds, while an aerated biofilter was found to be the most effective method for reducing odorous compounds. Interestingly, dimethyl sulfide and amines were removed in both aerobic and anaerobic conditions in the biofilter, but carbon disulfide and dimethyl disulfide were only removed in the biofilter under aerobic conditions, pointing to the importance of biological activity in these systems. Ozonation was effective in treating reduced sulfur compounds and converted ammonia to nitrate, which differs from the findings of Buyuksonmez where hydrogen peroxide was found to increase ammonia volatilization (Hwang et al. 1994).

Increasing aerobic conditions can reduce odor compounds both by increasing biological activity which degrades odorous compounds as well as limiting the anaerobic conditions that are the source of reduced compounds. Forced aeration in an aerated static pile of biosolids compost eliminated odor emissions of reduced sulfur compounds compared to a windrow pile, and reduced ammonia odor emissions by 72%. Filtering air from the aerated static pile through a biofilter of woodchips and compost reduced ammonia odor emissions by 98%. This reduction in ammonia was attributed to absorption by water, conversion to ammonium in slightly acidic conditions, and oxidation to nitrite and nitrate (Rosenfeld et al. 2004).

Little research has been performed on the attributes of soil amendments that make them visually appealing or unappealing. This is partly because visual aesthetics are qualitative judgments based on personal preference. That said, there are certain things which readily detract from the visual quality of soil amendments. Contaminants such as glass, metal, plastic and foam are considered unsightly by most users of soil amendments and for industries where the appearance of soil amendment is important such as commercial landscaping. These contaminants need to be physically removed by end users in commercial landscaping. Consistency in appearance, and the lack of recognizable feedstock material was found to be important among end users of mulch, as well as color, texture, and “feel” (Hartin and Crohn 2007). If most end users find natural soil to be appealing, then it can be assumed that soil amendments with similar qualities to natural soil will also be found appealing. In this same vein, a total solids content closer to that of soil will generally be found more appealing than a lower total solids content. Especially when total solids content of a soil amendment dip below 20%, non agricultural end users could find the material difficult to work with and unsightly.

3. Goals for a biosolids soil amendment product

As described in the "Market Potential" section, it is apparent that there is a market for increased use of biosolids based soil amendment products and at the very least there is the possibility to increase soil carbon stocks and reduce atmospheric CO_2 concentrations using biosolids soil amendments. However, there are potential issues with biosolids soil amendments which could limit their adoption and efficacy. As seen in the "Odor and Aesthetics" section, odors from biosolids can be offensive and must be managed in order for soil amendments to be used in non-agricultural settings. As seen in the "Quality Parameters for Soil Amendments" section, there is the potential for biosolids soil amendments (and with all soil amendments) to be phytotoxic or ineffective if certain parameters such as EC do not fall within ideal ranges.

The goal of this project was to develop a new soil amendment product using Class A biosolids from the city of San Francisco which allows the biosolids to be used in a wider range of applications than simply the amendment of agricultural fields. In order to address issues with odor and to create a product that better met quality parameters for soil amendments, biosolids were mixed with other feedstocks to create a novel product. This approach has already been successful for the city of Tacoma, WA with the TAGRO line of products.

This project created a set of novel biosolids products and evaluated their potential for use as a soil amendment based on three criteria: industry specifications for soil amendments, public acceptability of odor and appearance, and ability to improve plant growth. The biosolids soil amendments that this project created could be used in similar applications as compost, such as an amendment in landscaping and engineering projects or as a component of other products like manufactured topsoils. To evaluate whether the biosolids product would perform well in these scenarios, the product was compared to commonly held industry standards for compost. In landscaping and engineering, these standards take the form of specifications that a compost must meet in order to be used on a project. Specifications for manufactured topsoils made with compost are not as widespread as specifications for topsoils or compost alone. The original specification for compost manufactured topsoil simply uses an existing compost specification for the organic portion of the product and then has additional requirements for the mineral portion of the topsoil (TxDOT 2014). Therefore, a product which met general compost specifications could act as a base product which was then used to make other products like manufactured topsoils. In addition to meeting industry standards, the biosolids soil amendment product must be publicly acceptable in terms of odor and appearance. Lastly, the product must work well in its intended role as a soil amendment by improving the growth of plants.

To assess whether the products improved plant growth, they were compared to existing soil amendment products with a goal of performing as well or better than existing products. While the term “publicly acceptable” for odor and appearance infers that most members of a population find a material inoffensive, what this means in terms of an exact percentage of a population is not clearly defined. In order to evaluate whether the odor and appearance of products were acceptable, a goal of 70% of survey respondents finding odor and appearance inoffensive was used. To see if products met common industry standards for soil amendments, they were compared to a set of criteria developed from transportation agency specifications for compost as well as University of California extension agency recommendations for compost (AASHTO 2010; Caltrans 2015; WSDOT 2016; TxDOT 2014; Crohn 2016). While these specifications and recommendations were similar, there was some variation for certain parameters. The pH requirements were 5.0-8.5 in AASHTO, 5.5-8.5 in TxDOT, and 6.0-8.5 in WDSOT, Caltrans and Crohn 2016. The maximum limit for EC_5 was 4 dS/m in WSDOT, 5 dS/m in AASHTO and TxDOT and 10 dS/m in Caltrans. Where there were 3 different specifications for a parameter, the mid-range specification was used.

The goals for the biosolids products developed in this project were as follows:

- **Plant growth:** Biosolids soil amendment improves plant growth in a manner similar to or better than existing products.
- **Odor and aesthetics:** At least 70% of individuals find odor and appearance of biosolids soil amendment inoffensive.
- **Ideal ranges for quality parameters based on common specifications for compost:**
  pH: 5.5-8.5
  EC_5: <5 dS m^{-1}
  Organic matter content: >30%
  Stability: <8 $mgCO_2$-C gOM^{-1} day^{-1}
  C:N ratio: <25:1, >10:1
  Physical contamination: <1% contaminants by weight

4. Materials and Methods

4.1 Creating blended biosolids products

Biosolids for the project were collected from the SFPUC's Oceanside treatment plant in San Francisco. The biosolids were produced using a Temperature Phased Anaerobic Digestion process (TPAD) where solids are in a thermophilic digester at temperatures above 55° C for a retention time of 21 days and then sent to a mesophilic digester with temperatures of approximately 46° C for a retention time of 8 days. After digestion, the biosolids are dewatered using an FKC screw press to a total solids content of approximately 24%.

Ten feedstocks were selected from around the San Francisco Bay Area and Northern California for blending with the biosolids. Several factors were taken into account when selecting feedstocks. Feedstocks had to be within a reasonable distance from SFPUC operations. Materials with a high C:N ratio that could balance the low C:N ratio of biosolids were sought out. Feedstock particle size such that the majority of material passed through a 9.51 mm sieve (1/2") was important for a consistent looking product that could easily be incorporated into soil or used as a growing medium. Feedstocks from waste streams were prioritized over virgin materials, both due to the costs and environmental implications of using virgin materials in a full- scale operation. The feedstocks selected were as follows:

> Almond Fines (AF) – Fine particles of almond shells and nuts from almond processing. Produced in Linden, CA.
>
> Biochar (BC) – ¼" minus wood waste pyrolyzed at 600-700° C to create biochar. Produced in Willows, CA.
>
> Gypsum Board Fines (GB) – Processed gypsum board fines. Produced in San Jose, CA
>
> Lumber Fines (LF) – Self haul dimensional lumber waste (pallets, fences, clean C&D waste) which is processed in a grinder and then screened to 3/8" minus. Produced in Newark, CA.
>
> Redwood Shavings (RS) – Fine redwood shavings from sawmill activities. Produced in Davenport, CA.
>
> Redwood Sawdust (RSD) – Fibrous redwood sawdust from sawmill activities. Produced in Davenport, CA.
>
> Walnut Shells (WC) – Crushed walnut shells from walnut processing. Produced in Ripon, CA.
>
> Walnut Shell Char (WSC) – Walnut shells pyrolyzed at approximately 800° C. Produced in Winters, CA.
>
> Yard Waste Fines (YF) – Self haul yard waste comprised of woody and leafy materials which is processed in a grinder and then screened to 3/8" minus. Produced in Livermore, CA.
>
> Yard and Lumber Waste Fines (YLF) – Yard waste and dimensional lumber waste processed in a grinder and then screened to 3/8" minus. Produced in San Jose, CA.

Images of the feedstocks are shown in Figure 1 on the following page in alphabetical order.

Almond Fines Biochar Gypsum Board Fines Lumber Fines

Redwood Shavings Redwood Sawdust Walnut Shells

Walnut Shell Char Yard Waste Fines Yard Waste/Lumber Fines

Figure 1. Feedstocks used to blend with biosolids.

Sand used in blends and as a nutrient free control growing medium was procured in Washington due to the relative similarity of sand products used in horticultural applications. A number of commercially available materials were also used as controls. These included Sunshine Mix, a Sphagnum peat moss based potting mix that is commonly used in horticulture, Cedar Grove Compost, a yard food waste compost that is sold in the Seattle area and commonly used by home gardeners and landscapers, and two products made from Class A biosolids produced in Tacoma, WA. Tagro Mix is a general-purpose soil amendment made from mixing Class A biosolids with sand and sawdust. Tagro Potting Soil is a growing medium designed to be planted in directly without dilution. It is made from mixing Class A biosolids with sawdust and aged bark. Control soil amendment products were also sourced in Washington. The controls used are as follows:

Cedar Grove Compost (CG) – Municipal yard and food waste compost. Produced in Maple Valley, WA. Purchased from Dirt Exchange in Seattle, WA as fully mature material.

Sunshine Mix #3 Peat (P) – 70-80% Sphagnum peat moss, vermiculite, dolomite limestone. Produced in Canada. Used as a standard growing medium at the Douglas Research Conservatory at the University of Washington.

Sand (S) – Washed and screened sand sourced from the city of Tacoma's TAGRO operation.

Tagro Potting Soil (TP) - 8% class A biosolids, 61% aged bark, and 31% washed and screened sand, by volume. Produced in Tacoma, WA.

Tagro Mix (TM) – 40% class A biosolids, 40% kiln dried sawdust and 20% washed and screened sand, by volume. Produced in Tacoma, WA.

Eight blends were created by mixing biosolids and feedstocks at the same ratio as Tagro Mix, 40% biosolids, 40% feedstock, and 20% sand, by volume. The only feedstocks not mixed with biosolids at this ratio were biochar and walnut shell char. Due to the high EC of these materials they were blended at volumetric ratios of 50% biosolids + 25% yard waste fines + 25% char.

Three additional blends were also created without using sand, at a volumetric ratio of 50% biosolids + 50% feedstock. These feedstocks were yard waste fines (YF 100), lumber fines (LF 100), and yard waste fines/lumber fines (YLF 100). The number '100' was used in treatment labels to signify that it consists of 100% organic materials and contains no sand. The mixing ratios of the treatments used in the study are shown in Table 4. Materials were mixed by hand and allowed to cure in 5-gallon buckets. The buckets had an inch of crushed aggregate along the bottom as well as drainage holes to prevent anaerobic conditions from developing. Buckets were loosely covered with lids to allow airflow but prevent precipitation from entering and left to cure outside at the Douglas Research Conservatory at the University of Washington. Sufficient quantities of each blend to fill two 5-gallon buckets were made. The blends cured for 48 days before being used for plant growth trials. Cedar Grove and Tagro Mix controls were also kept outside in two 5-gallon buckets for this time period.

Table 4. List of treatments and controls. Materials cured for 30 day in 5-gallon buckets after which they were used in an odor and aesthetics survey and in germination and plant growth trials. Tagro Mix (TM) and Cedar Grove Compost (CG) were used as a biosolids and non-biosolids soil amendment control.

Treatment	**Ingredients**	**Volumetric proportions**
AF	Almond fines/Biosolids/sand	40% Almond fines, 40% biosolids, 20% sand
BC	Biochar/Biosolids/Yard Waste	25% Biochar, 50% biosolids, 25% yard waste fines
CG Control	Cedar Grove	100% Cedar Grove Compost
GB	Gypsum Fines/Biosolids/sand	40% Gypsum board fines, 40% biosolids, 20% sand
LF	Lumber fines/Biosolids/sand	40% Lumber fines, 40% biosolids, 20% sand
LF 100	Lumber fines/Biosolids	50% Lumber fines, 50% biosolids
RS	Redwood Shavings/Biosolids/sand	40% Redwood shavings, 40% biosolids, 20% sand
RSD	Redwood Sawdust/Biosolids/sand	40% Redwood sawdust, 40% biosolids, 20% sand
SF	SF Biosolids	100% San Francisco biosolids
TM Control	Tagro Mix	100% Tagro Mix (40% class A biosolids, 40% sawdust, 20% sand)
WS	Walnut shells/Biosolids/sand	40% Walnut shells, 40% biosolids, 20% sand
WSC	Walnut shell char/Yardwaste/Biosolids	25% Walnut shell char, 50% biosolids, 25% Yard waste fines
YF	Yard waste/Biosolids/sand	40% Yard Waste fines, 40% biosolids, 20% sand
YF 100	Yard waste/Biosolids	50% Yard waste fines, 50% biosolids
YLF	Yard-lumber fines/Biosolids/sand	40% Lumber/Yard waste fines, 40% biosolids, 20% sand
YLF 100	Yard-lumber fines/Biosolids	50% Lumber/Yard waste fines, 50% biosolids

All of the mixtures listed in Table 4 were evaluated for odor and appearance, analyzed for different soil variables, and used for growth trials. Three additional materials were analyzed for different soil variables and used in germination and plant growth trials, but not in the odor and appearance survey (Table 5). Tagro Potting Soil was used as a biosolids product control that was developed to perform well as a potting soil. Sand was used as a nutrient free growing medium to demonstrate plant performance without the addition of any nutrients. Lastly, a peat growing medium was used to represent a commercially available growing medium that is typically used for seedling germination and as a potting soil.

Table 5. List of additional control treatments used in germination and plant growth trials. These materials did not cure for 30 days in 5-gallon buckets and were not part of odor and appearance surveys.

Treatment	Ingredients	Volumetric proportions
P	Peat growing medium	100% Sunshine Peat Mix # 3
S	Sand	100% Sand
TP	Tagro Potting	8% class A biosolids, 61% aged bark, 31% sand

4.2 Physical and chemical analysis of materials

Three replicates of feedstocks and unblended biosolids were analyzed for total moisture by oven drying at 60° C for 2 days and percent organic matter by loss on ignition at 550° C for 2 hours (TMECC 5.07 USCC 2002). Three replicates of bulk density were measured by taking a sample of 710 mL of material and drying at 60° C for 2 days. Dried material was weighed and then the mass was divided by 710 to find the bulk density in g/cm^3. This is similar to TMECC 5.10 D (USCC 2002) except water holding capacity was not measured and a container of 710 ml was used to measure volume rather than a burette. After being ground in a hammer mill, three replicates of each feedstock and unblended biosolids were analyzed for total C and N using a Perkin Elmer Model 2400 CHN Analyzer. A 1:5 feedstock:deionized water slurry was made (TMECC 4.10, 4.11 USCC 2002) from air dried material. EC_5 and pH of these 1:5 slurries was measured using an Oakton Instruments PC 700. Particle size distribution and contamination with non-organic anthropogenic inerts (glass, plastic, metal, foam) were measured on three replicates by passing 710 mL of dried material through nested sieves and sorting through material to manually remove and weigh physical contamination.

After feedstocks were blended with biosolids, the resulting blends and control treatments were also analyzed. Blends and controls were analyzed using samples taken after 32 days of curing (pH, EC_5, CO_2 evolution, total C and N, % OM, available N, and Mehlich III extractable metals). Certain analyses were also performed on samples taken on day 1 after mixing (pH, EC_5).

As sand would damage the hammer mill, samples taken after blends had cured for 32 days were ground with a mortar and pestle and then analyzed for total C and N by combustion. Three replicates of each mixture were used for C and N analysis. The pH and EC_5 of the homogenized blends was measured using a 1:5 slurry of deionized water from air dried samples taken 1 day and 32 days after blending. Measurement of dry bulk density, particle size distribution, and contamination were measured for the mixtures as previously described. Samples from day 32 were analyzed for total moisture by oven drying at 60° C for 2 days and percent organic matter was determined by loss on ignition at 550° C for 2 hours. Three replicates were used for total moisture and percent organic matter. For all treatments and controls other than sand, on day 33 CO_2 evolution was measured over four consecutive days using NaOH traps according to TMECC 5.08 B (USCC 2002) using three replicates per treatment. CO_2 evolution was also measured on 4” diameter columns filled with each treatment using a Licor-6400 infrared gas analyzer (IFRG) and 6400-09 soil CO_2 flux chamber. Treatments were incubated for 1 day at approximately 27° C and then measured using IFRG on day 11 and day 34 after the treatments were mixed.

Samples taken at day 32 were refrigerated at approximately 4° C and analyzed within one week for NO_3^- and NH_4^+. Samples were prepared using the two suggested methods in TMECC 4.02 (USCC

2002). One set of samples was prepared using wet material, sieved through a 4 mm screen. The second set of samples was prepared by air drying material, homogenizing in a blender and sieving through a 4 mm screen. Available N was extracted from both sets of samples by adding 50 mL of 2M KCl to 10 g of material and shaking for 1 hour (Keeney and Nelson 1982). Because of the high water holding capacity of peat, 100 mL of 2M KCl had to be used in order to generate a sufficient amount of solution for analysis. Extractions were filtered using Whatman grade 40 filter paper and NO_3^- and NH_4^+ concentrations of the extractions were analyzed by colorimetry the same day using a Perstorp Analytical Model 500. Four blanks, 1 quality control sample, and 8 duplicates were run.

Available nutrients from all treatments and controls were determined using the Mehlich III extraction on samples taken at day 32 after blending. Two grams of material were extracted with 20 mL of Mehlich III extractant on a shaker for 5 minutes and filtered through Whatcom filter paper (Zhang et al. 2014). Extracted solutions were analyzed on a Thermo Scientific 6300 ICP for metals including Ca, K, P, S, B and Mg. Two quality control samples, 2 blanks, and 2 duplicates were run.

4.3 Plant growth trials

Germination assays were conducted using cucumber (*Cucumis sativus*) and radish (*Raphanus raphinistrum* ssp. *sativus*). Germination assays in a 1:1 compost:vermiculite blend are commonly used to assess phytotoxicity in the compost industry (TMECC 5.05 USCC 2002). For this study, assays were conducted in 100% of the soil amendment blends to provide a more sensitive assay for potential phytotoxicity. Twenty seeds of cucumber and twenty seeds of radish were sown in seedling trays filled with the different soil amendment blends and controls. Based on its sensitivity to VOAs and slight tolerance to salts cucumber is the standard plant used in bioassays by the US compost industry (TMECC 5.05 USCC 2002). Radish is one of two plants recommended for use in bioassays by the Canadian guidelines for compost quality (CCME 1996) and is not noted for salinity tolerance (Fipps 2003; Morales and Urrestarazu 2013). Seedling trays were kept in a temperature and light controlled greenhouse at the University of Washington Douglas Research Conservatory. Seedlings were watered daily by hand and allowed to drain freely. Germination success or failure was recorded and seedlings were rated qualitatively as poor, normal, or vigorous at 14 days after seeding. Seedlings were uprooted and photographed at 21 days after seeding.

Cascadia Blue Petunias (*Petunia* x *hybrida*) were sourced from Jason's Greenhouse in Yelm, WA. Cascadia Blue is a trailing growth habit Petunia. Plants were obtained before flowering at approximately 6 weeks after sowing. Petunias were selected as representative of plants home gardeners and landscapers grow. Additionally, flower production served as an index of growth response to treatments. The mixtures were evaluated in two scenarios. For the first scenario the blends were used as a potting soil: half gallon pots were filled solely with the biosolids soil amendments or controls. For the second scenario the mixtures were used as soil conditioners: half gallon pots were filled with a volumetric mixture of 50% treatment or control + 50% sand. This mimicked a situation where a home gardener or commercial landscaper applied a 5 cm layer of soil amendment that was incorporated into a mineral soil. Four replicates of each treatment were grown under each scenario (100% blend, or 50% blend + 50 % sand). Plants were grown in a temperature and light controlled greenhouse at the Douglas Research Conservatory using a randomized complete block design. Plants were hand watered daily and were allowed to drain freely without the use of saucers.

Plants were measured for height, widest and narrowest width at day 1, 8, 30 and 60. A shoot index was calculated using the following formula: ([(widest width + narrowest width)÷2]+height)÷2 (Hummel et al. 2014). Chlorophyll content was measured using a Konica Minolta SPAD-502 at day 1, 8, 30 and 60 days after transplanting. Chlorophyll content measurements were taken on three different leaves for each plant and averaged. Plants were harvested at soil level 62 days after transplanting, oven dried and weighed. The cumulative number of flowers produced by each plant was counted until 60 days after transplanting. Flowers were marked to avoid double counting.

4.4 Odor and appearance

University of Washington students in the Schools of Engineering, Forestry and Environmental Resources, Aquatic and Fishery Sciences, and staff at TAGRO were surveyed on the aesthetic quality of blends 1 day after they had been created and on the odor quality of the blends 1 day, 15 days, and 32 days after creation. The same participants were asked to participate for all odor assessments. There were 40 participants rating odor and aesthetics on day 1, 23 participants rating odor on day 15, and 32 participants rating odor on day 32. Participants were given a sealed, covered and numbered glass jar. Odor was measured by briefly unsealing the jar and smelling its contents. Odor was ranked on an intensity scale of 0 (no odor) to 5 (intense odor). Odor quality was ranked on a scale of +3 (very pleasant) to -3 (extremely offensive). Participants characterized the quality of odor by selecting a descriptor on an odor wheel developed for biosolids compost odors (Suffet et al. 2009). After assessing odor, participants removed a paper sheet that had been covering the glass jar to assess the aesthetic quality of the material on a scale from +3 (material looks very appealing for use in a yard) to -3 (material looks very unappealing). Two duplicate samples were used for every survey to assess the precision of participants in evaluating odors. Participants were given detailed instructions to help insure that all participants were rating odors and aesthetics in a similar manner. The samples were provided to evaluators in a random order for each evaluation

4.5 Statistical analysis

Statistical analysis was performed using R. Analysis of variance (ANOVA) and Tukey's HSD post-hoc test at an alpha of 0.05 were used for multiple means comparison of plant growth response. The Kruskal-Wallis and the Bonferroni post-hoc test at an alpha of 0.05 were used for multiple rank comparison of responses to the odor and appearance surveys. Linear and quadratic regression models were used to identify trends and analyzed for R^2 and p-value. P-values reported in the text are rounded to three decimal places. The two petunia growth trials (plants grown in 100% of blends vs. 50% blend + 50% sand) were analyzed separately. With the 50% blend + 50% sand petunia growth trial, analysis was performed using the initial properties of each blend as opposed to the properties of the resulting 50% blend + 50 % sand mixture in each pot.

5. Results

5.1 Properties of feedstocks

Characteristics of the feedstocks are shown in Table 6. Initial analysis of the feedstocks selected for blending with biosolids revealed problems with several materials. The EC_5 of most feedstocks other than biochar and walnut shell char ranged from 0.07 to 2.68 dS/m, however the EC_5 of the biochar and walnut shell char was excessively high (11.77 dS/m and 39.9 dS/m respectively). In addition, the pH of the walnut char was also high at 10.61. In order to avoid making blends that had a high potential for phytotoxicity, both char materials were combined with yard waste (EC_5 0.94 dS/m and pH 6.59) at a volumetric ratio of 50% biosolids + 25% yard waste fines + 25% biochar or walnut char. The C:N ratio of the almond fines was 14.7:1, suggesting that a blend created with this material and equal parts biosolids (C:N of 7.5:1) would have a lower than ideal C:N ratio.

Table 6. Properties of feedstocks mixed with biosolids. Standard error in parentheses where replicates were performed on each material. ND = Non detect. No C:N ratio was calculated for Sand. Percent Organic Matter by LOI (n=3), EC_5 and pH measured in 1:5 slurries with deionized water, total C and N by combustion (n=3), bulk density (n=3) and moisture content (n=3).

Material	Organic Matter, %	EC_5, dS/m	pH	C, %	N, %	C:N ratio	Bulk density,	Moisture content, %
Almond Fines	89.5 (0.15)	2.11	5.75	52.95	3.60	14.7	0.41	13.7 (0.17)
Biochar	41.8 (2.0)	11.77	7.30	52.04	0.13	410.8	0.11	78.7 (0.17)
Redwood Sawdust	97.8 (0.68)	0.07	6.94	38.70	0.09	428.4	0.09	62.2 (0.82)
Redwood Shavings	96.0 (0.82)	0.64	4.18	45.52	0.04	1101.2	0.05	12.1 (0.33)
Sand	1.0 (0.26)	0.01	7.42	0.08 (0.02)	ND		1.38	5.0 (0.00)
SF Biosolids	53.4 (0.24)	4.74	6.68	28.60	3.80	7.5	0.20	72.2 (0.17)
Lumber Fines	93.2 (1.07)	0.52	6.51	46.61	0.28	168.1	0.13	40.7 (0.17)
Yard Waste Fines	65.8 (1.89)	0.94	6.59	35.75	0.62	58.1	0.20	27.8 (0.73)
Walnut Shell Char	30.8 (0.23)	39.9	10.61	39.85	0.36	111.7	0.28	5.4 (0.49)
Walnut Shells	90.2 (0.58)	0.48	6.03	47.27	0.32	149.4	0.35	27.7 (9.92)
Gypsum Board	16.0 (0.09)	2.68	8.37	4.36 (0.03)	0.25	17.5	0.55	30.3 (0.33)
Yard/Lumber Fines	75.1 (5.18)	1.79	7.59	38.64	0.65	59.8	0.19	21.7 (0.67)
Tacoma Biosolids	64.7 (0.68)	3.31	7.30	28.18	3.76	7.5	0.17	73.2 (0.17)
Sawdust used in	98.5 (0.63)	0.41	4.85	47.70	0.03	1538.7	0.13	22.6 (0.38)

5.2 Properties of blended soil amendments

5.2.1 pH

Several characteristics of the blended soil amendments changed during the course of curing. The pH decreased slightly in all materials except for the almond fines blend (Table 7). Excluding the almond fines, the range in pH decrease between day 1 and day 32 was 0.09 to 0.84 with a mean decrease of 0.36 (SE 0.06). Decreases in pH during biosolids composting has been noted to occur as a result of organic acid production, nitrification, and ammonia volatilization (Pill and Goldberger 2009; Banegas et al. 2007; Martínez et al. 2009; Fang et al. 1998), and these processes are most likely responsible for the slight decreases in pH that occurred in materials curing for 32 days.

In general, the pH levels of the blends were all within the range of 5.5-8.5 found in TxDOT specifications as well as the AASHTO range of 5.0-8.5. The exception to this was the walnut shell char blend (WSC) which was excessively alkaline (pH of 10.13). This high pH could result in poor plant growth (Crohn 2016) and strong odors due to ammonia volatilization (Ernst and Massey 1960, Mills et al. 1974).

A pH of below 6.0 in compost is seen as a sign of immature material and potential phytotoxicity (Crohn 2016; Hartin and Crohn 2007). However, in biosolids products where low pH can be due to high rates of ammonia volatilization and not necessarily VOA production (Pill and Goldberger 2009; Banegas et al. 2007; Martínez et al. 2009; Fang et al. 1998), pH levels between 5-6 may not be problematic.

Table 7. pH of blended soil amendments from composite samples taken on day 1 and day 32. pH measurements made on a 1:5 slurry with deionized water (n=1).

Treatment	Ingredients	pH Day 1	pH Day 32	Change in pH
AF	Almond fines/Biosolids/sand	5.82	6.49	+0.67
BC	Biochar/Biosolids/Yard Waste	7.24	6.86	-0.38
CG	Cedar Grove	7.3	7.15	-0.15
GB	Gypsum Fines/Biosolids/sand	7.54	7.34	-0.2
LF	Lumber fines/Biosolids/sand	6.3	5.76	-0.54
LF 100	Lumber fines/Biosolids	6.13	5.72	-0.41
RS	Redwood Shavings/Biosolids/sand	5.95	5.69	-0.26
RSD	Redwood Sawdust/Biosolids/sand	6.13	6.04	-0.09
SF	SF Biosolids	6.32	6.23	-0.09
TM	Tagro Mix	6.72	6.57	-0.15
WS	Walnut shells/Biosolids/sand	6.28	5.57	-0.71
WSC	Walnut shell char/Yardwaste/Biosolids	10.13	10.09	-0.04
YF	Yard waste/Biosolids/sand	6.89	6.05	-0.84
YF 100	Yard waste/Biosolids	6.37	5.84	-0.53
YLF	Yard-lumber fines/Biosolids/sand	6.89	6.42	-0.47
YLF 100	Yard-lumber fines/Biosolids	6.71	6.19	-0.52

5.2.2 Electrical Conductivity

Electrical conductivity in the blends also changed during the course of curing with the EC_5 of all treatments increasing over the 32 days of curing except for the walnut shell blend (WS) (Table 8). In the walnut shell blend the EC_5 decreased from 1.04 dS/m at Day 1 to 0.95 dS/m at Day 32. This observed decrease may have been within the margin of error. For all other materials the increase in EC_5 ranged from 0.13 dS/m to 1.00 dS/m with a mean increase in EC_5 of 0.51 dS/m (SE 0.09). Materials were covered and therefore there was no possibility for leaching during curing. Increases in EC during biosolids composting has been frequently observed (Zubillaga and Lavado 2006; Martínez et al. 2009; Banegas et al. 2007; Fang et al. 1998). Both Martinez et al. (2009) and Fang et al. (1998) attributed this increase in EC to a loss of material via respiration and a subsequent concentration of salt content. Aslam et al. (2008) attributed an observed increase in EC to the production of VOAs, ammonium, and nitrate from biological activity.

The EC_5 of the same batch of SFPUC biosolids steadily increased over the course of the study, from an initial value of 4.74 dS/m when tested with other feedstocks on 2/9/17, to 5.68 dS/m on the first day of blending, and 7.17 dS/m after 32 days of curing. This highlights the fact that there was ongoing biological or chemical activity in the biosolids, although attempts were made to limit this before blending by storage at 4 C°. Drying is not a factor as the EC_5 is measured on a dry weight basis. The final EC_5 of the walnut shell char blend (WSC), unblended biosolids (SF), and the biochar blend (BC), were all above 5 dS/m, which is the upper limit for EC_5 found in specifications for compost used by the Texas Department of Transportation (TxDOT 2014) and the Washington Department of Transportation (WSDOT 2016).

Table 8. EC_5 measured from composite samples taken on day 1 and day 32 (n=1).

Treatment	Ingredients	EC_5 Day 1	EC_5 Day 32	Difference
AF	Almond fines/Biosolids/sand	0.95	1.60	+0.65
BC	Biochar/Biosolids/Yard Waste	4.55	5.55	+1.00
CG	Cedar Grove	1.68	2.15	+0.47
GB	Gypsum Fines/Biosolids/sand	2.00	2.31	+0.31
LF	Lumber fines/Biosolids/sand	1.03	1.38	+0.35
LF 100	Lumber fines/Biosolids	3.61	4.08	+0.47
RS	Redwood Shavings/Biosolids/sand	1.38	1.71	+0.33
RSD	Redwood Sawdust/Biosolids/sand	0.92	1.26	+0.33
SF	SF Biosolids	5.68	7.17	+1.49
TM	Tagro Mix	0.74	0.98	+0.25
WS	Walnut shells/Biosolids/sand	1.04	0.95	-0.09
WSC	Walnut shell char/Yardwaste/Biosolids	12.75	13.57	+0.82
YF	Yard waste/Biosolids/sand	1.07	1.33	+0.25
YF 100	Yard waste/Biosolids	2.93	3.41	+0.48
YLF	Yard-lumber fines/Biosolids/sand	1.27	1.40	+0.13
YLF 100	Yard-lumber fines/Biosolids	4.06	4.37	+0.31

5.2.3 Organic Matter

The organic matter content of the blends ranged from a high of 66% in the lumber fines w/out sand blend (LF 100), to a low of 13% in the gypsum board blend (GB) (Figure 2). The percent organic matter in the blends depended greatly on whether sand was added (Figure 3). Blends without sand had similar levels of organic matter to the non-biosolids soil amendment control (CG), while blends with sand had similar levels of organic matter to the biosolids soil amendment control (TM) which also contained sand.

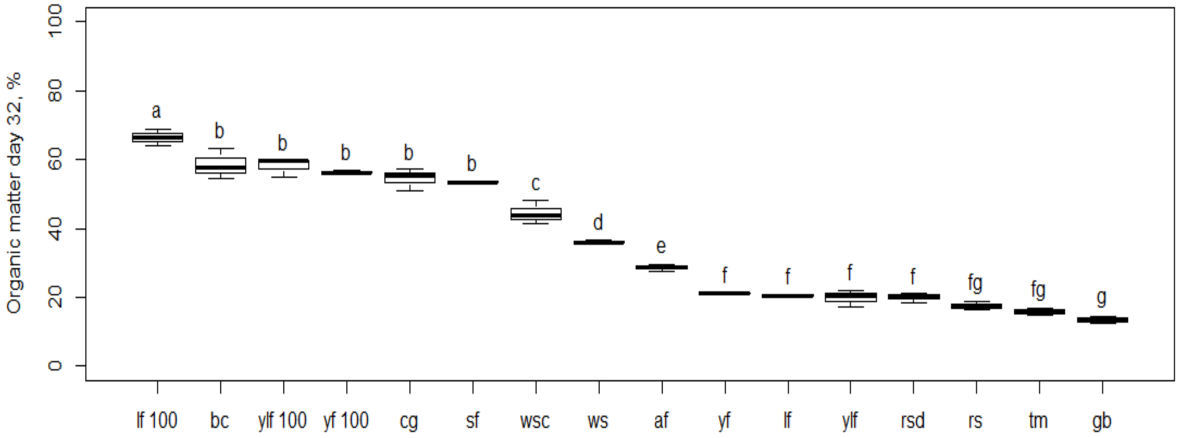


Figure 2. Organic matter concentration of treatments from composite samples taken on day 32 after mixing (n=3). Results with different letters are significantly different at p ≤ 0.05. Treatments are in order of greatest to lowest mean OM%. Exterior bars represent maximum and minimum values, interior bar represents median value, boxes represent upper and lower quartile.

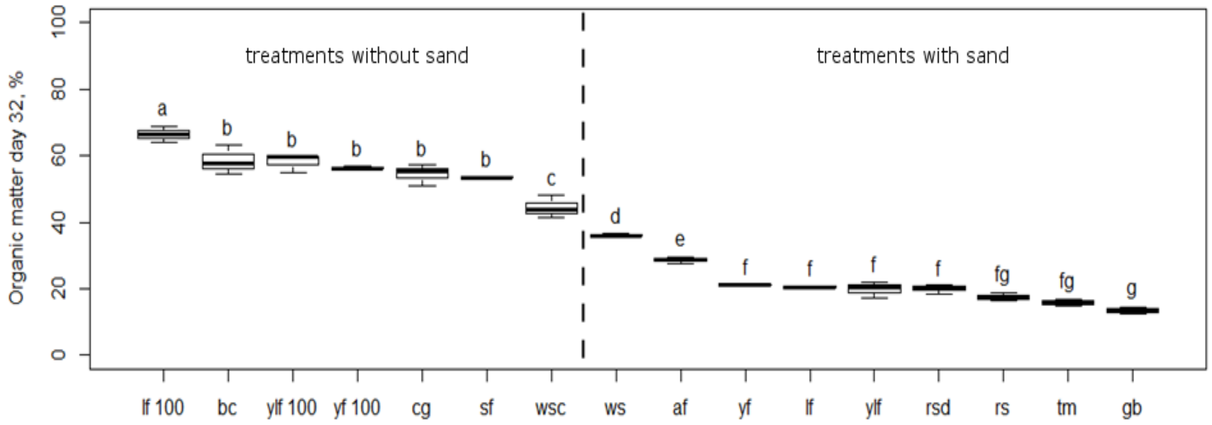


Figure 3. Impact of sand on organic matter concentration of treatments from samples taken on day 32 after mixing (n=3). Same data as Figure 2. Treatments to the right of the dashed line had sand added at a volumetric ratio of 20%. Results with different letters are significantly different at p ≤ 0.05.

The sand had a significantly higher bulk density and neglible organic matter content in comparison to the other feedstocks. While the added sand only accounted for 20% of the blends by volume, it accounted for a much higher proportion by dry weight which affected gravimetric measurements of organic matter. For example, the 50% lumber fines + 50% biosolids blend (LF 100) was 66% organic matter, while the 40% lumber fines + 40% biosolids + 20% sand blend (LF) was 21% organic matter. In this instance, although the percentage of organic feedstock was only reduced 20% by volume, the percentage of organic matter by weight is reduced by 68%. Common specifications for compost often require organic matter content by dry weight to be above 25% (AASHTO 2010; TxDOT 2014; Crohn 2016), 30% (Caltrans 2015) or even 40% (WSDOT 2016) as materials with lower levels of organic matter provide fewer of the benefits and nutrients associated with organic matter (Crohn 2016). If intended use of a material is on projects with specifications for at least 25% organic matter content, the treatments in this study with sand do not meet the requirements. However, due to high levels of N, P, and other nutrients biosolids compared to naturally occurring soils and commercially available composts, biosolids blends with organic matter concentrations lower than 30% could still perform well as a soil amendment.

5.2.4 CO_2 evolution

CO_2 evolution is a measurement of microbial respiration with greater flux of CO_2 indicating higher rates of decomposition and unstable blends that can be phytotoxic. Compost with rates of respiration above 8 mg per gram of organic matter per day is considered to be immature (USCC 2002, Crohn 2016). Mean CO_2 evolution from the control amendments ranged from 5.0 mgCO_2-C gOM^{-1} day^{-1} in the biosolids amendment control Tagro Mix (TM), to 1.4 mgCO_2-C gOM^{-1} day^{-1} in the non-biosolids amendment control Cedar Grove compost (CG) (Figure 4). The majority of biosolids blends, 11 out of 13, had higher rates of respiration ($p \leq 0.05$) than the Cedar Grove compost and 9 of the 13 biosolids blends were not statistically different from the Tagro Mix control ($p \leq 0.05$). With one exception, at Day 32 all of the mixtures had CO_2 evolution rates below the recommended threshold of 8 mg mgCO_2-C gOM^{-1} day^{-1}. The only blend above this threshold at Day 32 of curing was the almond fines blend (AF) with a mean respiration rate of 8.6 mgCO_2-C gOM^{-1} day^{-1}. The high rate of microbial activity that this respiration rate represents was visible within several days after mixing, by which time the almond fines blend in 5-gallon buckets was covered in mold.

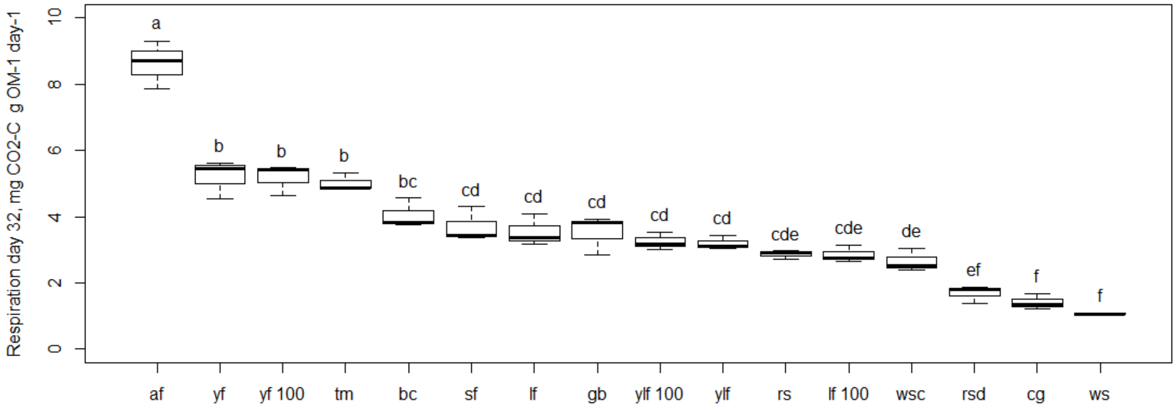


Figure 4. Microbial respiration per unit of organic matter from treatments on composite samples taken at day 32 (n=3). Results with different letters are significantly different at $p \leq 0.05$. Treatments are in order of greatest to lowest mean respiration. Exterior bars represent maximum and minimum values, interior bar represents median value, boxes represent upper and lower quartile.

Each pair of blends made with and without sand (YF and YF 100, LF and LF 100, YLF and YLF 100) was not statistically different in terms of respiration per unit OM. The addition of sand did not change the ratio of feedstock to biosolids in any of these blends, therefore it is to be expected that the organic matter in each pair of blends had the same level of stability.

Cedar Grove compost (CG) had gone through Washington State Ecology time and temperature requirements for pathogen destruction. It was maintained at 55°C for at least 15 days and was turned 5 times during this period (WAC 2003). This was followed by a curing period of a year to a year and a half (personal communication, Cedar Grove staff, 1/26/18. This suggests that the Cedar Grove compost was a very stable material.

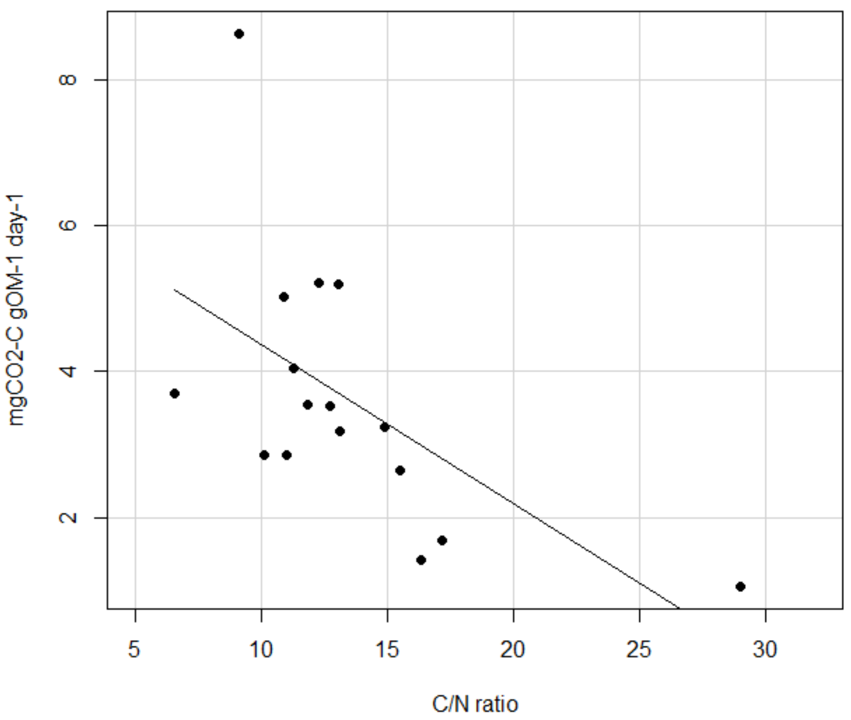


Figure 5. Microbial respiration on day 32 as a function of C:N ratio from samples taken on day 32. Adjusted r^2: 0.31, P value: 0.015

The relationship between the C:N ratio of the blends at day 32 was a significant determinant of CO_2 respiration per unit of organic matter at p=0.023 (Figure 5). Higher C:N ratios were associated with lower levels of microbial activity. After the unblended biosolids (C:N of 6.6:1), the almond fines blend had the lowest C:N ratio (9.1:1) and also had the highest rate of respiration. The rate of respiration in the unblended biosolids was much lower than in the almond fines blend and was statistically similar to 9 of other treatments with higher C:N ratios. The walnut shell blend (WS), Cedar Grove compost (CG), and the redwood sawdust blend (RSD) had the lowest respiration rate per unit of organic matter. These materials also had the highest C/N ratios, at 30:1, 16:1, and 17:1 for WS, CG, and RSD respectively.

In the blends made both with and without sand (YF vs. YF 100, LF vs. LF 100 and YLF vs. YLF 100), the blends without sand have significantly higher rates of respiration than their counterparts with sand when respiration is measured per unit of total solids (Figure 6). With this measurement it is possible to see that per unit of weight, the most biological activity is in the 50% yard waste + 50% biosolids blend (YF 100) due to the higher organic matter content in the blend and the biological accessibility of the carbon in the yard waste fines. The yard waste fines blend with sand (YF) had the highest rate of respiration per unit of weight of any material with sand other than the almond fines blend (AF), although this was not significant at $p \leq 0.05$. Materials which have higher rates of respiration per unit of total solids have a greater potential for self-heating. In terms of stability or potential for phytotoxicity however, it is respiration per unit of organic matter which best assesses whether the biodegradable material in a blend is decomposing too rapidly or not. Respiration per unit of weight does not provide a clear picture of how stable the organic matter of a material is as different materials can have different organic matter content (Brinton 2012). When using respiration per unit of organic matter to assess a soil amendments potential for phytotoxicity, it is important to note that if the amount of organic matter in a material is extremely small, even if this organic matter is highly unstable, there is less potential for the VOA production or oxygen depletion associated with microbial activity (Brinton and Tränkner 1999) to reach phytotoxic levels.

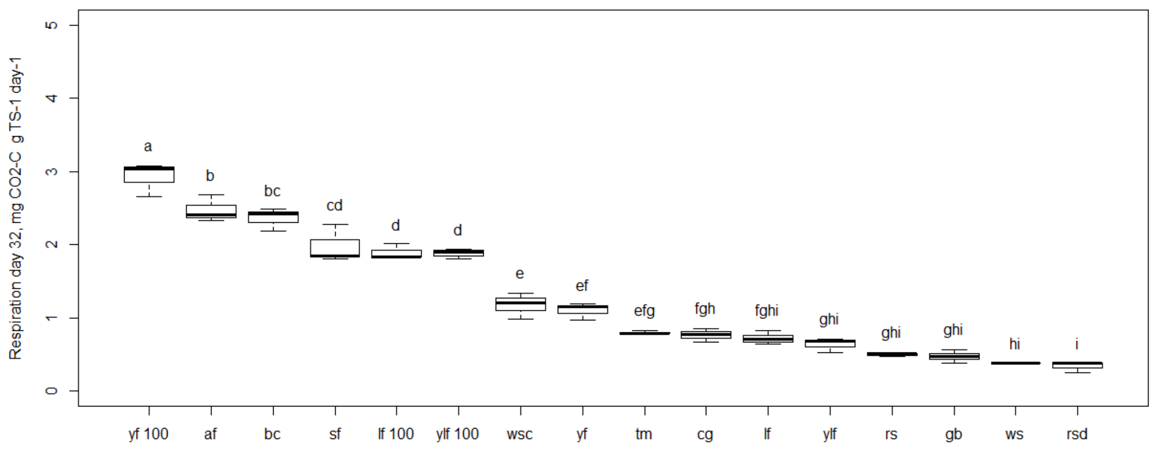


Figure 6. Microbial respiration per unit of total solids from composite samples taken on day 32 (n=3). Results with different letters are significantly different at $p \leq 0.05$. Treatments are in order of greatest to lowest mean respiration. Exterior bars represent maximum and minimum values, interior bar represents median value, boxes represent upper and lower quartile.

Respiration measured using an infrared gas analyzer was possibly inaccurate as the equipment is designed to measure soil respiration, which is typically below 12 ɥmol CO_2 m^{-2} s^{-1} (Shi et al. 2012; Hibbard et al. 2005), while values seen in the blends were as high as 559 ɥmol CO_2 m^{-2} s^{-1} for the almond fines blend (Figure 6). In addition, the IFRG measurements are an average of the respiration over a time span of several minutes. In contrast the NaOH trap method measures respiration across 4 days. Duplicate measurements on the almond fines blend showed high rates of variability on the same sample. The IFRG method is still helpful in identifying large trends though and the IFRG measurements corroborated the NaOH trap measurements in Figures 5 and 6. The almond fines (AF) blend is shown to be highly unstable and blends with more bioavailable carbon in the form of yard waste also exhibit more microbial activity. For both methods the yard waste fines blends (YF, YF 100) had high rates of respiration.

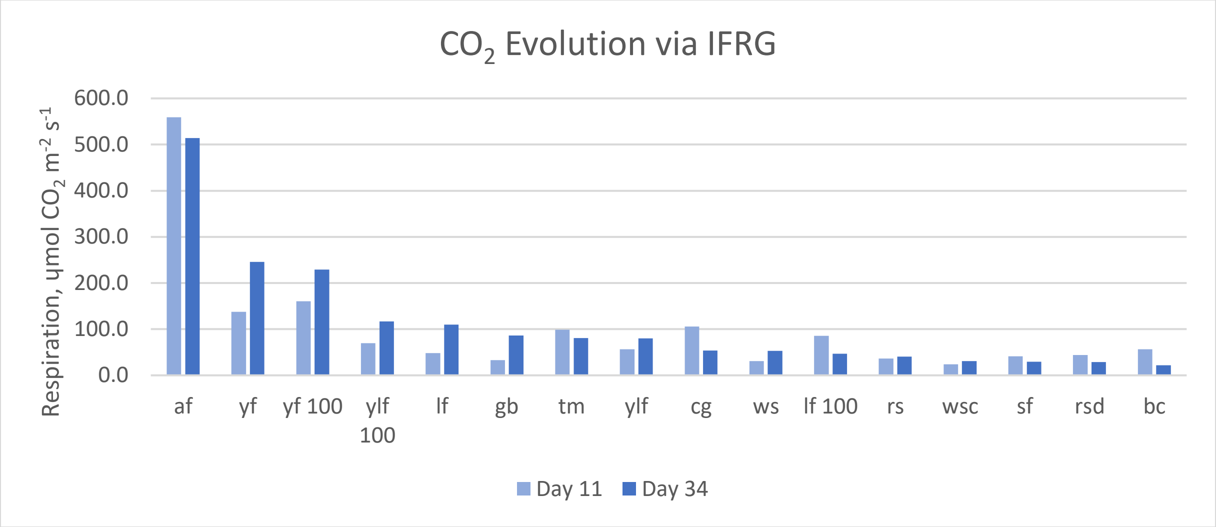


Figure 7. CO_2 evolution measured by IFRG on day 11 and day 34 (n=1). Treatments are ranked from highest to lowest respiration rate on day 34.

5.2.5 Available N

The Test Methods for the Examination of Compost and Composting (TMECC, USCC 2002), recommend two different sample preparation methods for available N analysis. One method involves air drying and homogenization followed by sieving while the other recommendation is simply to sieve the material wet. There were concerns that ammonia volatilization during air drying would cause a significant loss of available N so both methods were used. Indeed, in unblended biosolids (SF), there was a large drop in ammonium concentration in samples that were air dried compared to those processed wet (Figure 8). Also telling of the potential for volatilization during air drying, the walnut shell char blend (WSC), which had a pH of over 10, had virtually no ammonium in either duplicate which was air dried, suggesting that under alkaline conditions and a slightly elevated temperature, free ammonium in WSC quickly volatilized. This potential for volatilization in WSC is probably also why its ammonium content was the lowest of any treatment containing biosolids in both the samples that were processed wet and those that were air dried. Due to the loss of ammonia during air drying, only measurements made using fresh material were used in the analysis of variables affecting plant growth.

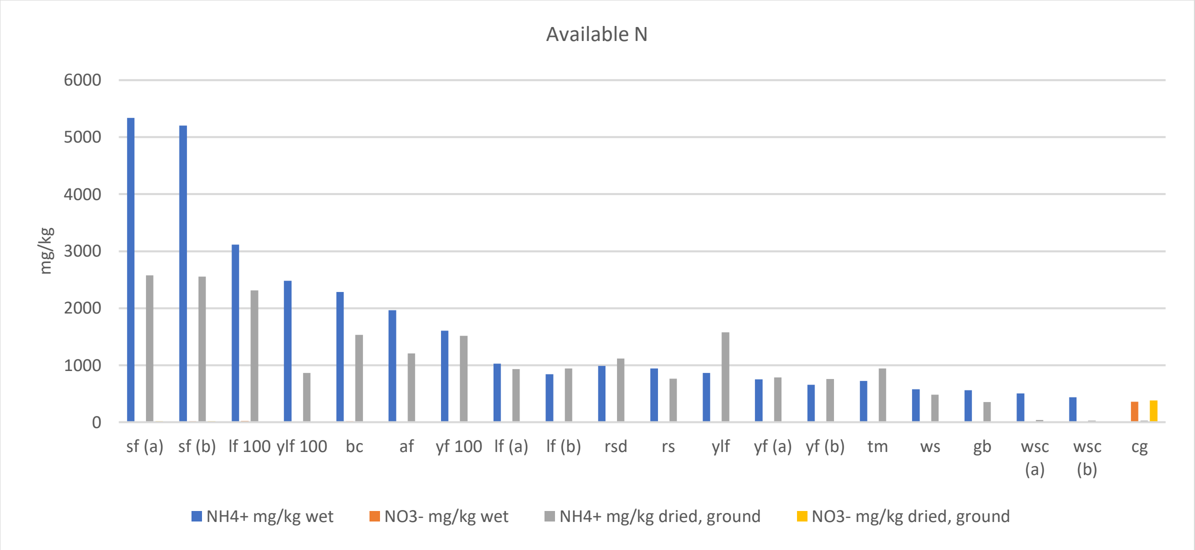


Figure 8. Available N from samples taken on Day 32. Treatments are in order of highest to lowest ammonium content. The qualifiers "wet" and "dried, ground" denotes how samples were prepared. Values for duplicate samples are shown next to each other. All concentrations are reported on a dry weight basis. Nitrate values are insignificant and not visible for all treatments except Cedar Grove Compost (CG).

Again the addition of sand, which is much heavier than any of the other materials and virtually devoid of N, greatly affects the available N measured in the different treatments. With the exception of almond fines blend (AF) and the walnut shell char blend (WSC), every biosolids blend that did not contain sand had higher levels of ammonium than the blends which contained 20% sand by volume. The almond fines blend (AF) contained sand, but was a mixture of two materials with over 3% N content which increased available N concentrations. The walnut shell char blend (WSC), did not contain sand, but experienced high rates of N loss to ammonia volatilization.

Ammonium concentration appeared to be mainly a function of total N content (Figures 9 and 10). The N content of treatments explained 60% of the variation seen in ammonium concentrations, and when the Cedar Grove compost (CG) control and the walnut shell char blend (WSC) with high rates of volatilization were removed, N content explained 87% of variation in ammonium. C:N ratio was not as accurate a predictor of ammonium concentration (Figure 11) and even with CG and WSC removed, C:N was only correlated with ammonium levels at p=0.097. The fact that ammonium content was more closely correlated with total N content than any other variable suggests that N mineralization rates were similar in all blends although total N levels varied between them.

Nitrate was not present in appreciable amounts in any of the blends which contained biosolids. Nitrifying bacteria are inhibited starting at ammonium concentrations as low as 400 mg/kg (Smith et al. 1998) and in low pH, high salt conditions (Malhi and Mcgill 1982). Ammonium concentrations in the treatments with biosolids were all above 400 mg/kg, explaining why there was no accumulation of nitrate. Cedar Grove compost, which contained no biosolids, was the only material with an appreciable amount of nitrate, at 357 mg/kg.

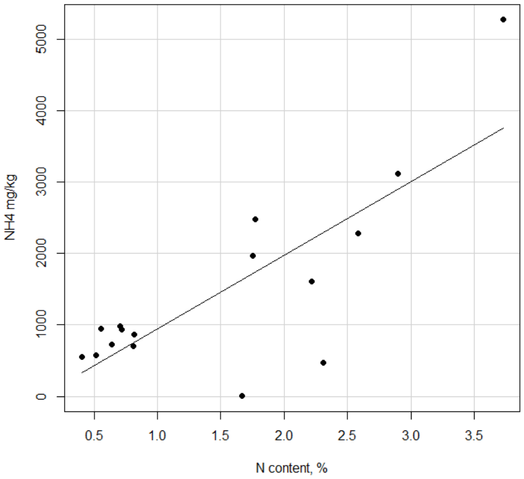


Figure 9. Ammonium concentration as a function of mean total N content. Ammonium and N content from samples taken on Day 32 Adjusted r^2: 0.60, p-value: <0.001

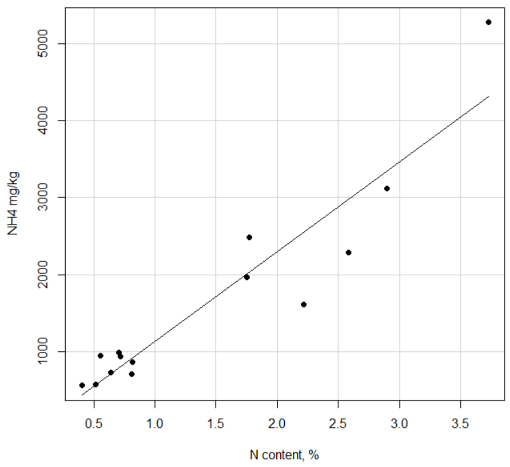


Figure 10. Ammonium concentration as a function of mean total N content in blends. Ammonium and N content from samples taken on day 32. Materials with little ammonium content removed: Cedar Grove compost (Low ammonium control without biosolids) and WSC (low ammonium due to high NH_3 volatilization). Adjusted r^2: 0.87, p-value: <0.001

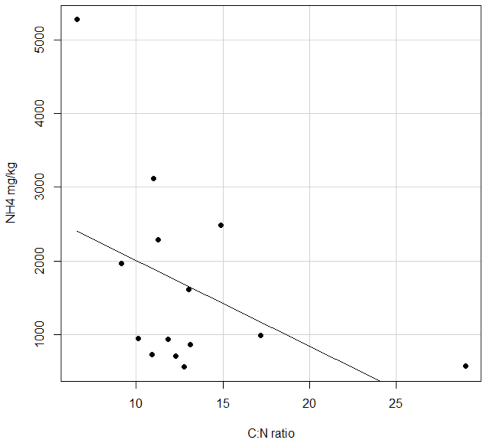


Figure 11. Ammonium concentration as a function of C:N ratio in blends with Cedar Grove compost (control) and WSC (high NH3 volatilization) removed. Adjusted R^2: 0.15, p-value: 0.097

5.2.6 Total N

Total N of the treatments was a function of the initial N content in the feedstocks and the biosolids. Addition of sand again greatly affected the N content, which is measured as a percentage of total weight (Figure 12). Of all the blends with sand added, the almond fines blend (AF), a mixture of two materials with N content over 3%, had the highest total N content. All other blends with sand had significantly lower N content than blends without sand.

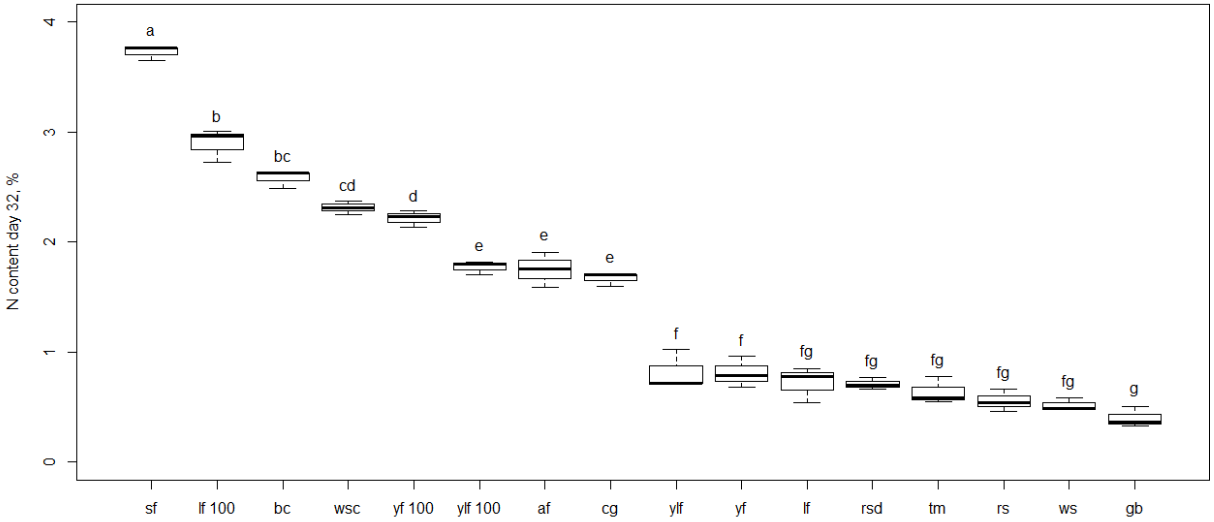


Figure 12.Total N content of blends from composite samples taken on day 32 (n=3). Results with different letters are significantly different at p <0.05. Treatments are in order of greatest to lowest mean total N. Exterior bars represent maximum and minimum values, interior bar represents median value, boxes represent upper and lower quartile.

The final N content of the blends was largely a question of averaging the N content of the initial feedstocks and the biosolids. For example, the 50% biosolids + 50% yard waste fines blend (YF 100) combined two materials which were 3.80 and 0.62% N. The average of these two values is 2.21%, which is the same value as the mean N content in the YF 100 blend (n=3). The bulk density of these two materials, biosolids and yard waste fines, happens to be identical (0.20 g/cm^3) but when materials of different density are used, the gravimetric, as opposed to volumetric proportions of each material in the blend must be used when calculating the predicted N content. Table 9 is an example of this calculation. Figure 13 shows that predicting N content of blends based on N content of feedstocks is relatively accurate. Differences between predicted and measured values could be due to ammonia volatilization when N is overpredicted, C mineralization when N is underpredicted or due to imprecision in bulk density measurements and volume measurement during blending.

Table 9. Example of calculating predicted total N in blends based on feedstock N content and bulk density for the 25% yard waste + 25% biochar + 50% biosolids blend (BC).

Material	N content, %	Bulk Density, g/cm^3	% of blend by volume	% of blend by weight	Contribution to Total N
Biosolids	3.8	0.2	0.5	0.56	2.14
Yard waste fines	0.62	0.2	0.25	0.28	0.17
Biochar	0.13	0.11	0.25	0.15	0.02
			Calculated Total N		2.34
			Measured Total N		2.58

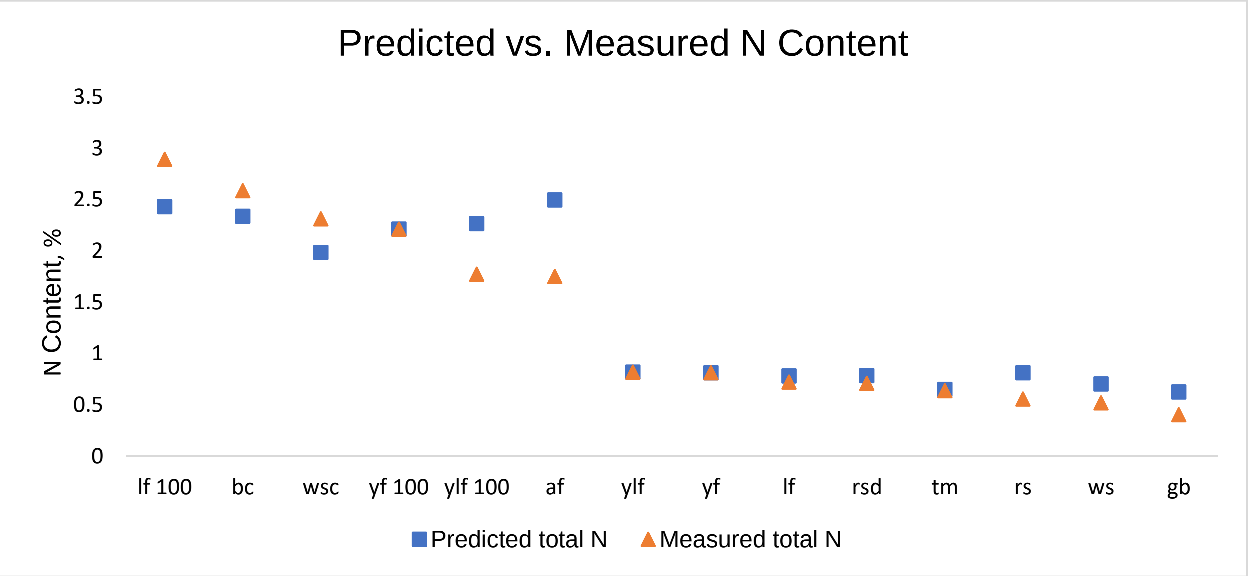


Figure 13. Predicted versus measured total N. Predicted values are from calculations using measured feedstock total N shown in Table 9. Measured values are mean of composite samples taken from day 32.

5.2.7 C:N Ratio

The C:N ratio of the blends depended on the initial C and N content of the materials being mixed as well as C loss to respiration and N loss to volatilization. SFPUC biosolids (SF), had a mean C content of 28.6% (n=3) when measured with other feedstocks on 2/9/2017, but 32 days after the blends had been mixed (51 days later on 3/26), this had dropped to a mean of 24.5%, (n=3) representing a 14% decrease. The respiration rate of the biosolids measured on day 32, 3.7 mg CO_2-C g OM^{-1} day^{-1}, accounts for a 12% decrease in C content. It is possible that respiration rates were higher before day 32, which would account for the remaining 2% decrease in C content. N content in the biosolids also dropped from a mean of 3.80% to 3.73% (n=3), representing a roughly 2% decrease in total N content. This drop in N content is within the margin of error and may not represent a real change due to ammonia volatilization.

Common recommendations for compost require a minimum C:N ratio of 10:1 and a maximum ratio of 25:1 (Crohn 2016). The walnut shell blend (WS) exceeded the maximum due to a feedstock with both a high C:N ratio of 149 and a relatively high bulk density of 0.35 g/cm^3 which meant the C:N ratio of the walnut shells exerted a larger influence on the final ratio of the blend which was mixed volumetrically. Both the almond fines blend (AF) and the unblended biosolids (SF) had C:N ratios which were below 10:1 (Figure 14).

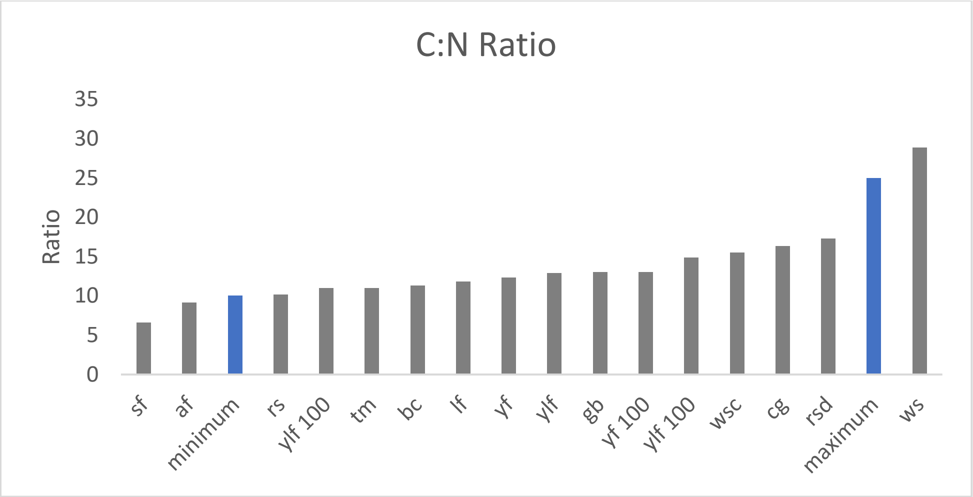


Figure 14. C:N ratio of blends from samples taken on day 32. Treatments are ranked from lowest to highest C:N ratio. Common minimum and maximum limits for compost are included (Crohn 2016). C:N ratios are calculated as the ratio between the mean of 3 replicates of total C and the mean of 3 replicates of total N for each material.

5.2.8 Physical characteristics

Particle size distribution by weight was simply a function of particle size distribution in the initial feedstocks. Requirements for particle size distribution vary greatly depending on the intended use of a soil amendment. A basic requirement is at least 95% of material passing through a 16mm sieve and at least 70% passing through a 9.5mm sieve (Caltrans 2015). All the blends met this requirement although the Cedar Grove compost control (CG), had slightly less than 70% of material passing through a 9.5mm sieve (Figure 15). Contamination with inert materials such as glass, plastic, metal or foam was not an issue in any material except for the gypsum board blend (GB), which contained 0.3% contamination content by weight. The gypsum board feedstock contained a mean of 1.2% contamination by weight. Blends which contained sand, a feedstock with more than 80% passing through the 2mm sieve, had a larger portion of material by weight passing through the 2mm sieve than blends which were not mixed with sand.

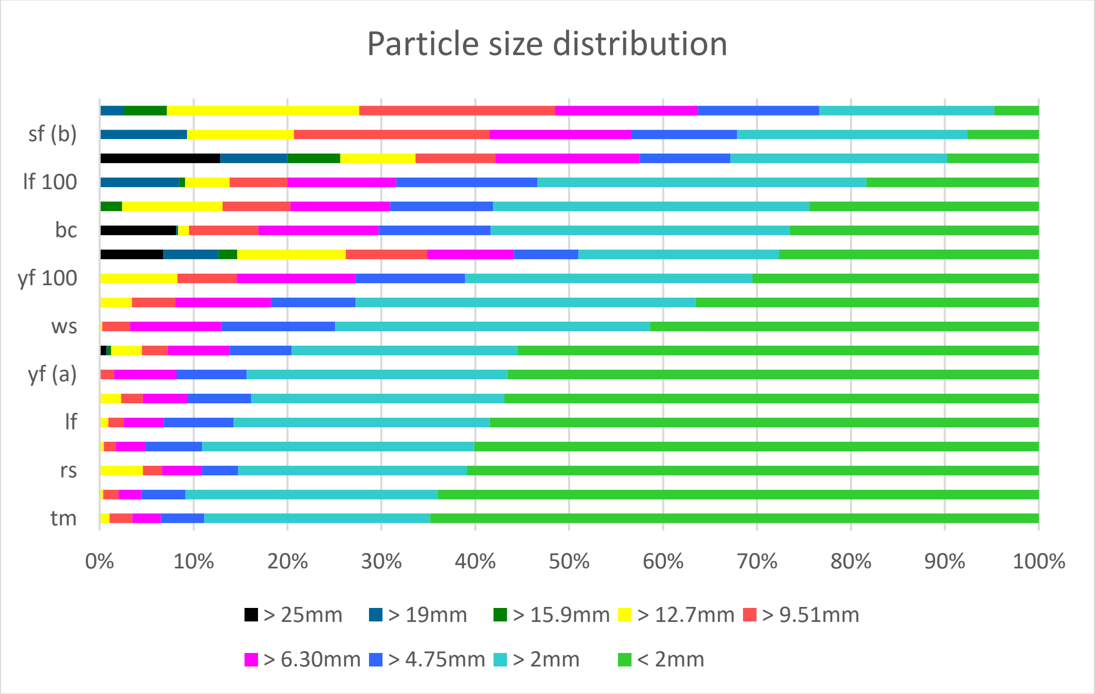


Figure 15. Particle size distribution of treatments measured on samples taken from day 32. Duplicate samples are shown next to each other.

Bulk density was higher in blends which contained sand. The gypsum board blend and walnut shell blend both contained relatively dense feedstocks at 0.55 and 0.35 g/cm^3 respectively and these blends had the highest bulk density. After gypsum board fines, almond fines was the feedstock with the highest bulk density, at 0.41 g/cm^3, however with high rates of respiration, 2.47 mg CO_2-C g TS^{-1} day^{-1} on day 32, there was at least an 8% loss in mass and probably even greater losses if respiration was higher during the initial weeks after the blend was created. This mineralization of carbon could be responsible for giving the almond fines blend a relatively low bulk density despite being made with a high bulk density feedstock.

The predicted bulk density of blends, calculated based on the volume of feedstocks in each blend and the bulk density of those feedstocks, is generally close to the actual measured bulk density of the blends (Figure 16). Every blended treatment other than Tagro Mix (TM) has a measured bulk density lower than the predicted bulk density, suggesting that CO_2 respiration may have caused the blends to lose mass. Tagro Mix was the only material blended with city of Tacoma biosolids as opposed to San Francisco biosolids and possibly behaved differently as a result. Biosolids mixed with yard waste has been shown to increase bulk density as macro and mesopores are filled in (Belyaeva et al. 2012) and this could be happening with the Tagro Mix. It is also possible that this was an inaccurate bulk density measurement.

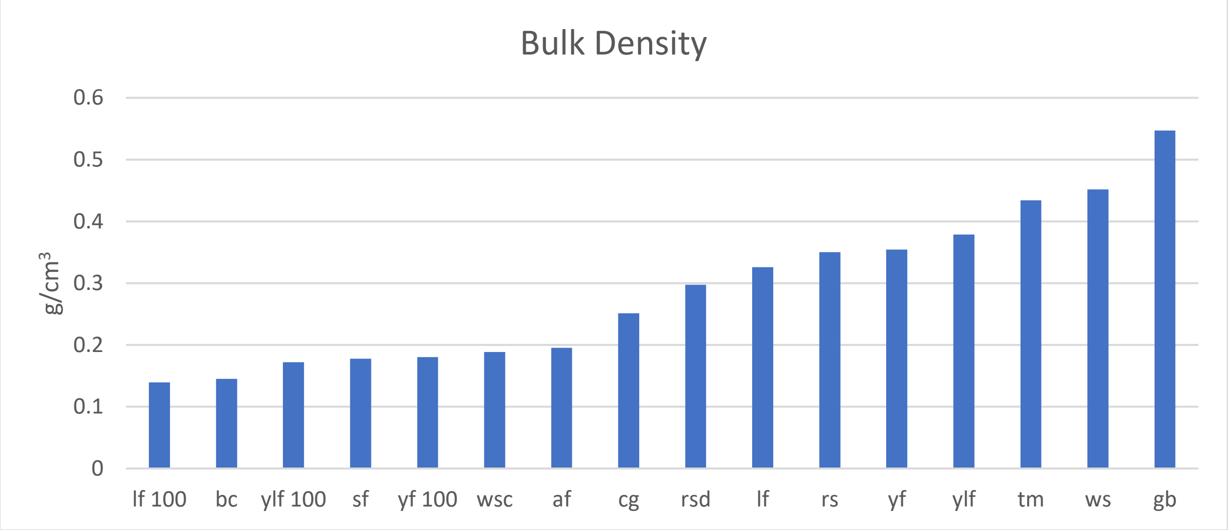


Figure 16. Bulk density of blends from samples taken on day 32 (n=1).

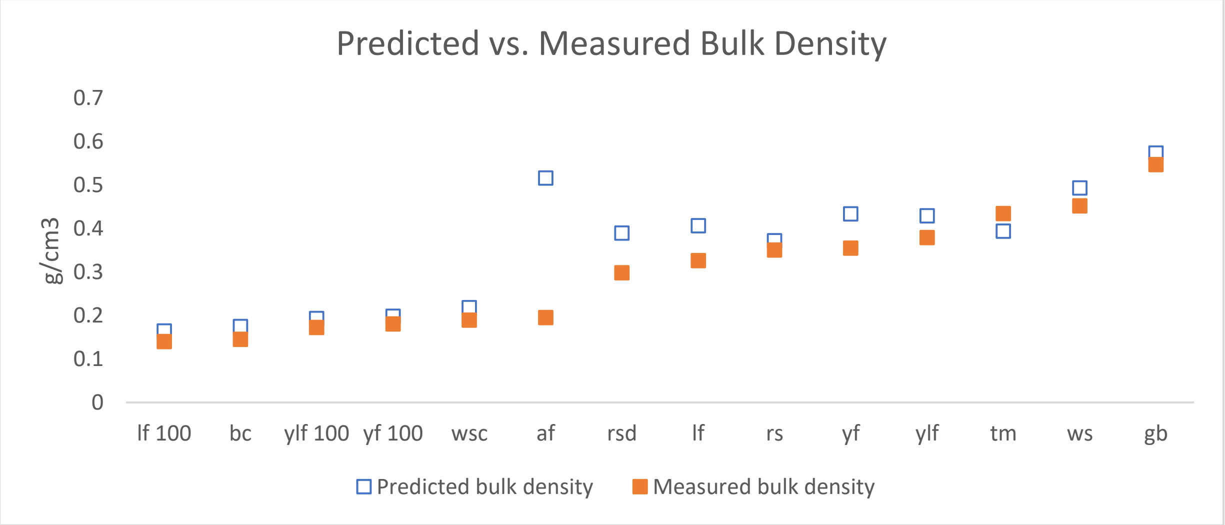


Figure 17. Predicted versus measured bulk density from Day 32. Predicted bulk density is calculated from the measured bulk density of feedstocks and the volume of each feedstock in blends. Unblended biosolids (SF) and Cedar Grove compost (CG) were not created by blending different materials and are not included in this figure.

5.2.9 Parameters used to judge soil amendment quality

While the bulk density, particle size, C:N ratio, OM%, and total N content of the blended amendments were largely determined by the values and mixing ratios of the initial feedstocks other properties were altered by biological activity. EC, pH, available N, and to some extent C:N ratio and OM%, were modified over the course of 32 days of curing. Measurable CO_2 flux showed that the blended amendments were all biologically active and this activity impacts certain properties in the blends.

Specifications for soil amendments vary depending on a project's goals. Basic specifications for compost used by state department of transportation agencies can be taken as a general set of acceptable ranges for soil amendments. It is possible that blended biosolids products may still perform well as a soil amendment even though they do not meet certain specifications for compost as these specifications are designed for a different purpose. For example, several blends which had a pH slightly below 6, a lower limit for pH in some compost specifications (Caltrans 2015; WSDOT 2016), were some of the best performing blends in the petunia growth trials. As AASHTO and TxDOT specifications have minimum pH requirements of 5.0 and 5.5, a minimum pH of 5.5 was set as a goal for this project (AASHTO 2010, TxDOT 2014). Despite these compost specifications being designed for a different type of soil amendment, they can still be useful in identifying red flags for phytotoxic conditions in the blended biosolids amendments. Table 10 reviews the acceptable ranges for each measurement that were discussed earlier in this section and whether treatments met those ranges. No blends had contamination with anthropogenic inerts (glass, plastic, metal, foam) above 1% by weight and this parameter has not been included in Table 10.

Table 10. Ability of treatments to meet common compost specification ranges. The sources for these ranges is described on pg. 38 and 39. No materials had contamination with anthropogenic inert material above 1% by weight and this specification has not been included in the table. Green values signify a blend falls within the range called for in specifications and red values mean that the blend falls outside of that range.

Treatment	Organic Matter	EC_5	pH	C:N Ratio	CO2 evolution
	> 30%	< 5 dS/m	5.5-8.5	10:1 - 25:1	< 8 mg CO_2-C mg OM^{-1} day^{-1}
af	28.69	1.60	6.49	9.13	8.63
bc	58.53	5.55	6.86	11.29	4.05
gb	13.41	2.31	7.34	12.77	3.53
lf	20.50	1.38	5.76	11.83	3.54
lf 100	66.37	4.08	5.72	10.99	2.85
rs	17.57	1.71	5.69	10.11	2.86
rsd	20.02	1.26	6.04	17.20	1.69
sf	53.44	7.17	6.23	6.57	3.71
ws	36.15	0.95	5.57	28.99	1.06
wsc	44.31	13.57	10.09	15.53	2.65
yf	21.18	1.33	6.05	12.28	5.21
yf 100	56.32	3.41	5.84	13.05	5.19
ylf	20.03	1.40	6.42	13.13	3.19
ylf 100	58.12	4.37	6.19	14.89	3.24

5.3 Odor and Aesthetics

5.3.1 Odor

The odor survey was performed on Day 1, Day 15 and Day 32 after mixing. Odor intensity was rated on a scale of 0 to +5, with 0 being an unnoticeable odor and +5 being a very strong odor. Participants used descriptors from the biosolids compost odor wheel (Suffet et al. 2012) to describe odors. Survey participants ranked odor quality on a scale of -3 to +3 (-3,-2,-1,0,+1,+2,+3) with negative values representing an offensive odor and positive values representing a pleasing odor. Statistical comparisons between the mean rank of treatments was performed on odor intensity and odor quality. The percentage of individuals who found a material's odor offensive to any degree was calculated. In order to assess the degree to which a material could be offensive or appealing as opposed to its median score, cumulative positive and negative ratings were calculated. A material's cumulative positive score was calculated by adding all positive scores, while a material's cumulative negative score was calculated by adding all negative scores. Cumulative positive and negative scores were normalized to the number of participants on Day 1 as not all participants were able to attend all three survey days.

The intensity of odor decreased from day 1 to day 32 in every blend except for the almond fines blend (AF) which had a dramatic increase in microbial activity between day 1 to day 32 (Figure 20). Previous work has shown a positive correlation between odor intensity and CO_2 flux from microbial activity for biosolids (Rosenfeld 1999). As part of a separate study, CO_2 flux measured weekly on cubic yard piles made from the biosolids and the yard waste fines used in this study showed microbial activity decreased steadily over the course of a month in both the blended and unblended biosolids (SFPUC internal data). As odor production (other than ammonia) is microbially mediated, this decrease in microbial activity can explain the reduction in odor intensity seen between day 1 and day 32 in the treatments. In particular, production of reduced sulfur compounds is shown to decrease in biosolids over time (Drennan and Distefano 2010). Ammonia volatilization in biosolids also decreases over time (Harmel et al. 1997; Drennan and Distefano 2010) which is another explanation for the decrease in odor in the blends from day 1 to day 32.

On Day 32 odor intensity was lowest in the Cedar Grove control (CG) while the Tagro Mix control (TM), had the 4th most intense odor of any material (Figure 19). As discussed earlier, a threshold for public acceptability was set as less than 30% of respondents finding odor offensive. By Day 32, the majority of blends (10 out of 13) met this threshold.

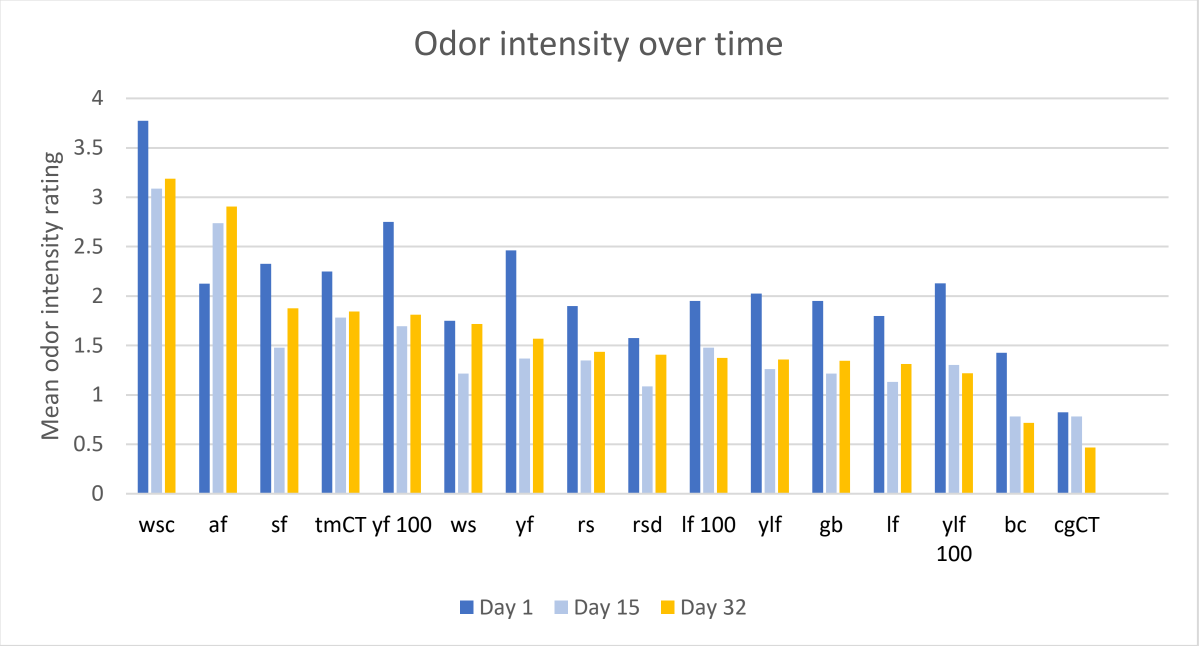


Figure 18. Intensity of odor on days 1, 15, and 32. Odor was ranked on a scale of 0 to 5 with 5 being the most intense odor. Values in this chart are the mean intensity for a material from all rankings on that day. Treatments in this figure are ranked in order of highest to lowest intensity on day 32. CT represents a control amendment, either Tagro Mix (TM) or Cedar Grove compost (CG). Values for unblended biosolids (SF) and the yard waste fines blend (YF) are the mean of duplicate samples.

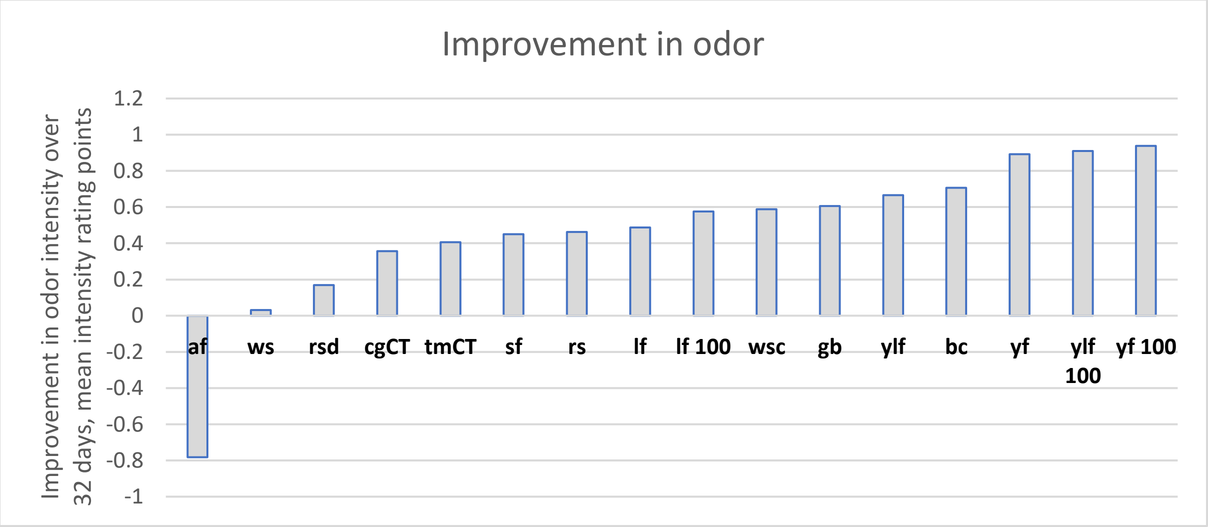


Figure 19. Improvement in odor intensity over 32 days. Ratings were calculated on a 0 to 5 scale. Positive values show the improvement in odor intensity over 32 days, i.e. the drop in mean odor intensity rating on the 0 to 5 scale between Day 1 and Day 32. Negative values show a worsening of odor intensity, i.e. the increase in mean odor intensity rating between Day 1 and 32. CT denotes a control amendment, either Tagro Mix (TM) or Cedar Grove compost (CG). Values for unblended biosolids (SF) and the yard waste fines blend (YF) are the mean of duplicate samples.

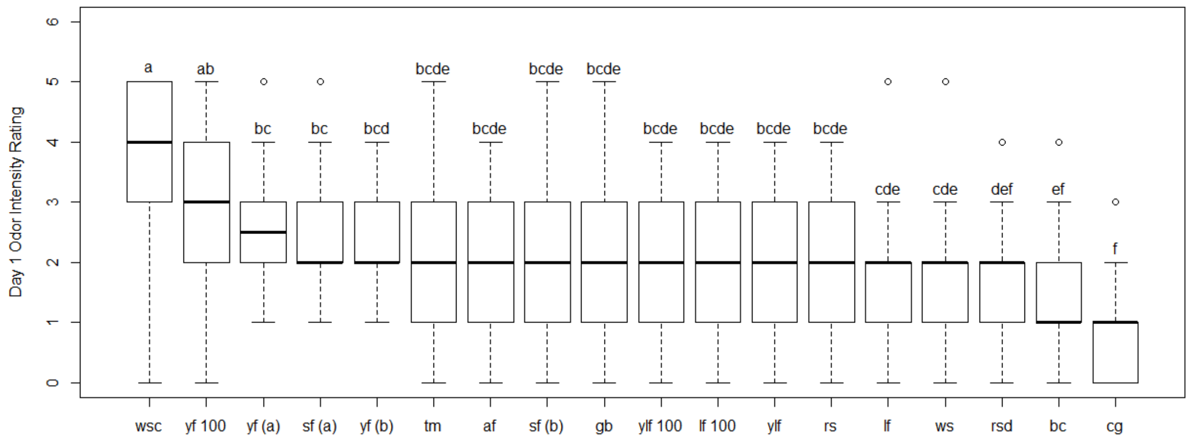


Figure 20. Comparison of mean rank in odor intensity rating of treatments on Day 1. Results with different letters are significantly different at $p < 0.05$. Treatments are in order of greatest to lowest mean rank. Exterior bars represent maximum and minimum values, interior bar represents median value, boxes represent upper and lower quartile. Open circles represent outlying values. Duplicate samples in SF and YF are denoted by the letters (a) and (b)

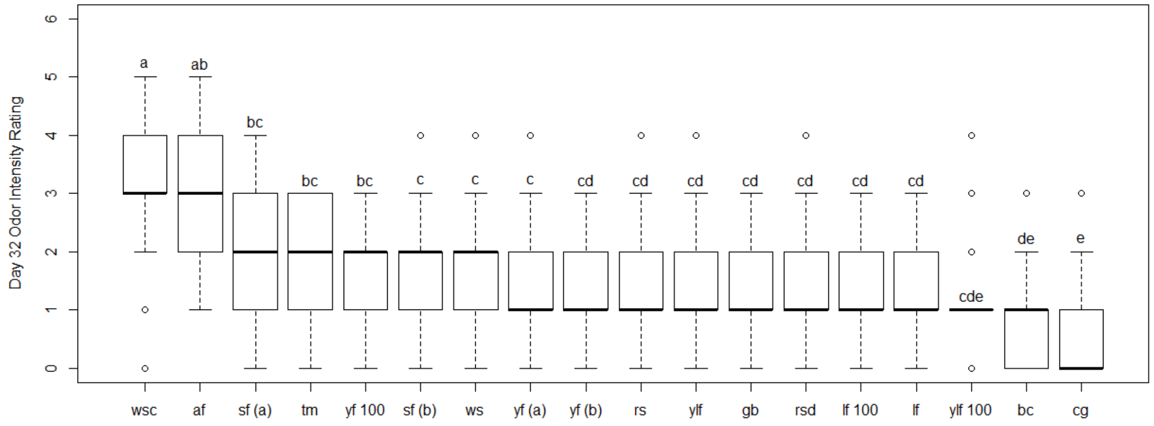


Figure 21. Comparison of mean rank in odor intensity rating of treatments on Day 32. Results with different letters are significantly different at $p < 0.05$. Treatments are in order of greatest to lowest mean rank. Exterior bars represent maximum and minimum values, interior bar represents median value, boxes represent upper and lower quartile. Open circles represent outlying values. Duplicate samples in SF and YF are denoted by the letters (a) and (b).

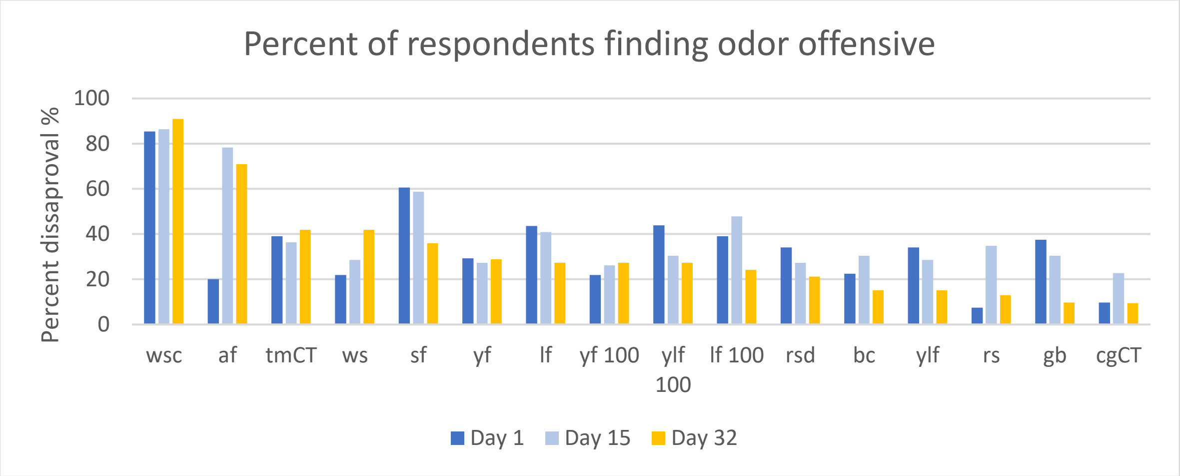


Figure 22. Percent of respondents finding odor offensive on days 1, 15, and 32. Any rating of -1,-2,-3 was counted as a respondent finding odor offensive. Treatments are ranked by highest to lowest percent of respondents finding odor offensive on day 32. CT represents a control amendment, either Tagro Mix (TM) or Cedar Grove compost (CG). Values for unblended biosolids (SF) and the yard waste fines blend (YF) are the mean of duplicate samples.

Of the control treatments tested, the survey participants found Cedar Grove compost (CG) to have a relatively inoffensive and unnoticeable odor. On day 32, the compost had the lowest odor intensity rank and the lowest percentage of respondents finding the odor offensive. This favorable assessment of the blend by respondents may be related to the stability of the blend. The respiration rate of 1.4 mg CO_2-C gOM^{-1} day^{-1} was one of the lowest measured. In addition, Cedar Grove had the lowest ammonium concentration of any material reducing the potential for ammonia volatilization. The biosolids amendment control, Tagro Mix (TM), was ranked as having a more intense odor Day 32 than every material except the almond fines blend, walnut shell char blend and unblended biosolids (AF, WSC, and SF). Out of 16 materials TM had 14th highest percentage of respondents finding odor offensive on Day 32. Tagro Mix was the only biosolids product in the odor trial made with Tacoma biosolids and all other blends had San Francisco biosolids. The difference in biosolids may have as much to do with the odor ratings of Tagro Mix as the feedstocks and ratios used to make the blend.

On Day 32, two blends were statistically similar to the odor intensity of Cedar Grove compost.

All blends other than the walnut shell char (WSC) were statistically similar or lower to the odor intensity of the Tagro Mix control (Figure 21) on Day 32. As both Cedar Grove compost and Tagro Mix are successfully marketed to the general public, this suggests that all blends other than WSC could be used in a variety of applications without significant problems due to odor.

Of the different materials tested the biochar blend (BC) had the lowest odor intensity rank after Cedar Grove compost (CG). As Rosenfeld et al. (1999) and Ahmed et al. (2016) demonstrated, activated carbon is effective at adsorbing odors due to its reactivity and large surface area. Biochar can have high surface area and behave like activated carbon. This is likely why the biochar blend rated favorably for odors.

The gypsum board blend (GB) had the second lowest percentage of respondents finding odor offensive and second best odor quality rank on Day 32 (Figure 23 and 24). Decreases in ammonia volatilization ranging from 13-66% were reported when Gypsum was added during composting (Tubail et al., 2008). The proposed mechanism for this observed reduction was the conversion of ammonium carbonate to ammonium sulfate which is less prone to volatilize (Tubail et al. 2008). Gypsum ($CaSO_4$) content was not measured in the gypsum board feedstock, although the gypsum board and biosolids blend measured with the Mehlich III extraction contained 1.2% Ca and 0.6% S by weight, with a volumetric sulfur content more than 5 times higher than any other material, and was made from ground gypsum board, suggesting an appreciable gypsum content. It is possible the gypsum board blend (GB) had low ammonia volatilization due to gypsum content although actual analysis of gypsum content would need to be performed to test this hypothesis.

Respondents judged several of the mixtures to have very offensive odors. Walnut shell char (WSC) consistently ranked as the blend with the highest odor intensity and the most offensive odor quality over the three survey sessions. Due to the blend’s high pH of 10, there was a high rate of ammonia volatilization. This is corroborated by the fact that the most commonly used description of WSC from the odor wheel provided was “ammonia”. The ammonia volatilization began almost immediately after mixing as survey respondents sampled odors within the first 24 hours after the blends were created and found WSC to have strong ammonia odors on Day 1.

While the walnut shell char blend had an offensive odor almost immediately, respondents initially found the almond fines blend (AF) to have a pleasant odor, ranking it second to only the redwood shavings blend in terms of pleasant odor and most commonly describing the odor as “woody” on Day 1. However, due to the low C:N ratio and relatively high N concentration of the blend, there was a large increase in microbial activity between Days 1 and 15. On Day 15 and Day 32, AF ranked worse than every blend other than WSC in terms of odor quality and intensity, with the most common descriptor on both days being “moldy”.

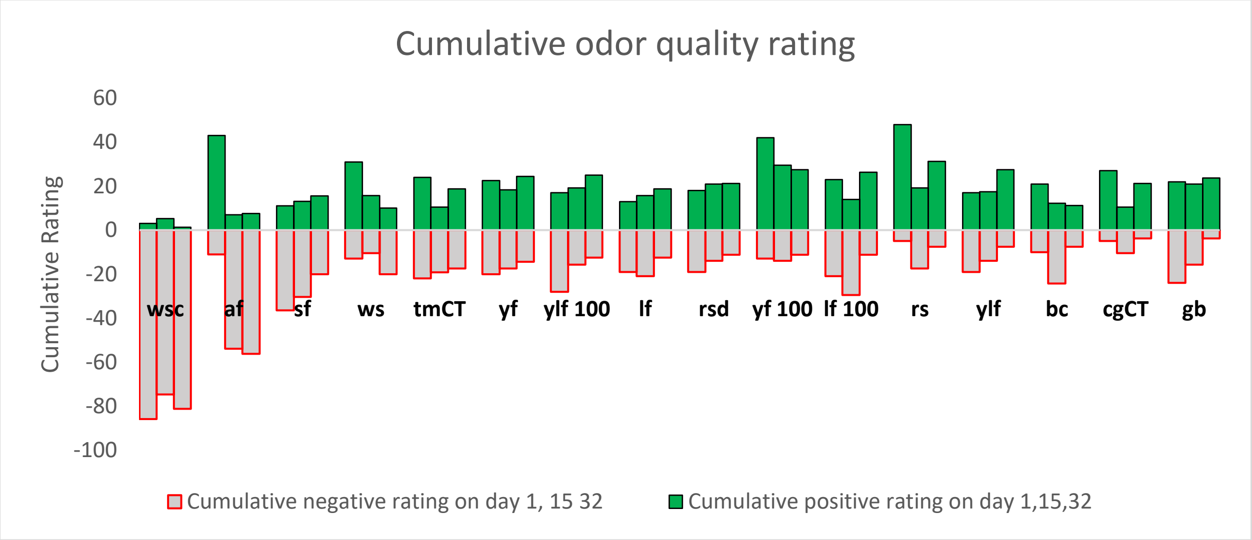


Figure 23. Cumulative negative and positive odor ratings on Days 1, 15, and 32. For each treatment, the first bar represents Day 1, the second bar represents Day 15, and the third bar represents Day 32. Cumulative positive rating is the sum of all positive ratings a material received (+1, +2, or +3). Cumulative negative rating is the sum of all negative ratings (-1,-2,-3). Treatments are ranked by lowest negative rating on day 32. CT represents a control amendment, either Tagro Mix (TM) or Cedar Grove compost (CG). Values for unblended biosolids (SF) and the yard waste fines blend (YF) are the mean of duplicate samples.

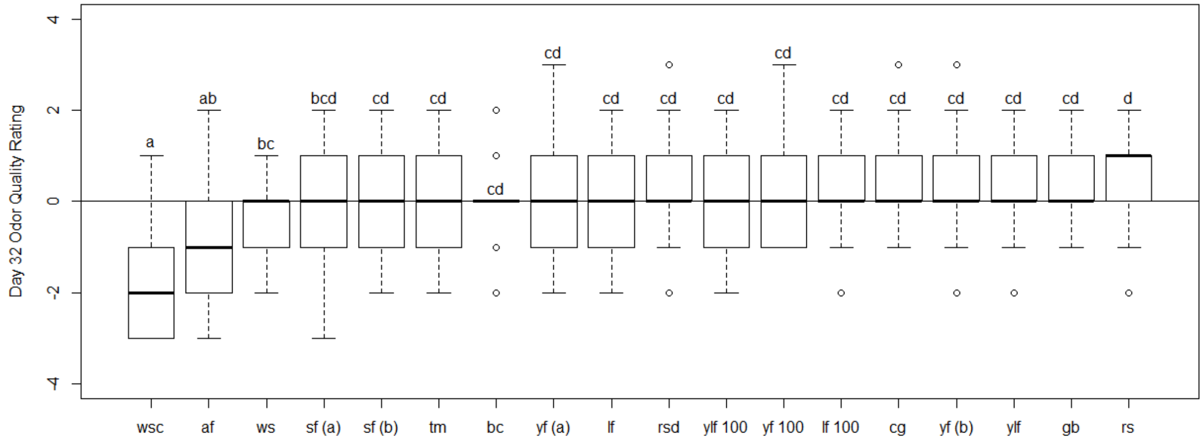


Figure 24. Comparison of mean rank in odor quality rating of treatments on Day 32. Results with different letters are significantly different at p <0.05. Treatments are in order of greatest to lowest mean rank. Exterior bars represent maximum and minimum values, interior bar represents median value, boxes represent upper and lower quartile. Dots represent outlying values. Duplicate samples in SF and YF are denoted by the letters (a) and (b).

It is difficult to determine precise mechanisms behind negative odors. Different mechanisms are likely responsible for offensive odors across the different blends in this study. One potential explanation for inoffensive odors is low C content. As described earlier, the gypsum board blend (GB) was found to have very low odors. Other than sand, GB had the lowest C content of any feedstock with just 4.4% C by weight. When analyzing Day 32 odors of just the blends created with SFPUC biosolids and excluding controls which had different mechanisms for odor production, increasing volumetric C content was correlated with higher odor intensity (p=0.007), worse negative odor rating (p=0.003), worse positive odor rating (p=0.002), and increased percentage of respondents finding odor offensive (p<0.001) (Figures 25-38). Increasing volumetric N content was also significantly correlated with worse negative odor rating (p=0.022), increased percentage of respondents finding odor offensive (p=0.017), and increased odor intensity (p=0.022), but negative correlation with positive ratings was weaker (p=0.076). It appears that higher quantities of C in blends led to higher odor production by providing more material for microbes to break down. However, there was no significant correlation with measurements of odor and respiration other than a weak correlation between intensity on Day 32 and respiration per unit of volume on Day 32 at p=0.099. Stepwise regression showed that the addition of multiple variables did not improve single variable models for explaining measurements of odor.

Due to their extreme negative odors, WSC and AF acted as leverage points for statistical analysis to find more significance in pH and EC (due to high levels of these measures in WSC) and CO_2 flux per unit of OM (due to high levels in AF). High pH and CO_2 flux per unit of OM appear to be good predictors of odors in biosolids products with highly offensive odors, but they do not explain variation in odor quality between the other treatments. Other than the two materials with the most intense odors (WSC and AF), and the two with the least intense odors (CG and BC), there was little variability in mean odor intensity rankings with the remaining materials having statistically similar odor intensity rankings on Day 32. This lack of variation makes it difficult to find clear trends. When removing WSC and AF from the analysis, volumetric C content remains a significant predictor of odor with increasing C content associated with worse odor. With WSC (pH 10.1) and AF (pH 6.5) removed pH becomes significantly correlated with negative odor rating in the opposite direction, with pH increasing to closer to neutral correlated with less offensive odors (p=0.025). (Figure 29). The pH in the remaining mixtures ranged from 5.6 to 7.3.

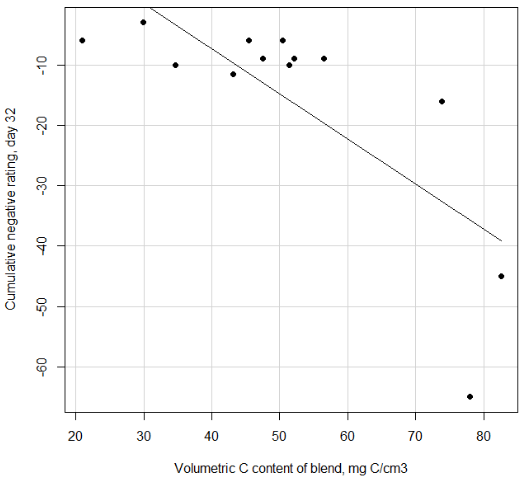


Figure 25. Cumulative negative rating on day 32 vs. Volumetric C content. Blends only, no controls. Adjusted r^2: 0.52, P value: 0.003

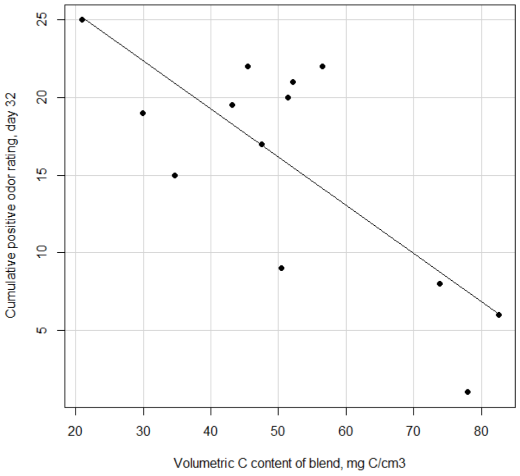


Figure 26. Cumulative positive rating on day 32 vs. Volumetric C content. Blends only, no controls. Adjusted r^2: 0.55, P value: 0.002

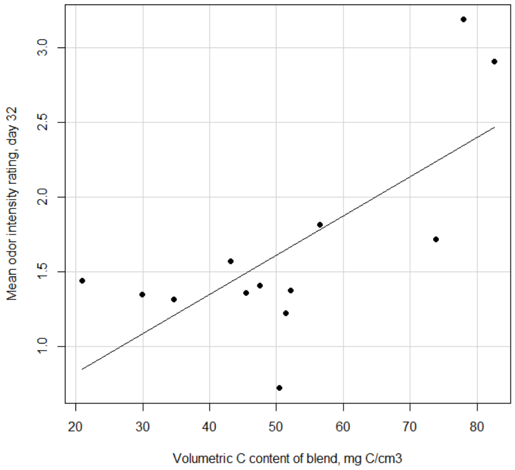


Figure 27. Mean odor intensity on day 32 vs Volumetric C content. Blends only, no controls. Adjusted r^2: 0.46, P value: 0.007

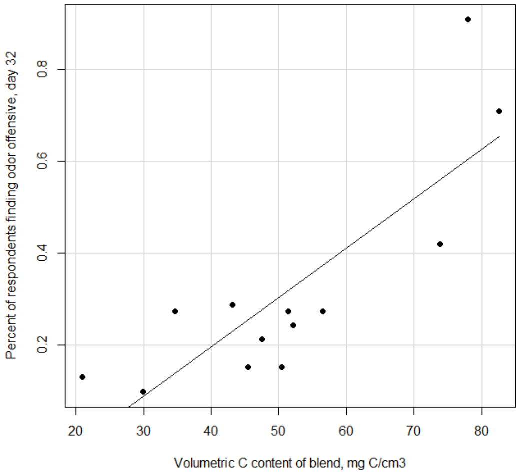


Figure 28. Percent of respondents finding odor offensive on day 32 vs. Volumetric C content. Blends only, no controls. Adjusted r^2: 0.65, P value<0.001

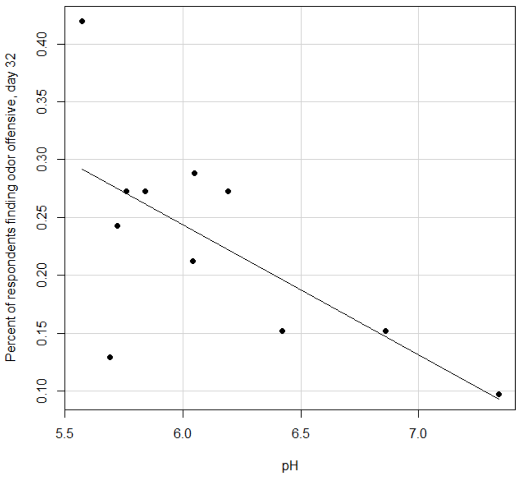


Figure 29 Percent of respondents finding odor offensive on day 32 vs pH. Blends only, no controls, AF and WSC leverage points removed. Adjusted R^2: 0.38, P value: 0.035.

The methods used in this study for evaluating odors allowed for a better understanding of their quality and characteristics but are less precise than a dilution to threshold measurement using olfactometers. It was also possibly difficult for respondents to distinguish between odor intensity and negative odors. Odor intensity was strongly correlated with the cumulative negative rating and percent negative rating of blends($p<.001$). Two duplicates were used during odor surveys to evaluate the precision of respondents in assessing odors (Table 11). While in general respondents gave similar ratings to the duplicates including some matching ratings, there is clearly variation in the ratings given to identical materials by the same individuals.

With more precise measurements of odor as well as controlling for certain variables like pH or microbial activity, a better understanding of odor production in these treatments would be possible. There are several points that are clear from the results of this study as well as the literature though. A biosolids product with a pH of 10 has high rates of ammonia volatilization that individuals find offensive. A product with CO_2 flux greater than 8 mg CO_2-C gOM^{-1} day^{-1} is undergoing high rates of decomposition and can smell offensive. This is also the upper limit for respiration found in common compost specifications (TxDOT 2014; Caltrans 2015; WSDOT 2016; AASHTO 2010). The addition of biochar and gypsum appears to reduce the intensity of odors. Biochar with a high pH however can cause ammonia volatilization.

Table 11. Ratings given by respondents to duplicate odor samples on days 1, 15, and 32. Respondents were not aware there were duplicate samples.

		Day 1	Day 15	Day 32
Cumulative negative rating	sf	-40	-20	-18
	sf	-33	-15	-14
	yf	-17	-10	-9
	yf	-23	-10	-14
Cumulative positive rating	sf	10	8	10
	sf	12	7	15
	yf	25	12	22
	yf	20	9	17
Average intensity	sf	2.5	1.5	2.0
	sf	2.1	1.5	1.8
	yf	2.6	1.4	1.7
	yf	2.4	1.3	1.5
Percent finding odor quality offensive	sf	68	65	41
	sf	56	52	31
	yf	32	27	36
	yf	29	27	21
Most common odor descriptor	sf	earthy	earthy	earthy
	sf	musty	earthy	musty
	yf	earthy	earthy	earthy
	yf	earthy	earthy	earthy

While individuals gave varied odor descriptions from the supplied odor wheel for each blend, the most commonly used descriptor for every treatment other than almond fines (AF) and walnut shell char (WSC) was "earthy" (Table 12). This term does not represent a negative connotation. The odor wheel from Suffet et al. 2009 shows that earthy odors are an indication of geosmin. Geosmin has a very low detection threshold of 0.9 ppb (Korpi et al. 2009). It is best described as the smell of wet forest floor or of soil after rain and is a secondary metabolite of mesophilic actinomycetes, the dominant microbial actor during the final stages of composting and during compost curing (Jimnez and Garcia 1989).

Table 12. The most commonly used odor description from the biosolids compost odor wheel (Suffet et al. 2009) on Days 1, 15, and 32. SF has two descriptions on Days 1 and 32 as there were two replicates of this material on each day and the most commonly used descriptor was different for each replicate. Descriptions for the YF duplicate were identical on all three survey days.

		Most commonly used description of odor from odor wheel		
Treatment	**Ingredients**	**Day 1**	**Day 15**	**Day 32**
af	Almond fines/Biosolids/sand	woody	moldy	moldy
bc	Biochar/Biosolids/Yard Waste	earthy	earthy	earthy
cg	Cedar Grove	earthy	earthy	earthy
gb	Gypsum Fines/Biosolids/sand	earthy	earthy	earthy
lf	Lumber fines/Biosolids/sand	earthy	earthy	earthy
lf 100	Lumber fines/Biosolids	woody	earthy	earthy
rs	Redwood Shavings/Biosolids/sand	woody	earthy	earthy
rsd	Redwood Sawdust/Biosolids/sand	earthy	earthy	earthy
sf	SF Biosolids	earthy/musty	earthy	earthy/musty
tm	Tagro Mix	woody	earthy	earthy
ws	Walnut shells/Biosolids/sand	earthy	earthy	woody
wsc	Walnut shell char/Yardwaste/Biosolids	ammonia	ammonia	ammonia
yf	Yard waste/Biosolids/sand	earthy	earthy	earthy
yf 100	Yard waste/Biosolids	earthy	earthy	earthy
ylf	Yard-lumber fines/Biosolids/sand	earthy	earthy	earthy
ylf 100	Yard-lumber fines/Biosolids	musty	earthy	earthy

5.3.2 Appearance

The survey on appearance was performed only on Day 1 after mixing. Survey participants ranked appearance on a scale of -3 to +3 (-3,-2,-1,0,+1,+2,+3) with -3 being representing an offensive appearance and +3 representing a pleasing appearance. Statistical comparisons between the mean rank of treatments was performed (Figure 32). The percentage of individuals who found a material's appearance offensive to any degree was also calculated (Figure 30). This ranged from a high of 45% of individuals finding the appearance redwood sawdust blend (RSD) offensive, to a low of only 7.5% of individuals finding the yard waste fines w/out sand blend (YF 100) offensive. The Kruskal-Wallis mean rank test also found the yard waste fines without sand blend (YF 100) to rank the most favorably, while the redwood sawdust blend (RSD) was the most offensive after one of the unblended biosolids (SF) samples. 34% of respondents found appearance of Cedar Grove compost (CG) unappealing while the Tagro Mix control (TM) had a 24% disapproval rating. The three blends with the smallest disapproval rating contained no sand: LF 100 at 15%, YLF 100 at 13%, and YF 100 at 8%. It is important to note the lack of meaningful statistical distinction between the appearance ratings. The Bonferonni post hoc test on the Kruskal Wallis analysis of mean rank showed that the majority of the treatments, 16 out of 18, did not receive statistically different ratings in the appearance survey (p<0.05).

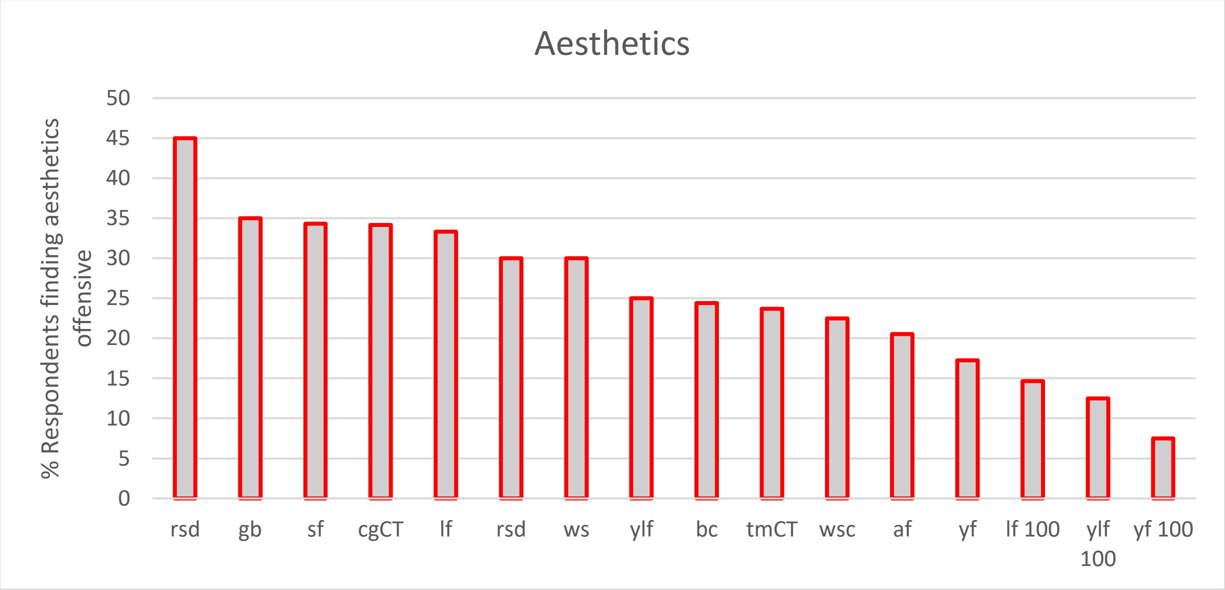


Figure 30. Percent of respondents finding aesthetics of a material unappealing to some degree on Day 1 after mixing. Treatments are ranked from largest to smallest percentage finding aesthetics unappealing. CT represents a control amendment, either Tagro Mix (TM) or Cedar Grove compost (CG). Values for unblended biosolids (SF) and the yard waste fines blend (YF) are the mean of duplicate samples.

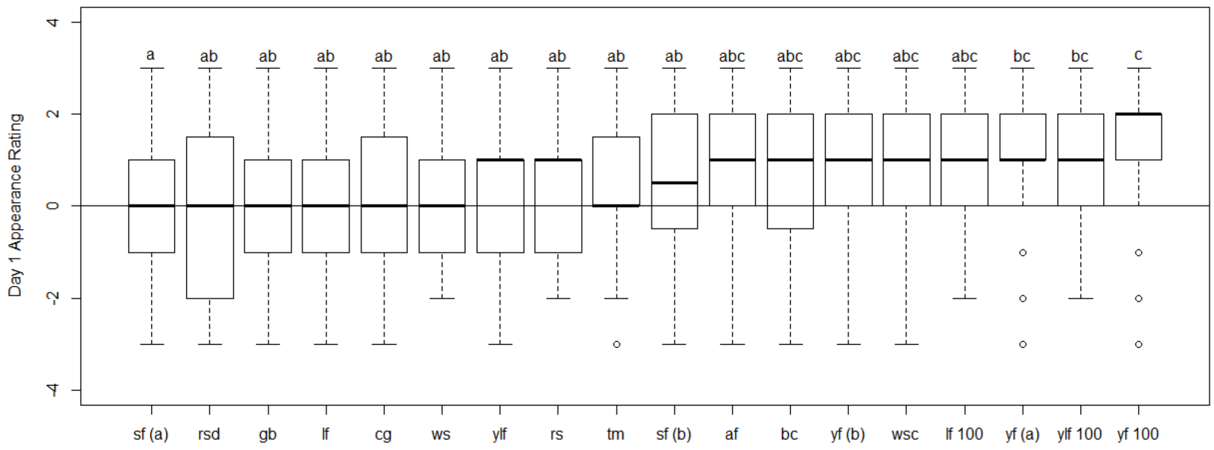


Figure 31. Comparison of mean rank in appearance rating of treatments on Day 1. Results with different letters are significantly different at p <0.05. Treatments are in order of greatest to lowest mean rank. Exterior bars represent maximum and minimum values, interior bar represents median value, boxes represent upper and lower quartile. Dots represent outlying values. Duplicate samples in SF and YF are denoted by the letters (a) and (b).

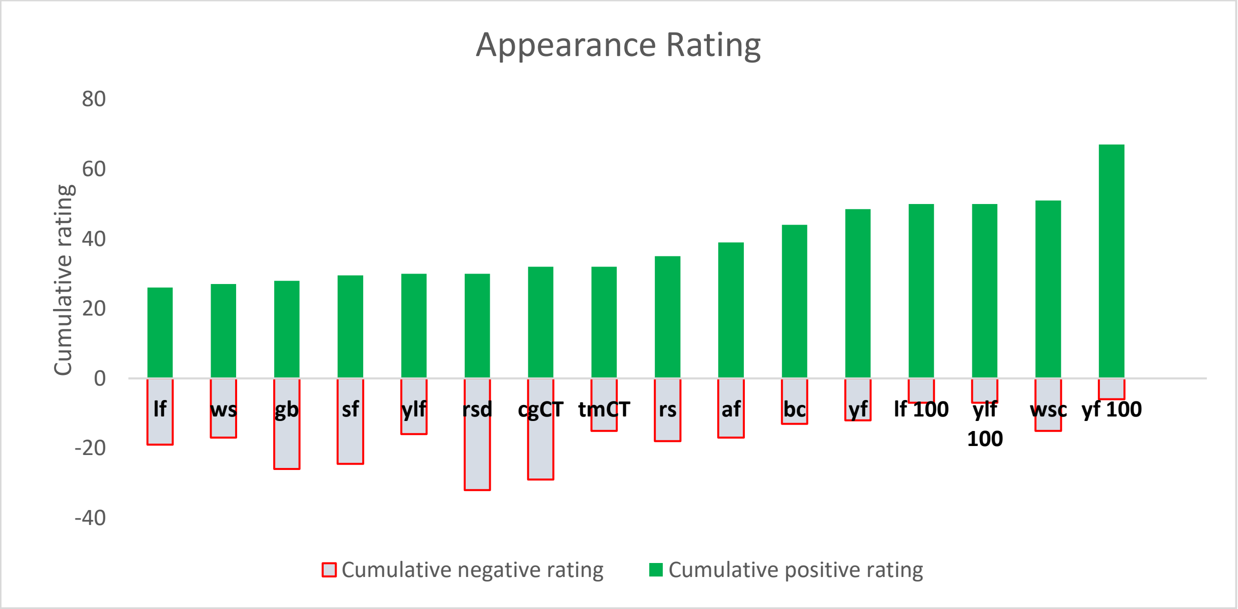


Figure 32. Cumulative and negative rating of material aesthetics. Cumulative positive rating is the sum of all positive ratings a material received (+1, +2, or +3). Cumulative negative rating is the sum of all negative ratings (-1,-2,-3). Treatments are ranked from lowest to highest cumulative positive rating. Values for unblended biosolids (SF) and the yard waste fines blend (YF) are the mean of duplicate samples.

The appearance of the blends that didn't contain sand were generally viewed as more favorable than the blends with sand. In the Kruskal Wallis mean rank test, 5 out of the 7 highest ranking blends contained no sand (YF 100, WSC, YLF 100, LF 100, and BC). These materials mixed well with the biosolids to create a relatively uniform looking material. The yard waste fines blend without sand (YF 100) arguably looked the most similar to a natural soil in terms of color and texture, which could explain its position as the highest rated blend for aesthetics. The control soil amendments Tagro Mix (TM) and Cedar Grove compost (CG) had the same cumulative positive rating, with individuals who found the materials appealing giving them the 9th highest positive score out of the 16 materials rated. Individuals who found Cedar Grove and Tagro Mix unappealing gave Cedar Grove the 2nd worst rating of any material and Tagro Mix the 8th worst rating out of 16 materials. The two controls did not have statistically different mean ranks on the appearance survey.

Although almond fines (AF) had a relatively high cumulative positive rating when judged on day 1, it is almost certain that if the aesthetics survey had been given on day 15 or day 32 instead, the almond fines blend would have fared quite poorly as the material became covered in mold. The two materials with the worst cumulative negative ratings, the redwood sawdust blend (RSD) and Cedar Grove compost (RSD and CG) had large chunks of material mixed in with finer pieces. In the commercial compost industry, it is often assumed that the home gardener customer prefers a finer compost with a consistent particle size and this would explain why RSD and CG performed poorly in the appearance survey.

The Gypsum Board (GB) blend had the third worst negative rating, third lowest positive rating and third lowest mean rank. The material had a slightly unnatural looking grey color that may have contributed to its poor scoring. Although statistically similar, there was a large difference in the mean rank of the two duplicate unblended biosolids samples (SF), one of which had worst mean ranking for appearance rating, possibly due to the unfamiliar appearance of biosolids.

5.3.2 Criteria for odor and appearance

One of the goals of this project was to evaluate whether the appearance and odor of the blends would be acceptable to the public. As discussed earlier, a threshold of at least 70% of respondents finding appearance (measured on day 1) and odor (measured on day 32) inoffensive was used to determine if blends were publicly acceptable. Table 13 displays if blends met these criteria or not. Blends with some amount of yard waste or lumber fines were the only blends to pass both odor and appearance acceptability criteria (BC, LF 100, YF, YF 100, YLF, YLF 100). The Cedar Grove control did not pass the criteria for appearance and the Tagro Mix control did not pass the criteria for odor, however both of these products are successfully marketed to the general public, suggesting that the criteria set here are too stringent.

Table 13. Treatment performance on project criteria for odor and appearance. Cells in green had an odor or appearance that was inoffensive to at least 70% of survey respondents for odor measured on day 32 and appearance measured on day 1.

Treatment	Odor	Appearance
af	Fail	Pass
bc	Pass	Pass
gb	Pass	Fail
lf	Pass	Fail
lf 100	Pass	Pass
rs	Pass	Fail
rsd	Pass	Fail
sf	Fail	Fail
ws	Fail	Fail
wsc	Fail	Pass
yf	Pass	Pass
yf 100	Pass	Pass
ylf	Pass	Pass
ylf 100	Pass	Pass

5.4 Plant growth trials

As discussed in the methods section, 3 additional materials were used in the germination and plant growth trials that were not used in the odor trials. Tagro Potting Soil was used as an additional biosolids product control. Sand was used as a nutrient free growing medium to demonstrate plant performance without the addition of any nutrients. Lastly, a peat growing medium was used to represent a common growing medium used for seedling germination and potting soil. The properties of these blends are shown in Table 14.

Table 14. Properties of materials used in plant growth trials which were not cured in 5 gallon buckets with other treatments. For % OM, total C, N and moisture content n=3, standard error is in parenthesis. EC_5, pH and bulk density n=1.

Material	Abbreviation	Organic Matter, %	EC_5, dS/m	pH	C, %	N, %	C/N ratio	Bulk density, g/cm3	Moisture content, %
Peat	P	65.3 (0.46)	1.21	5.07	31.51 (0.34)	0.77 (0.01)	40.8	0.10	38.0 (3.46)
Tagro Potting	TP	50.4 (0.94)	1.89	4.91	20.34 (0.61)	1.16 (0.02)	17.5	0.28	53.5 (1.32)
Sand	S	1.0 (0.26)	0.01	7.42	0.08 (0.02)	ND	-	1.38	5.0 (0.00)

5.4.1 Germination Assays

When germination in a 1:1 amendment : vermiculite mixture falls below 80% of a vermiculite or potting soil control, the amendment is deemed “immature” according to standards used by the US Compost Council (TMECC 5.05 USCC 2002). For this trial seedlings were planted directly into amendments without the addition of vermiculite to better highlight potential phytotoxicity. Cucumber, sensitive to the VOAs in immature compost (TMECC 5.05 USCC 2002) and radish, sensitive to EC (Fipps 2003; Morales and Urrestarazu 2013) were used for the germination assays. Achieving 80% germination success without dilution with vermiculite was expected to be more difficult than with vermiculite dilution. In spite of this, all treatments were at or above the 80% threshold except the almond fines, walnut shell char, gypsum board, and biochar blends and sand (AF, WSC, GB, BC and S). AF, WSC and GB were below the 80% germination rate with both cucumber and radish while biochar (BC) was only below 80% germination with the radish assay and sand (S) was only below 80% germination with the cucumber assay. In both the radish and cucumber germination assays, Peat (P), Tagro Potting (TP) and Cedar Grove compost controls (CG) performed well, with high germination rates and vigorous seedlings (Figure 33 and 34). Germination success in P, TP, and CG was 100% with cucumbers and 100% for P and CG and

95% for TP with radish. Germination in the Tagro Mix control (TM) was 80% with cucumbers and 95% in radish.

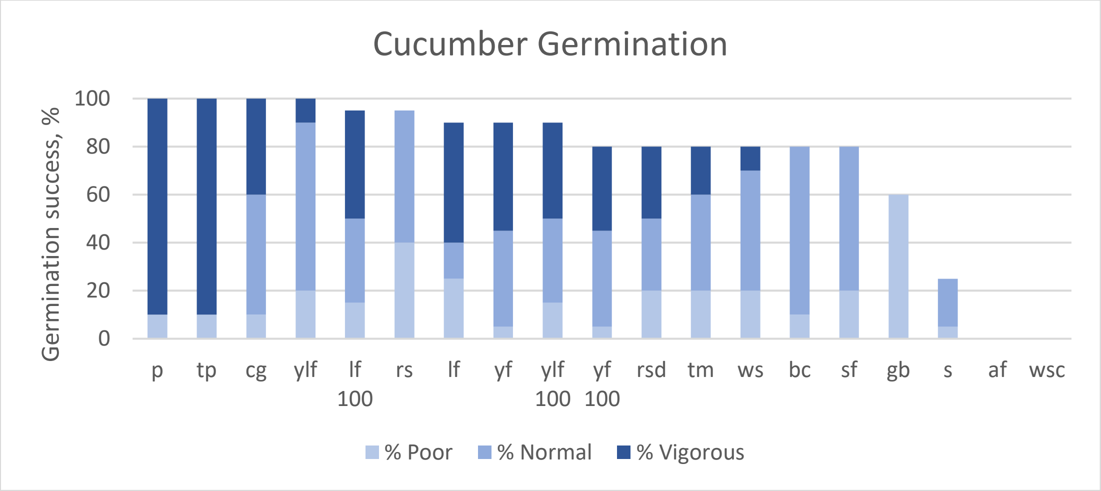


Figure 33. Cucumber germination in undiluted treatments, n=20. Ranked by order of germination rate followed by seedling vigor: poor, normal or vigorous. Seedling health is a relative and qualitative measure.

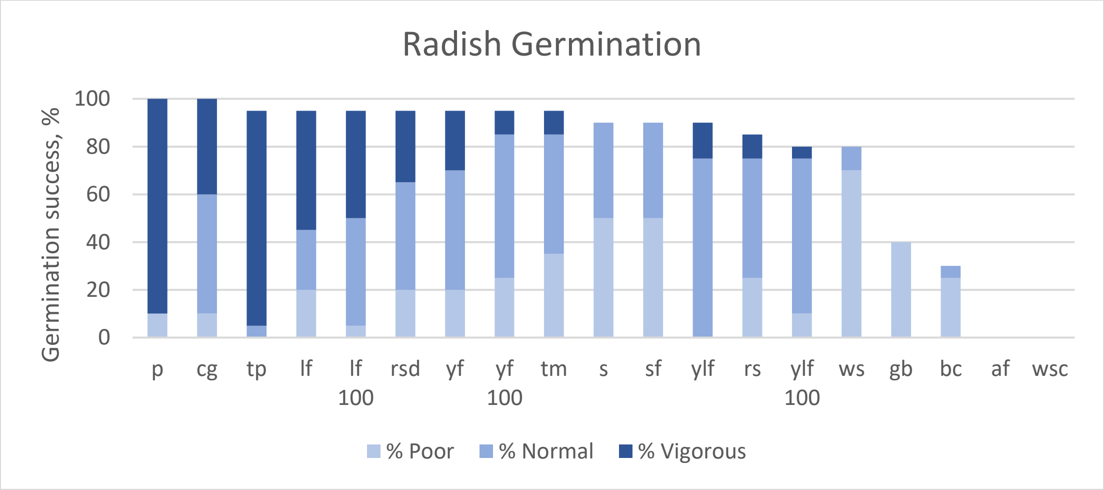


Figure 34. Radish germination in undiluted treatments, n=20. Ranked by order of germination rate followed by seedling quality. Ranked by order of germination rate followed by seedling vigor: poor, normal or vigorous. Seedling health is a relative and qualitative measure.

The walnut shell char blend (WSC) clearly inhibited seedling germination with 0% germination in both the radish and cucumber assays. A number of factors in this blend likely contributed to this including a pH of 10.1, an EC_5 of 13.6 dS/m, and high rates of ammonia volatilization. The almond fines blend (AF) also clearly inhibited seedling germination with 0% germination in both assays. High rates of respiration and visible signs of mold indicated high rates of active decomposition in the blend that may have led to anaerobic conditions or phytotoxic VOA production.

While the gypsum blend (GB) inhibited germination in both cucumber (60% germination) and radish (40% germination), the mechanism for phytotoxicity in this blend is not as readily apparent compared to AF and WSC.

Poor germination of cucumbers in Sand (S) was possibly due to physical obstruction and seeds sinking to the bottom of seedling trays when sand had a slurry like consistency during irrigation. Germination of radish in sand was above 80%. Germination of radish in the biochar blend (BC) was only 20%. The biochar feedstock had an EC_5 of 11.8 dS/m and the final biochar blend had an EC_5 of 5.6 dS/m, suggesting excess salinity may have been a factor in the reduced germination. The unblended biosolids (SF) had an EC_5 of 7.2 dS/m however, and radish germination was 90% in this treatment. Across all treatments EC_5 was a good predictor of germination success in radish, with higher EC_5 correlated with lower germination rates at $p=0.013$ (Table 15). The correlation between EC_5 for cucumber germination was only significant at $p=0.102$, but when sand, which affected germination for physical reasons, was removed from analysis, correlation was significant at $p=0.025$.

Table 15. Correlation coefficient table for variables with significant correlation with germination success. Variables in soil amendments are measured from samples taken on Day 32. ***p<0.01, **p<0.05, *p<0.10

	Cucumber germination	Radish Germination
EC_5	-0.39	-0.56**
pH	-0.70***	-0.62***
Volumetric N content	-0.33	-0.53**
Respiration per unit of OM	-0.42**	-0.36*

Higher pH was strongly correlated with poor germination for both cucumber ($p<.001$) and radish ($p<0.001$) (Figure 35) with certain blends of pH higher than 7 having poor germination. There were several blends where the observed phytotoxicity may have been related to other factors but the blends also had relatively high pH. This could have skewed results to give more significance to pH. The almond fines blend (pH 6.49) had issues with high rates of active decomposition, the biochar blend seemed to have problems with EC (pH 6.86, EC_5 5.5 dS/m), as did the walnut shell char blend (pH 10.09, EC_5 13.6 dS/m) and the gypsum board blend (pH 7.34) possibly had lower germination success due to phytotoxic levels of an undetermined element and germination was not poor due to pH of 7.34.

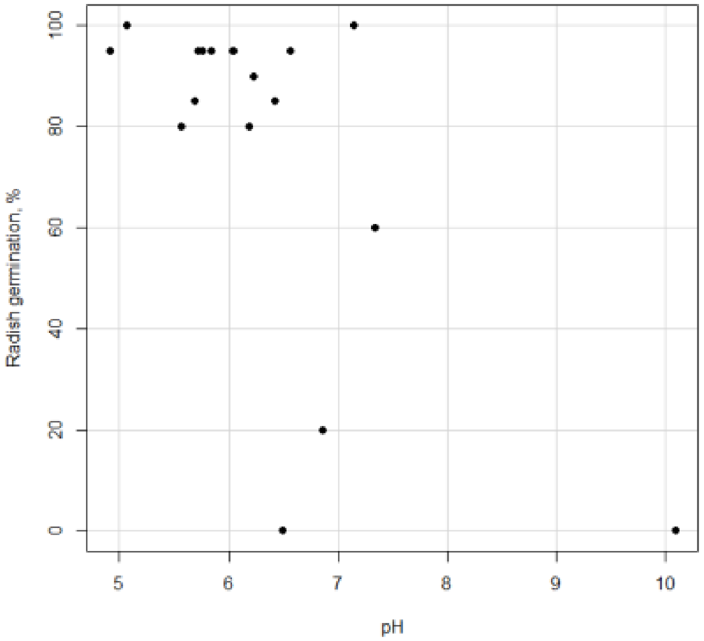


Figure 35. Radish germination as a function of pH in materials measured on Day 32. There is a correlation between high pH and lower germination, adjusted r^2=0.35 p=0.004

The significance of several other variables appears to have been driven by a single treatment. For example, high total N content was correlated with decreased germination in both radish and cucumber for the full data set. However, when the almond fines (AF) blend was removed from analysis, this correlation was no longer significant at p<0.10. Similar to this, when AF was included, higher measurements of respiration are significantly correlated with lower germination, but without AF, this correlation is no longer significant at $p<0.10$. Certainly, high rates of respiration as found in AF negatively impact germination, for the purposes of statistical analysis however, AF has an outsized effect on findings.

High EC and ammonia, and high rates of active decomposition were responsible for germination rates below 80% in cucumber and radish germination assays. These results suggest that as mixed, the walnut shell char (WSC), almond fines (AF), biochar (BC) and gypsum board blend (GB), are unsuitable for use as a potting soil. While BC only had a 20% germination success in the radish assay, it fared better in the cucumber assay with an 80% success rate. The germination assay was designed to assess phytotoxicity due to immature compost, not EC, and for this reason, cucumber with its relatively higher tolerance to salinity is used (USCC 2002). As the discussion on EC in the literature review showed, high EC is especially problematic in potting soils, but when incorporated into existing soils where precipitation is high and elevated EC is not a concern a material like the biochar blend could still be an effective amendment.

The majority of treatments met the criteria this study set for 80% germination success: 9 out of 13 for the radish assay and 10 out of 13 for cucumber assay. It is important to note that this germination assay was conducted without dilution of the blends with vermiculite, while the standard germination assay used by the US compost industry is a 1:1 amendment : vermiculite blend (TMEC 5.05 USCC 2002). The criteria for germination in this study is therefore more stringent than commonly used. The 9 treatments which met the 80% threshold for both cucumber and radish germination would not likely be phytotoxic to seedlings when used as a soil amendment.

5.4.2 Petunia growth trial

The petunia growth trial measured the growth response of petunias to the blends at two application rates. Petunias were grown in ½ gallon pots that were filled entirely with blends (referred to as full blend), or ½ gallon pots that were filled with a mixture of 50% sand and 50% blend by volume (referred to as half blend). A summary of results for the full blend and half blend trial are discussed separately. Response to the different blends was measured using a range of indices. Height, widest and narrowest width were measured at 4 points in time during the growth trial and used to calculate a shoot growth index (Hummel et al. 2014). Chlorophyll content was measured 4 times during the trial, total number of flowers produced was tallied throughout the trial, and dry above ground biomass was measured at the end of the trial. The different amendments used in the petunia growth trial are shown in Table 16. Images of the petunias grown in each amendment at each application rate are shown in Appendix A.

Table 16. Overview of treatments and controls used in the Petunia growth trials. *Peat, Sand, and Tagro Potting controls were not cured for 32 days in buckets or used in odor and appearance trials.

Treatment	**Ingredients**	**Volumetric proportions**
af	Almond fines/Biosolids/sand	40% Almond fines, 40% biosolids, 20% sand
bc	Biochar/Biosolids/Yard Waste	25% Biochar, 50% biosolids, 25% yard waste fines
gb	Gypsum Fines/Biosolids/sand	40% Gypsum board fines, 40% biosolids, 20% sand
lf	Lumber fines/Biosolids/sand	40% Lumber fines, 40% biosolids, 20% sand
lf 100	Lumber fines/Biosolids	50% Lumber fines, 50% biosolids
rs	Redwood Shavings/Biosolids/sand	40% Redwood shavings, 40% biosolids, 20% sand
rsd	Redwood Sawdust/Biosolids/sand	40% Redwood sawdust, 40% biosolids, 20% sand
sf	Unblended SF Biosolids	100% San Francisco biosolids
ws	Walnut shells/Biosolids/sand	40% Walnut shells, 40% biosolids, 20% sand
wsc	Walnut shell char/Yard waste/Biosolids	25% Walnut shell char, 50% biosolids, 25% Yard waste fines
yf	Yard waste fines/Biosolids/sand	40% Yard Waste fines, 40% biosolids, 20% sand
yf 100	Yard waste fines/Biosolids	50% Yard waste fines, 50% biosolids
ylf	Yard-lumber fines/Biosolids/sand	40% Lumber/Yard waste fines, 40% biosolids, 20% sand
ylf 100	Yard-lumber fines/Biosolids	50% Lumber/Yard waste fines, 50% biosolids
Controls	**Ingredients**	**Volumetric proportions**
p*	Peat growing medium	100% Sunshine Peat Mix # 3
s*	Sand	100% Washed sand
tp*	Tagro Potting Soil	8% class A biosolids, 61% aged bark, 31% sand
cg	Cedar Grove	100% Cedar Grove Compost
tm	Tagro Mix	100% Tagro Mix (40% class A biosolids, 40% sawdust, 20% sand)

5.4.3 Growth response of petunias grown directly in amendments

Mean dry biomass yield (n=4) ranged from a low of 2.2 g in the almond fines blend (AF), to a high of 24.2 g in Tagro Potting Soil (TP) (Figure 36). The Cedar Grove (CG) and Tagro Mix (TM) controls yielded a mean of 10.0 g and 11.7 g of biomass respectively. The majority of the blends, 11 out of 13, had statistically similar or greater biomass production than the Cedar Grove (CG) and Tagro Mix (TM) controls at $p<0.05$. Two out of 13 blends were statistically similar to Tagro Potting Soil (TP), the biochar blend and the yard waste fines w/out sand blend (BC and YF 100). All 13 blends had statistically similar or greater yields of biomass than the Peat control (P), which produced 6.4 g of biomass.

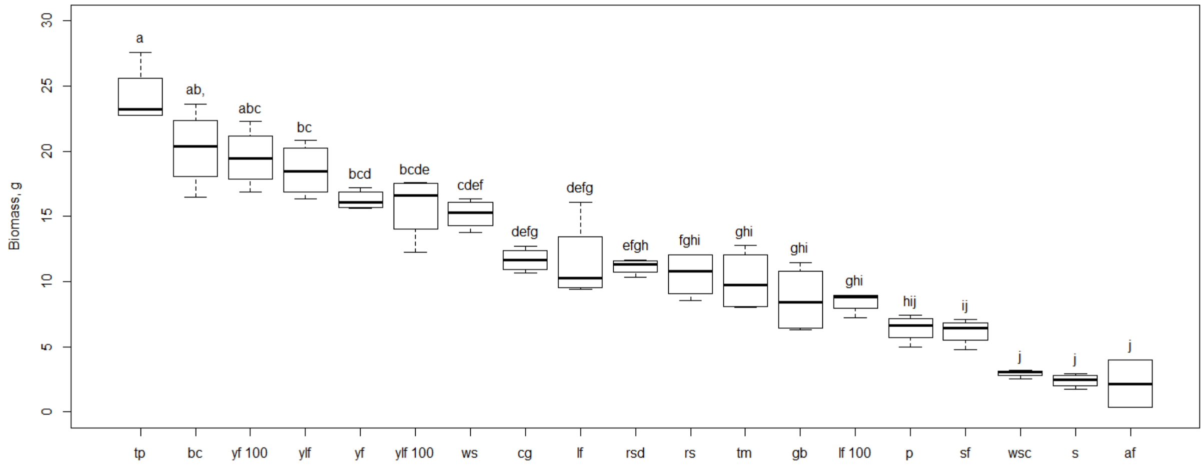


Figure 36. Dry biomass of petunias grown in full blends (100% of treatment). Treatments are in order of highest to lowest mean biomass. Results with different letters are significantly different at $p < 0.05$. Control amendments are Tagro Potting (TP), Cedar Grove compost (CG), Tagro Mix (TM), and Peat (P).

Mean total flower yield ranged from a high of 216.5 in the biochar blend (BC) to a low of 15 in the almond fines blend (AF) (Figure 37). The Cedar Grove (CG) and Tagro Mix (TM) controls yielded a mean of 136 and 140 flowers respectively. The majority, 11 of the 13 blends, had statistically similar or greater flower yield than the Cedar Grove control (CG) and Tagro Mix control (TM) at $p<0.05$. Tagro Potting Soil (TP) yielded a mean of 205 flowers. Eight out of 13 blends had statistically similar or greater flower yield than Tagro Potting Soil. Twelve out of 13 blends had statistically similar or greater flower yield than the Peat control (P), which produced a mean of 73 flowers.

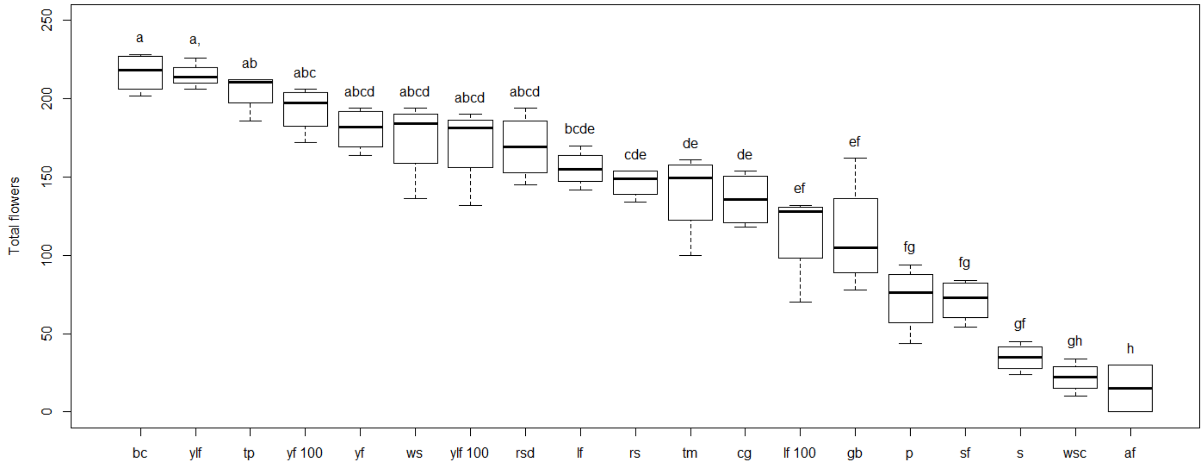


Figure 37. Flowers produced in petunias grown in 100% of treatment. Treatments are in order of highest to lowest mean number of flowers. Results with different letters are significantly different at $p < 0.05$.

The majority of blends (11 out of 13) performed as well or better than the Tagro Mix and Cedar Grove compost controls in terms of both biomass and flower yield. As noted above, only two blends matched the biomass yield of Tagro Potting Soil (TP). TP is formulated as a growing medium which is planted directly into. The blending ratios of the Tagro Potting (TP) recipe is less similar to the blends created in this trial than Tagro Mix (TM). Tagro Potting soil is approximately 8% biosolids by volume whereas the blends created for this study contain 40-50% biosolids by volume. Tagro Mix is 40% biosolids by volume. Figures 38-40 below compare the yardwaste fines w/out sand blend (YF 100) to the Tagro Mix and Cedar Grove controls (TM, CG). Cascadia Blue petunias have a moderately trailing growth habit, trailing stems are normal.

Figure 38. - Petunias grown in the yard waste fines w/out sand blend (YF 100), 50% yard waste fines + 50% biosolids. Petunias grown in full blend. Lines are at 10 cm intervals. All replicate plants for this treatment are shown.

Figure 39. Petunias grown in Tagro Mix (TM) control amendment, 40% Sawdust, 40% Biosolids, 20% Sand. Petunias grown in full blend. Lines are at 10 cm intervals All replicate plants for this treatment are shown.

Figure 40. Petunias grown in Cedar Grove compost (CG) control amendment. Petunias grown in full amendment. Lines are at 10 cm intervals. All replicate plants for this treatment are shown.

Based on the flower and biomass yields from petunias grown at the full blend application rate, 11 of the blends could be used as a soil amendment with similar or better results than Cedar Grove compost or Tagro Mix. The top 6 yielding blends for both flowers and biomass were the biochar, yard waste fines w/out sand, yard/lumber fines, yard waste fines, yard/lumber fines w/out sand and walnut shell blend (BC, YF 100, YLF, YF, YLF 100, WS). These blends all had statistically significant higher biomass yields than Tagro Mix (TM), and as will be discussed later, had little or no foliar chlorosis. Other than the walnut shell blend, these all contained some amount of yard waste fines. The lumber fines, redwood sawdust, redwood shavings, gypsum board fines, and lumber fines w/out sand blends (LF, RSD, RD, GB, LF 100) had statistically similar biomass yields to the Tagro Mix and Cedar Grove controls. Other than the gypsum board fines (GB), petunias grown in these blends all displayed foliar chlorosis by the end of the trial. This chlorosis is detailed in images in Appendix A. The two blends which performed significantly worse than Cedar Grove and Tagro Mix were the almond fines and walnut shell char blends (AF, WSC). In order to understand why BC, YF 100, YLF, YF, YLF 100 and WS performed well in this trial, it is helpful to begin by understanding why LF, RSD, RD, GB, and LF 100 did not perform as well as the top blends and why AF and WSC performed poorly. In the following sections, possible mechanisms for poor performance in blends will be described. This will be followed by a discussion of what ranges of measured parameters in blends were found to be ideal for promoting petunia growth in this study. The results of the half blend trial are best discussed in the context of application rate effects and will be covered after mechanisms of poor performance in the full blend and ideal parameter ranges for petunia growth are discussed.

5.4.4 Treatments with poor plant response

When blends are used like a potting soil and petunias are grown in 100% of each treatment, the almond fines (AF) and walnut shell char blends (WSC) yield less biomass than any other amendment with biosolids ($p<0.05$). As with the germination assay, high EC and alkaline conditions that resulted in high rates of ammonia volatilization were likely responsible for poor performance in WSC (Figure 41). In AF, two replicates died while the two other replicates recovered after a period of stunted growth (Figure 42). This stunted growth remained visible at the base of plants grown in AF which recovered (Figure 43).

Figure 41. Petunias grown in the walnut shell char blend (WSC), 25% walnut shell char, 25% yard waste fines, 50% biosolids. Plants grown in full blend. Lines are at 10 cm intervals. All replicates for this treatment are shown.

Figure 42. Petunias grown in the almond fines blend (AF), 40% almond fines, 40% biosolids, 20% sand. Plants grown in full blend. Lines are at 10 cm intervals. All replicates for this treatment are shown.

Figure 43. Stunted portion of petunia grown in 100% almond fines blend (AF).

High rates of microbial respiration in AF, 8.6 mg CO_2-C gOM^{-1} day^{-1}, indicate the blend had rates of decomposition high enough to produce phytotoxic conditions due to the production of VOAs or through O_2 depletion(Brinton and Tränkner 1999). It appeared that if plants could survive phytotoxic conditions for long enough, the AF blend eventually became less phytotoxic either through stabilization of microbial activity or the leaching of phytotoxic compounds. Stunted portions of the plants which grew during the initial period of phytotoxicity can be seen in Figure 43. Biomass produced by the surviving replicates in AF was still significantly lower than all other blended amendments other than WSC.

Petunias grown in sand (S) unsurprisingly produced very little biomass as there were virtually no nutrients in the material (Figure 44). Plants were pale green and lower leaves were chlorotic, both of which are typical symptoms of N deficiency (Stevens 2002). Plants were probably only able to grow because of the nutrients present in the plug used to start the seedlings.

Figure 44. Petunia grown in 100% sand (S). Note pale green color of leaves overall and chlorosis of lower leaves.

Figure 45. Petunia grown in 100% peat (P). Note pale green color of leaves overall and chlorosis of lower leaves and bracts.

Plants grown in the peat growing medium (P) were similarly stunted due to nutrient deficiencies (Figure 45). The peat growing medium was not amended with any inorganic fertilizers as is directed by the product labeling. Although the peat had a total N of 0.77%, it had a high C:N ratio of 41:1 which limits N mineralization and increase N immobilization. Mehlich III extractable phosphorus content of the peat was also the lowest of any treatment at 137 mg/kg. While there is some purple discoloration on leaves, this occurs on newer growth and is therefore not likely due to P deficiency as P is a mobile nutrient in plants. The pale green leaves and chlorosis of older growth points to N deficiency as the cause for low yields in the peat treatment.

While the biomass produced by petunias grown in 100% unblended biosolids (SF) was statistically similar to that grown in 100% peat, the N dynamics between the two treatments were dramatically different. The unblended biosolids (SF) had a mean ammonium content of 5,270 mg/kg and a C:N ratio of 7.5:1. There was certainly no potential for N deficiency in this treatment. Instead, such high levels of ammonium were likely what limited petunia growth. Plants in the Solanaceae family are sensitive to ammonium toxicity (Britto and Kronzucker 2002). Symptoms include interveinal chlorosis which begins on young leaves, scattered necrotic spots beginning on lower and mid-level leaves, and necrosis beginning on leaves lower on stems (Nelson and Hsieh 1971, Matson and Peters 2011, Petrovic et al. 2009). These visual symptoms are strikingly similar to those seen in the petunias grown in unblended biosolids (SF) at the full blend and half blend application rate as can be seen in Figures 46 and 47.

Figure 46. Petunias grown in 100% unblended biosolids (SF). Note scattered necrotic spots.

Figure 47. Petunias grown in 50% biosolids 50% sand (SF HLF). Note interveinal chlorosis of young leaves.

5.4.5 Ammonium and nutrient toxicity/deficiency

Biomass and flower yields of petunias grown in 100% of blends were significantly correlated with a quadratic function of volumetric ammonium content at p=0.028 and p=0.002 respectively

(Figures 48 and 49). Low levels of ammonium were associated with low yield of biomass and flowers and petunias grown in these treatments exhibit foliar symptoms of N deficiency. High levels of ammonium are also associated with low levels of growth. KCl extraction of ammonium is designed to pull ammonium off of exchange sites and will remove ammonium which would not have been desorbed by water (B. Wang et al. 2015). It is therefore not possible to know what levels of ammonium were in solution versus bound to exchange sites in these different treatments. Assessments of phytotoxicity due to ammonium content would be more accurate if CEC of treatments was known or the level of ammonium in solution had been measured.

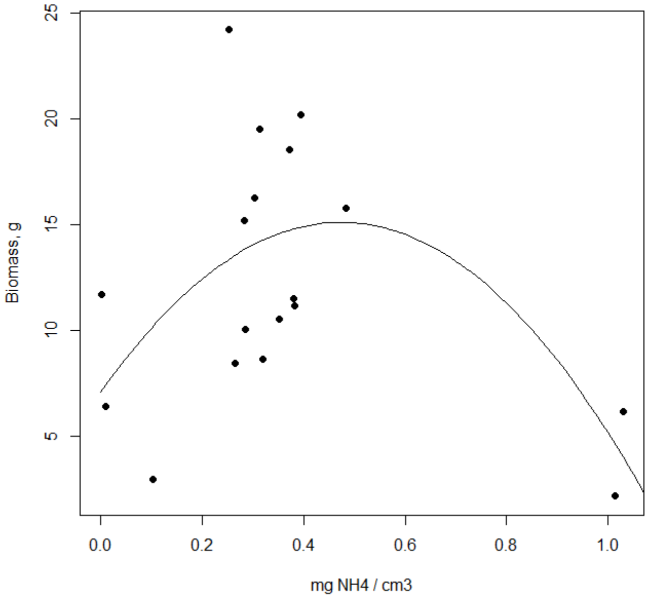


Figure 48. Biomass vs. volumetric ammonium content of treatments and controls on Day 32. Petunias grown in 100% of blend. Adjusted r^2: 0.30, p-value: 0.028

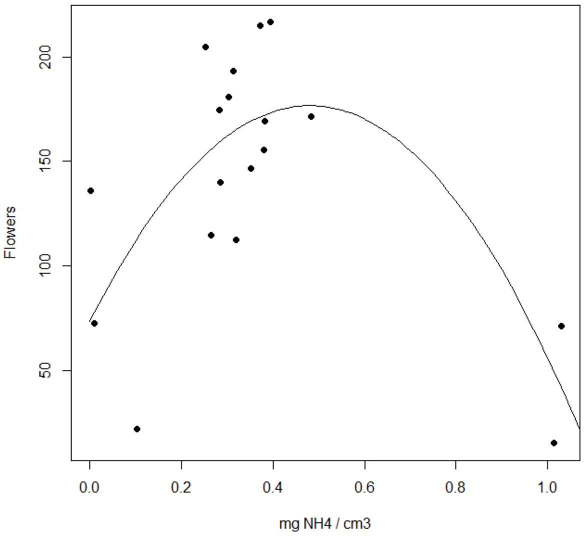


Figure 49. Flowers vs volumetric ammonium content of treatment and controls on Day 32. Petunias grown in 100% of blend. Adjusted r^2: 0.51, p-value: 0.002

Interveinal chlorosis of young leaves was present in most blends, if only very faintly in some. Interveinal chlorosis of young leaves and browning of older leaves, and the appearance of speckled spots on lower leaves was more intense in petunias grown in 100% the redwood sawdust blend, redwood shavings blend, lumber fines blend, lumber fines without sand blend and Tagro Mix (RSD, RS, LF, LF 100, TM) These symptoms are visible in the image results shown in Appendix A. As noted above, interveinal chlorosis of on young leaves, scattered necrotic spots begging on lower and mid level leaves, and necrosis beginning on leaves lower on stems are symptoms of ammonium toxicity (Nelson and Hsieh 1971, Matson and Peters 2011, Petrovic et al. 2009). Below are a series of photos illustrating similar symptoms in petunias grown in the LF100 and RS blends.

Petunias grown in 100% of the Redwood Sawdust blend (RS). Note interveinal chlorosis on young leaves and browning of older leaves.

Petunias grown in 100% of the Lumber Fines w/out Sand blend (LF 100). Note browning and speckling of lower leaves.

Petunias grown in 100% of the Redwood Sawdust blend (RS). Browning and necrosis of lower leaves

Foliar symptoms of ammonium toxicity in New Guinea Impatiens (Impatiens hawkeri). From Mattson et al. 2011

RSD, RS, LF, LF 100 and TM all displayed similar foliar symptoms as shown in the pictures above. These blends exhibiting this pattern of foliar chlorosis had significantly lower yields than BC, YF 100, and YF – blends which did not exhibit foliar symptoms of nutrient imbalance. Based on the similarity of the foliar symptoms in RSD, RS, LF, LF 100 and TM to documented symptoms of ammonium toxicity, this is a possible theory for why they had lower yields in the potting soil scenario. This cannot be determined conclusively however without tissue analysis.

The three high yielding blends without chlorosis (YF, YF 100 and BC) all have higher rates of respiration per unit of OM than plants displaying the above-mentioned pattern of foliar chlorosis (this is not significant for BC however). The high yielding non-chlorotic plants also have lower gravimetric ammonium levels than plants with the foliar chlorosis pattern (when comparing blends with sand to each other and blends without sand to each other). Immobilization of N is positively correlated with respiration (Luxhoi et al. 2004) suggesting there could be more microbial immobilization of ammonium in YF, YF 100 and BC, materials which all contained yard waste fines. In addition, as biosolids and yard waste compost matures, CEC which can hold ammonium increases as C compounds in a material gain more carboxylic functional groups (Butler et al. 2001; Brewer and Sullivan 2003).

Further evidence to the theory of ammonium toxicity is that the while the walnut shell blend (WS) and gypsum board blend have similar biomass yields as the foliar chlorosis pattern blends, the walnut shell blend (WS) and gypsum board blend (GB) do not exhibit the pattern of foliar symptoms that RS, RSD, LF and LF 100 do, and WS and GB also have the lowest levels of ammonium of any blend other than the walnut shell char (WSC) which had high N loss to volatilization. Of blends made using SFPUC biosolids, the biochar blend (BC) had the highest mean biomass and flower yield of petunias grown in 100% of blends although this was not statistically significant. This blend was made of 50% biosolids + 25% yard waste fines + 25% biochar. Biochar is known to sorb ammonium (B. Wang et al. 2015; Takaya et al. 2016) The biochar blend showed no foliar symptoms of toxicity.

Petunia grown in 100% of the Walnut Shell Blend (WS). While yielding statistically similar amounts of biomass and flowers, this plant shows none of the patterns of foliar toxicity as found in RS, RSD, LF, TM and LF 100. It has lower gravimetric ammonium content and higher C:N ratios than these blends.

Another potential hypothesis for the foliar symptoms seen in RSD, RS, LF, LF 100 and TM is a reaction to allelopathic terpenes in the wood used to make the blends. Allelopathy from tree species has been well documented (Rathinasabaathi et al. 2005, Duryea et al. 1999) and coast redwood (*Sequoia sempervirens*) contains terpenes (Okamoto et al. 1981, Ward et al. 1997) which can have an allelopathic effect (Maclaren 1983). This could explain the foliar symptoms seen in RSD and RS. With regard to tree species in the Pacific Northwest that could be the source of sawdust used in TAGRO Mix, Western Red Cedar (*Thuja plicata*) is shown to produce phytotoxins, although Douglas Fir (*Pseudotsuga menziessi*) was found to not have allelopathic effects (Del Moral and Cates 1971). It is difficult to say what the species make-up of the recycled lumber fines would be in LF and LF 100, but it is possible allelopathic terpenes are playing a role in the foliar symptoms seen in these blends as well. The facility which produces the lumber fines sorts redwood lumber into a separate pile to make a redwood fines product, so the allelopathic effect in LF and LF 100 would have to come from a different species. The theory of allelopathy would not explain why speckled necrosis which is seen in RSD, RD, LF, LF 100, and TM is also seen in the unblended biosolids (SF) which contained no wood products.

As noted in the blend properties section, ammonium content was correlated with C:N ratio, with higher C:N ratios associated with lower concentrations of ammonium. Unsurprisingly then, C:N ratio was correlated with biomass and flower yield of petunias grown in 100% of blends in a manner similar to ammonium, albeit at lower statistical significance (Figures 50 and 51). Biomass as a quadratic function of C:N ratio was only significant at p=0.051 while flowers as a quadratic function was significant at p=0.043. The top 5 yielding treatments all had a C:N within the range found in common compost recommendations of 10:1-25:1. This is shown in figures 50 and 51 with areas shaded green representing the range between 10:1 and 25:1.

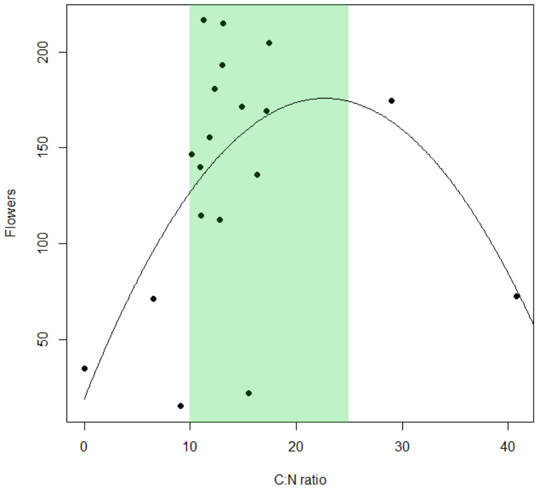


Figure 50. Flowers vs C:N ratio of blends from Day 32. Petunias grown in 100% of blend. Green bar represents range found in common compost specifications. Adjusted r^2: 0.24 p-value: 0.043

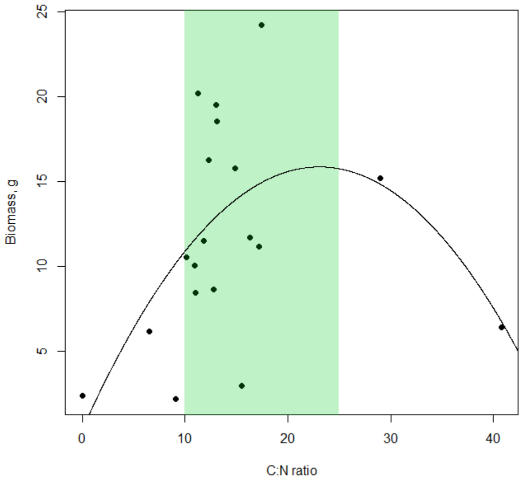


Figure 51. Biomass vs. C:N ratio of treatments and controls from Day 32. Petunias grown in 100% of blend. Green bar represents range found in common compost specifications. Adjusted r^2: 0.22 p-value: 0.051

While it was not possible to find a statistical relationship between the C:N of the *feedstock* used to make each blend and the biomass or flower yield in petunias grown in 100% of each blend, a scatter plot of yield versus feedstock C:N may indicate that blending biosolids with feedstocks that have a C:N between 50:1 and 200:1 resulted in blends that grew higher yields of biomass and flowers (Figure 52).

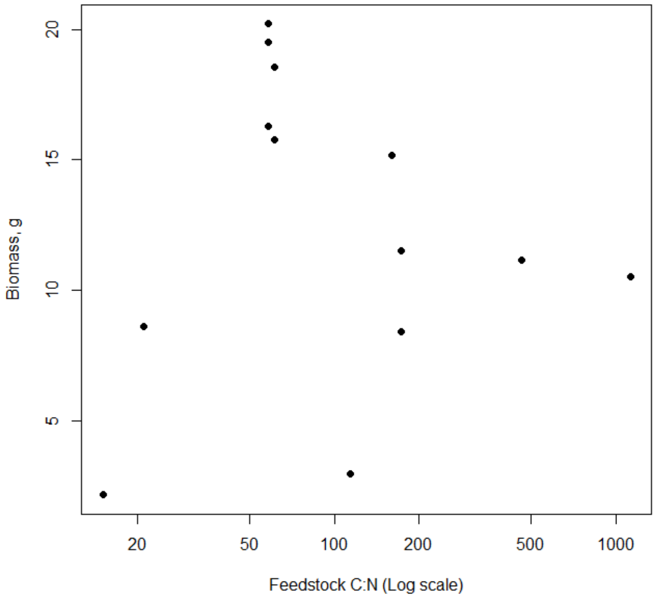


Figure 52. Biomass vs C:N ratio of feedstock. Petunias grown in 100% of blends. Only blends made with SFPUC biosolids, no controls.

Tagro Potting Soil (TP) had the highest mean yield of biomass and third highest mean yield of flowers although this was not statistically significant. This product was designed to be 100% of the growing medium that plants were grown in, i.e. a potting soil. The product contains 8% biosolids by weight, had a ratio of 1.68:1 ammonium:nitrate and was the only material with biosolids to have an appreciable amount of nitrate. The low level of biosolids in this mix, large content of aged bark along with the curing that is done prior to use were likely factors in the lower levels ammonium concentrations.

While the gypsum board blend (GB) did not present signs of possible ammonium toxicity or allelopathy and had low levels of KCl extractable ammonium plants grown in this mixture exhibited unusual foliar discoloration that were likely an indication of some type of nutrient deficiency or toxicity. This was the case for petunias grown in both the full blend and half blend trials for GB (Figures 53-56). In GB, germination success was 60% in both the radish and cucumber assay.

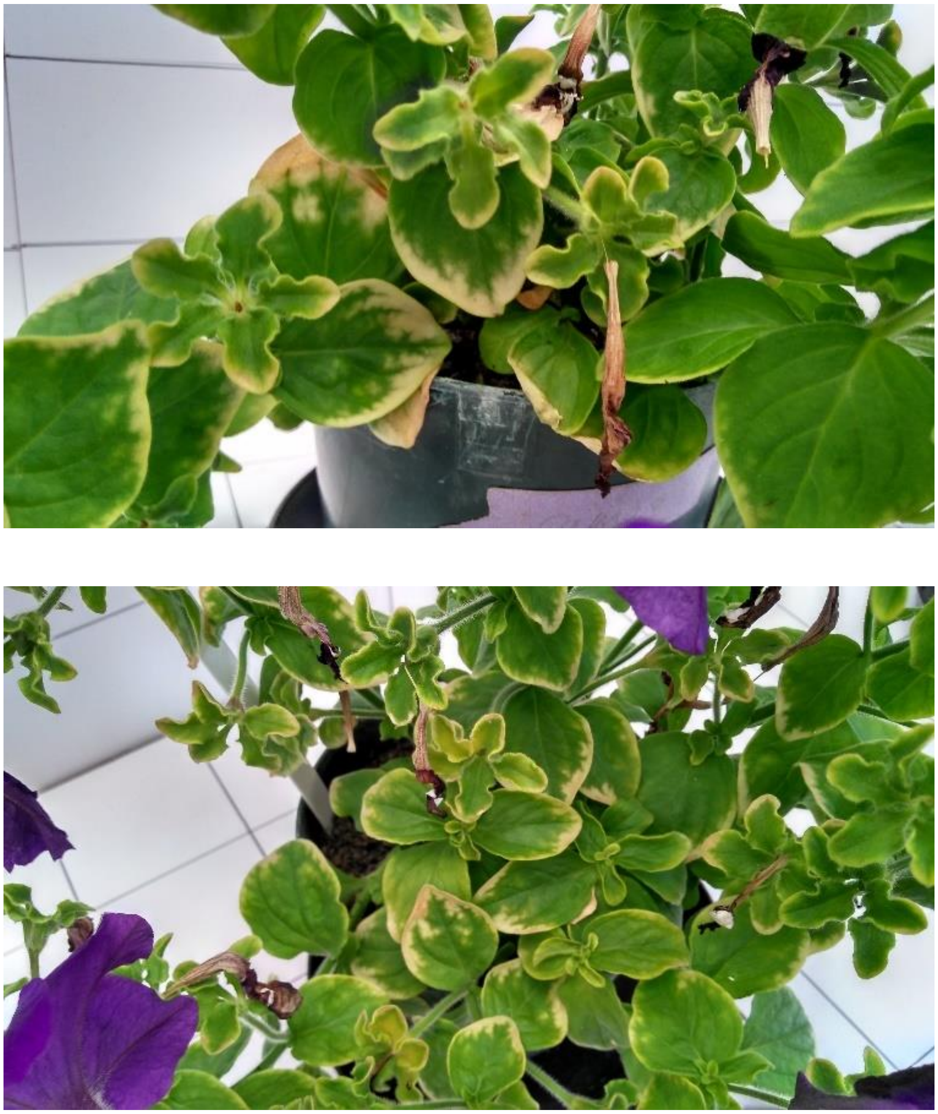


Figure 53 and Figure 54. Pronounced whitening of leaf margins of petunias grown in 50% gypsum board blend (GB) and 50% sand (half blend). Symptoms appear to mainly affect older growth. Symptoms are worse than in petunias grown in 100% gypsum board blend (full blend).

Figure 55 and Figure 56. Whitening of leaf edges of petunias grown in 100% gypsum board blend (GB). Symptoms appear to mainly affect older growth. Symptoms appear less severe than on petunias grown in 50% gypsum board blend + 50% sand.

In the petunia growth trial, petunias grown in GB developed white leaf margins tips on older growth. These symptoms are similar to those of Boron toxicity. Boron toxicity symptoms appear first on older leaves, with Boron concentrating in leaves more than other parts of the plant and within leaves, boron concentrates in leaf margins at much higher rates than in the rest of the leaf creating chlorotic leaf tips and edges (Gupta et al. 1985). A mean concentration of 43 mg/kg of B was found using the Mehlich III extraction (n=2) in the GB blend which was 5 times higher than the average B concentration of other blends approximately twice as much B than the material with the next highest levels. Fly ash compost derived growing media with total B levels of 28 mg/kg measured by nitric acid extraction resulted in yield reductions of 45% in beans and 55% in cucumber (Brinton et al. 2008). Boric acid is a common ingredient in gypsum board at concentrations of 300 to 1,500 mg/kg depending on the type of gypsum board (Rio Tinto 2016) and it is therefore unsurprising that the highest levels of Mehlich III extractable boron were found in the gypsum board blend. Decrease in germination due to B toxicity has also been shown in the literature which could explain the low levels of radish and cucumber germination in GB. In safflower (*Carthamus tinctorius*), reduction in germination on filter paper due to B started at 2mg/L, at 4 mg/L there was only a 24% germination rate and by 8 mg/L there was 0% germination (Ashagre et al. 2014).

The incidence of white tipped foliage was higher in the half blend + half sand scenario than the full blend scenario. An unsupported theory to explain this is that there would be lower CEC per unit of volume in the blend with sand, creating a scenario where there could be more soluble B in the pots. Tissue levels of B in petunias were not measured and Mehlich III extractable B does not equate to total B or B in solution. In addition, while commonly used as a measure of available plant nutrients the Mehlich III extraction has not been calibrated for plant response to B. The threshold for boron toxicity symptoms in potato (Solanum tuberosum) and bell pepper (Capsicum annuum), plants in the Solanaceae family to which petunias belong, is 2 mg/L (Gupta et al. 1985). The sensitivity of petunias to excess B is not known though. While it is a potential hypothesis, it is not possible to conclude that B toxicity was the cause of poor germination in the GB blend. It is also highly likely that the observed foliar symptoms were the result of a nutrient deficiency rather than toxicity.

5.4.6 Organic matter

While a quadratic function of organic matter could be used to explain variation in flower yield in petunias grown in 100% of blends at p=0.039 (Figure 57), the ranges required by compost specifications did not seem to be useful. As seen in Figure 57 where the area shaded green represents the requirements of compost specifications, treatments which fell below 30% OM still performed well. This was the same case in the half blend + half sand scenario. Compost end users desire a product which is over 30% organic matter as excessive mineral sediment in a product represents material that must be paid for but does not contribute to the efficacy of a traditional compost (Crohn 2016). However, biosolids based soil amendments can still be quite effective at improving plant growth even with levels of organic matter below 30%. Indeed, Cedar Grove compost (CG) was 55% OM, yet in the half blend + half sand scenario, Cedar Grove compost had lower yields of biomass and flowers than all the biosolids blends which had less than 30% OM. Biosolids products, with their higher levels of N and P, remain effective even if they do not meet the same organic matter requirements set for compost.

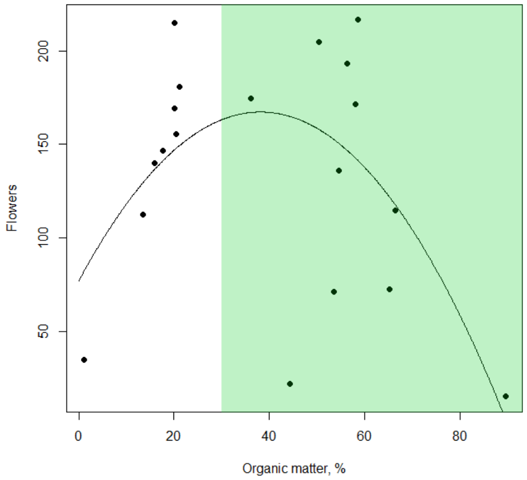


Figure 57. Flowers as a quadratic function of percent organic matter in treatment or control from Day 32. Petunias grown in 100% of treatment or control. C:N range called for in common compost specifications is shaded in green. R^2: 0.25, p-value: 0.039

5.4.7 Microbial respiration

As mentioned earlier, the almond fines blend was phytotoxic due to high rates of microbial activity. Common compost specifications put a maximum limit of 8 mg CO_2-C g OM^{-1} day^{-1} on respiration. Biomass of petunias vs. respiration and the range found in specifications is shown in Figure 58. When respiration was within the range required by specifications there was no meaningful trend amongst the petunias grown in either full blends or half blend + half sand. However, the one blend with respiration rates above the specification limit (AF) was clearly phytotoxic and this limit appears to be worthwhile for biosolids soil amendment products to adhere to.

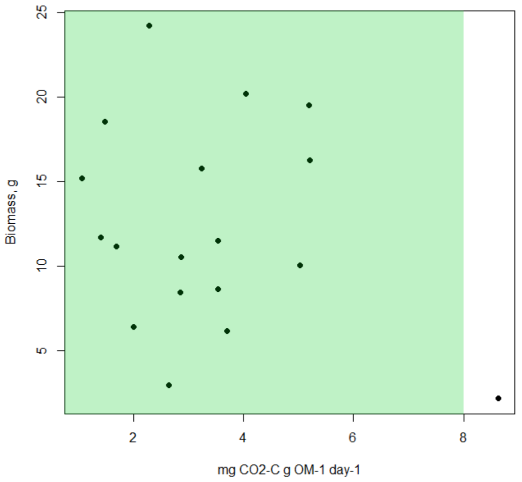


Figure 58. Biomass vs microbial respiration on Day 32. Respiration range called for in common compost specifications is shaded in green. Petunias grown in 100% of blends.

5.4.8 Electrical conductivity

As with microbial respiration, biomass of petunias vs. EC_5 (Figure 59) shows that when blends are within the limit required by common compost specifications, EC_5 seems to have little effect on biomass and there are no meaningful trends. Once EC_5 levels go above the specification limit biomass starts to decrease with increasing EC_5. This phenomenon was the same with biomass and flower yield from petunias grown in both full blends and half blend + half sand scenarios. There is some variance in the EC_5 limits set by different compost specifications. WSDOT sets a limit of 4 dS/m, TxDOT and AASHTO set a limit of 5 dS/m and Caltrans has a limit of 10 dS/m (AASHTO 2010; TxDOT 2014; Caltrans 2015; WSDOT 2016). More data points are needed to make any conclusive observations about EC of biosolids products used at high applications and plant response. Based on the results of the petunia growth trials it appears that products with an EC_5 up to 6 dS/m can still be effective, while going much above this level can cause yield reductions.

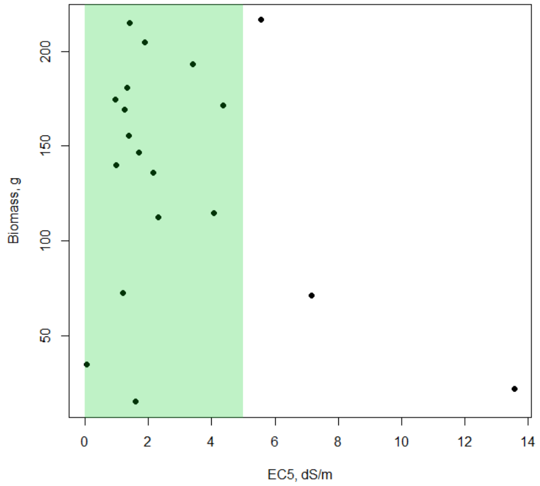
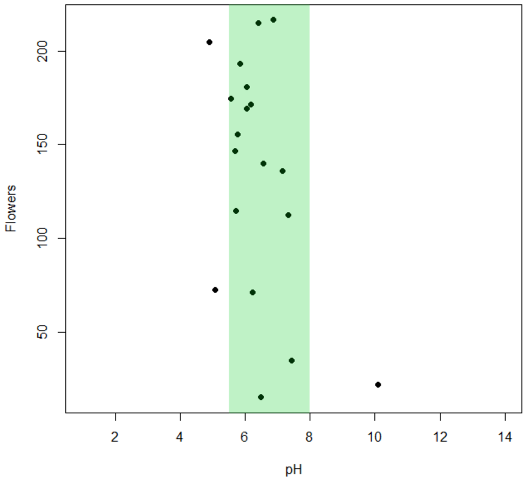


Figure 59. Biomass vs. EC_5 in treatment or control on Day 32. Petunias grown in full blend. Area shaded green is range called for in common compost specifications.

5.4.9 pH



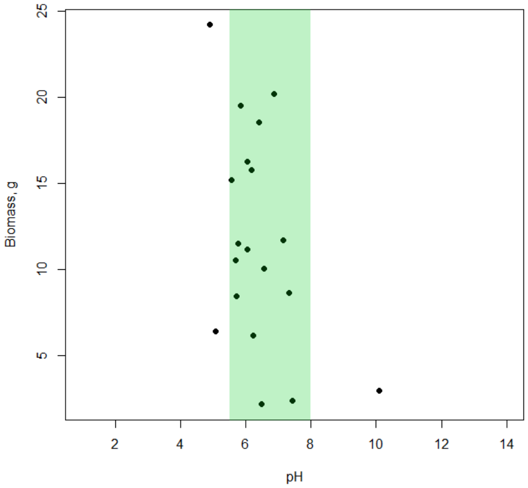


Figure 60 Flowers vs. pH of treatment or control on Day 32. Petunias grown in 100% of treatment or control. Area shaded green is range called for in common compost specifications.

Figure 61. Biomass vs. pH of treatment or control on Day 32. Petunias grown in 100% of treatment or control. Area shaded green is range called for in common compost specifications.

Although common compost specifications can sometimes call for a pH range of 6-8, the results from this study show that amendments with pH lower than 6 should also be acceptable. Figures 60 and 61 show biomass and flower yield vs pH in petunias grown in 100% of blends with the pH range of 5.5-8 shaded in green. Statistical analysis in fact shows that biomass and flower yield increase with decreasing pH at $p=0.051$ for biomass and $p=0.037$ for flowers. This is due to the leverage point of the high pH walnut shell char blend (WSC) and with the removal of this blend from analysis there is no longer a significant correlation between yield and pH at $p<0.10$. High biomass and flower yields are still possible with amendments of pH lower than 6 and no trend of reduction in yield was observed once blends cross the threshold below pH 6. Specifications from the American Association of State Highway and Transportation Officials have a lower pH limit of 5 and TxDOT has a limit of 5.5 which seems more appropriate given these findings (AASHTO 2010; TxDOT 2014).

5.4.10 Manganese

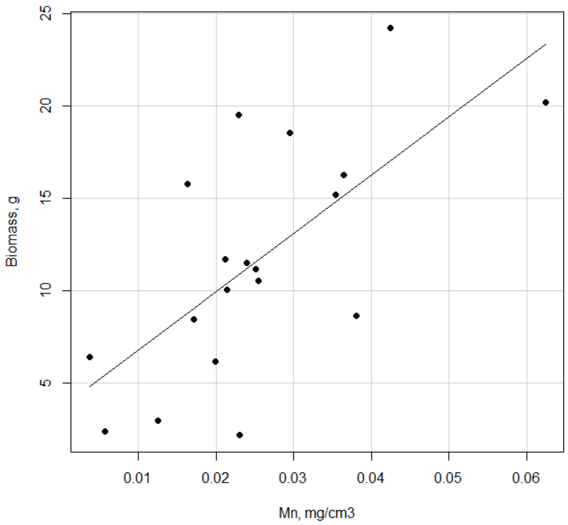


Figure 62. Biomass vs. volumetric Manganese content of treatment or control. Petunias grown in full blend. Adjusted r^2 : 0.42, p-value: 0.002

Biomass and flower yield in plants grown in 100% of blends was positively correlated with volumetric Manganese content at $p=0.002$ for biomass and $p=0.002$ for flowers (Figure 62). For plants grown in half blend + half sand Mn content was only significant at p=0.051 in biomass yield and not significant for flower yield at p=0.36. It seemed doubtful Mn content was a causal factor in increasing plant yield as plant requirements for this nutrient are relatively low. However, there have been reports that excess ammonium can reduce uptake of Mn with reduction in Mn much greater than for Mg, Ca and K (Cox and Reisenauer 1977). Given that exceedingly high ammonium levels was a theory for suppressed growth in some blends, reduction in Mn uptake which led to Mn deficiency is a hypothesis which could be tested with leaf tissue analysis. This hypothesis would explain why Mn content was positively correlated with biomass and flower yield in the full blends.

The sand and peat (S, P) treatments had the lowest levels of Mn as well as low biomass and flower yields. However, excess ammonium would not have been a factor in the low yields and reduced Mn uptake of petunias grown in sand and peat. Given that a relationship between Mn content and high levels of ammonium would only be important in treatments with biosolids, the correlation between Mn and petunia yields was analyzed again with treatments which did not contain biosolids removed. With the peat, sand, and Cedar Grove treatments (P, S, CG) removed, correlation between Mn content and flower yield was still significant at p=0.025, as was correlation between Mn and biomass yield at p=0.014. Variation in biomass yield in treatments which contained biosolids was better explained by a function with an interaction term between manganese and ammonium content (p=0.008) than with a quadratic function of ammonium content (p=0.059) and the interaction term was significant at p=0.051. However, variation in flower yield in treatments which contained biosolids was better explained by the quadratic function of ammonium content (p=0.003) than by a function with an interaction term between manganese and ammonium (p=.014) with the interaction term not (p=0.075). Given the low levels of Mn required for plant growth, it is possible the relationship found here between yield and Mn content is coincidental.

5.4.11 Lower application rates

The yield differences between treatments became much less distinct at lower application rates, i.e. growing petunias in half sand + half blend as opposed to growing petunias in the full blend. For example, with biomass yield of petunias grown in half sand + half blend, there is no statistical difference ($p<0.05$) between 12 of the 17 blends (Figure 63) and with flower yield there is no statistical difference between 15 of the 17 blends ($p<0.05$) (Figure 64). Mean biomass yield (n=4) ranged from a high of 22.0 g in the yard waste w/out sand blend (YF 100) to a low of 5.5 g in the Cedar Grove control (CG). The other controls, Tagro Potting Soil and Tagro Mix (TP, TM) yielded 18.4 g and 16.6 g of biomass respectively. Similar to petunias grown in almond fines (AF) at the full blend rate, two replicates in the half blend rate died while two survived and eventually started to grow normally. This created a large amount of variation in biomass and flower yield for AF as seen in figures 63 and 64.

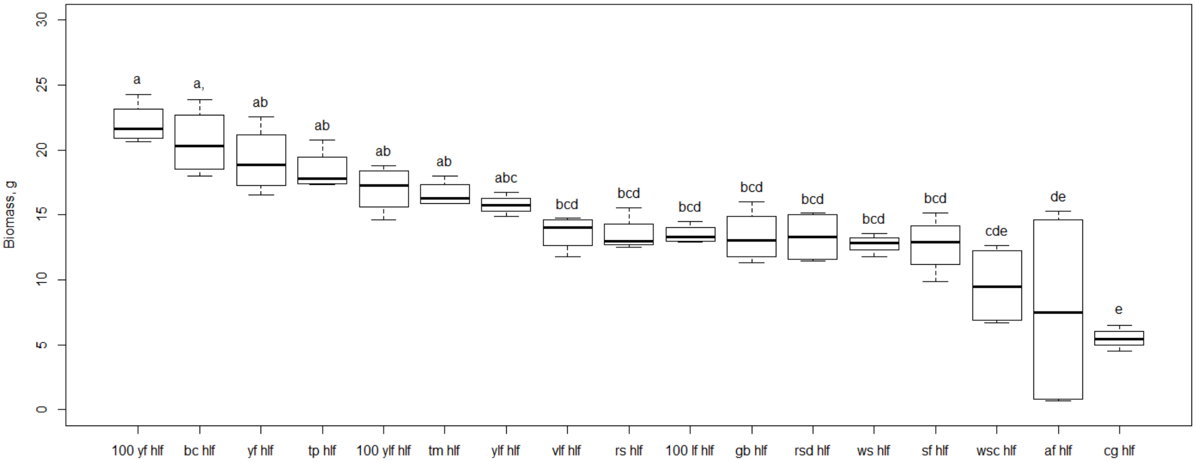


Figure 63. Dry biomass of petunias grown in 50% blend + 50% sand. Treatments are in order of highest to lowest mean biomass. Results with different letters are significantly different at $p < 0.05$.

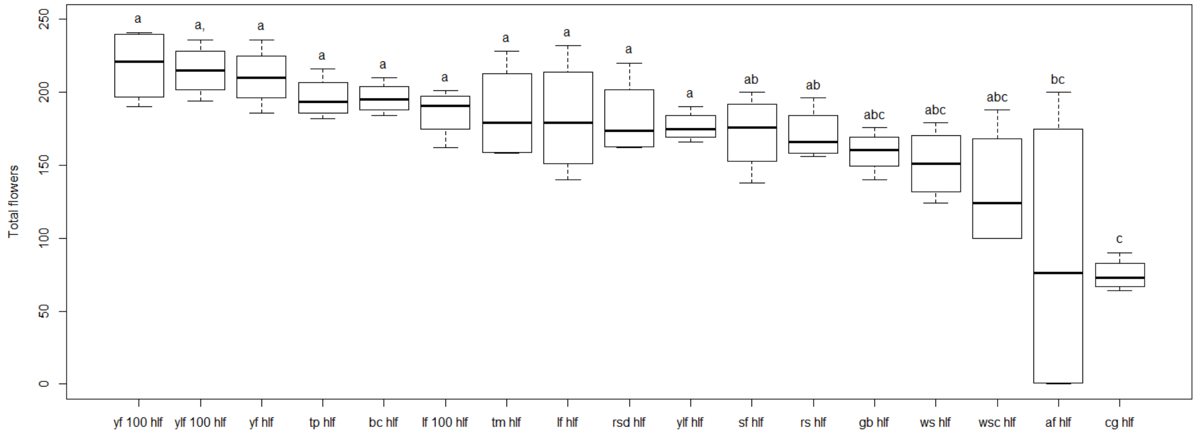


Figure 64. Number of flowers produced by petunias grown in 50% treatment + 50% sand. Treatments are in order of highest to lowest mean number of flowers. Results with different letters are significantly different at $p < 0.05$.

Mean flower yield (n=4) ranged from a high of 218 in the yard waste fines w/out sand blend (YF 100) to a low of 75 in the Cedar Grove control. The Tagro Potting Soil and Tagro Mix controls (TP, TM) had mean yields of 196 and 186 flowers respectively. The majority of blends, 11 out of 13, were statistically similar to the Tagro controls in terms of biomass yield ($p<0.05$). In terms of flower yield, 12 out of 13 blends were statistically similar to the Tagro controls ($p<0.05$). Other than the almond fines and walnut shell char blends, all blends had statistically higher biomass yields than the Cedar Grove control. This suggests that the majority of blends created in this study could be expected to work as well as established biosolids soil amendments and better than yard waste compost at improving plant growth when used as a soil amendment applied at a depth of 5 cm.

Due to there being less variation between the treatments at the lower application rate, most of the trends which were statistically significant at the higher application rate were no longer significant. Trends with ammonium and manganese remained significant however. Flower yield as a quadratic function of ammonium content was still significant at $p<0.001$ as was biomass yield at $p=0.011$. Biomass as a function of Mn content was significant at $p=0.05$, but flower yield was no longer significantly correlated with Mn content ($p=0.36$).

Symptoms of nutrient imbalances (or allelopathy) were still visible in the half blend scenario. Although the difference between the 4th and 14th highest yielding blends was not statistically significant, qualitative differences in the foliage were clearly visible (Figures 65-66). Blends which showed foliar signs of stress in the full blend also showed some degree of symptoms in the half blend: the lumber fines without sand, lumber fines, yard waste/lumber fines without sand, yard waste/lumber fines, redwood shavings, and redwood sawdust blends (LF 100, LF, YLF 100, YLF, RS, RSD). While it is not possible to know without conducting tissue analysis, ammonium toxicity is one potential hypothesis for these foliar symptoms. Allelopathy from wood products in the blends is another potential hypothesis.

Figure 65. Petunias grown in 50% Yard waste fines blend + 50% sand. (YF HLF). No signs of foliar nutrient imbalances.

Figure 66. Petunias grown in 50% Redwood Sawdust Blend + 50% sand (RSD HLF). Note speckling on the lower right hand leaf.

Table 17 on the following page shows the difference for each blend in petunia growth response between the full blend or half blend scenario. Blends which were phytotoxic have improved yields at the lower application rate, but they still perform poorly compared to other treatments. Almond fines, walnut shell char, and unblended biosolids (AF, WSC, and SF) had the lowest yields at the full blend application rate. When the volume of the mix was diluted by 50% with sand in the half blend scenario, biomass yield more than doubled.

Table 17. Biomass of petunias grown at two different application rates, 100% of blend, and 50% blend + 50% sand. Treatments are in order of greatest percent increase of biomass when grown at the lower application rate.

Treatment	Biomass grown in full amendment, g	Biomass grown in half amendment + half sand, g	Percent increase with lower application rate, %
af	2.2	7.7	257
wsc	3.0	9.6	222
sf	6.2	12.7	105
tm	10.0	16.6	65
lf 100	8.4	13.5	60
gb	8.6	13.4	55
rs	10.5	13.5	28
rsd	11.2	13.3	19
lf	11.5	13.6	18
yf	16.3	19.2	18
yf 100	19.5	22.0	13
ylf 100	15.8	17.0	8
bc	20.2	20.6	2
ylf	18.5	15.8	-15
ws	15.2	12.8	-16
tp	24.2	18.4	-24
cg	11.7	5.5	-53

Tagro Potting (TP), which was designed to be used at the full blend application rate, decreased in yield at the lower application rate, probably due to low concentration of biosolids, but still yields the 3rd highest biomass. With Cedar Grove (CG), the blend with the lowest levels available N of any treatment, yields decrease by more than half at the lower application rate. It is not readily apparent why the walnut shell blend and the yard/lumber fines blend (WS, YLF) decreased in yield with lower application rates. The WS had the second lowest ammonium content of any treatment with biosolids and the highest C:N ratio of 29:1. This suggests that petunias grown in the lower application rate of WS had access to less N which resulted in a mean biomass yield 2.4 grams lower in the half blend.

The blends which had the highest yields at the full blend rate also had the highest yields at the half blend rate – the biochar, yard waste fines, yard waste fines without sand, yard waste/lumber fines without sand blends and Tagro Potting Soil (BC, YF, YF 100, YLF 100, and TP). Other than Tagro Potting Soil which had a slight decrease in yield, these blends only had slight increases in yield at the lower application rate. Notably the biochar blend (BC) had almost no change in yield between the two application rates, lending credibility to the hypothesis that BC performed well because it sorbed excess ammonium. If excess ammonium were indeed a problem in BC, then a reduction in application rate would have improved yield, yet yield remains virtually unchanged between the two application rates.

5.4.12 Correlation with germination and growth response

Flower and biomass yield in petunias grown in full blends were positively correlated at $p<0.001$ with cucumber germination success. Radish germination success was not significantly correlated with these indicators ($p=0.094$ for flowers and $p=0.231$ for biomass). For petunias grown in the half blend trials, the only significant relationship is a positive correlation between flower yield and cucumber germination at ($p=0.043$). The cucumber germination assay was slightly more sensitive than the radish assay. There were 6 treatments at or above 90% germination success and 9 treatments at or above 85% with cucumber, however for radish there were 9 treatments at or above 90% and 13 treatments at or above 85%. This increased sensitivity in the cucumber assay is reflected in it being a better predictor of petunia performance in the full blend trial (Table 18).

Table 18. Correlation coefficients for germination assays and indicators of plant performance in the petunia growth trial. ***$p<0.001$, ** $p<0.01$, *$p<0.10$

	Cucumber germination	Radish germination
Petunia Flowers	0.74***	0.39*
Petunia Biomass	0.64***	0.29

5.4.13 Correlation with odor and growth response

Measurements of odor quality and odor intensity were significantly correlated with biomass yield of petunias grown in full blends as well as cucumber and radish germination (Table 19). The more intense or offensive the odor of a blend, the worse it performed as a soil amendment or potting soil. Cucumber germination was especially sensitive to blends with intense and offensive odors and its germination success was significantly correlated ($p<0.001$) for all measurements of odor. There are no significant correlations between yield and odor measurements in the half blend scenario at $p<0.05$.

Table 19. Correlation coefficients for measurements of odor and plant response. Biomass and number of flowers from petunias grown in the full blend scenario 100% of treatment. *** significant at ($p < 0.001$), ** significant at ($p < 0.01$), * significant at ($p < 0.1$)

	% finding odor offensive	Negative odor rating	Positive odor rating	Mean odor intensity	Number of flowers	Biomass	Cucumber germination	Radish germination
% finding odor offensive	-							
Negative odor rating	-0.97***	-						
Positive odor rating	-0.78***	0.77***	-					
Mean odor intensity	0.92***	-0.90***	-0.57*	-				
Number of flowers	-0.72**	0.76***	0.55*	-0.72**	-			
Biomass	-0.60*	0.64**	0.45*	-0.63**	0.95***	-		
Cucumber germination	-0.85***	0.91***	0.75***	-0.85***	0.78***	0.66**	-	
Radish germination	-0.64**	0.74**	0.74***	-0.57*	0.53*	0.39	0.86***	-

5.4.15 Correlation between measurements of petunia growth response

Dry biomass and the total number of flowers produced by each treatment in the full and half blend trials were closely correlated at $p<0.001$ (Figure 67). Flower production appears to level off at the higher rates of biomass production. Shoot index is also well correlated with dry biomass and flower production at $p<0.001$ (Figure 68). Given the potential for human error in hand measuring plants, as well as the irregular, cascading growth habit of the petunias used in this study, it is possibly a slightly less accurate assessment of plant performance in the different treatments compared to flower and biomass yield.

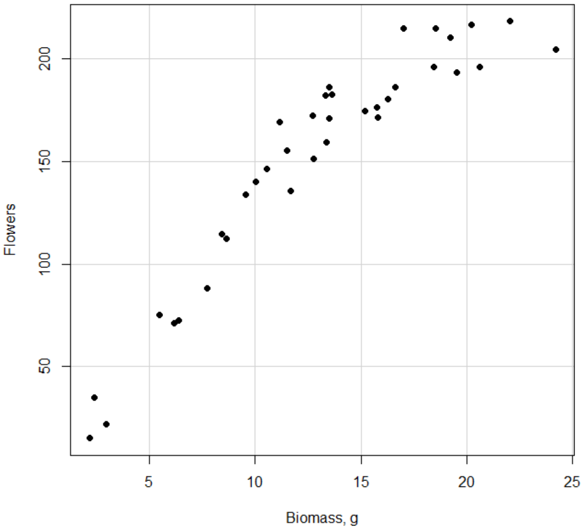


Figure 67. Flowers as a function of dry biomass in treatments. Petunias from both application rates (100% of blends, 50% blend+50% sand. Adjusted r^2: 0.87, p-value: < 0.001

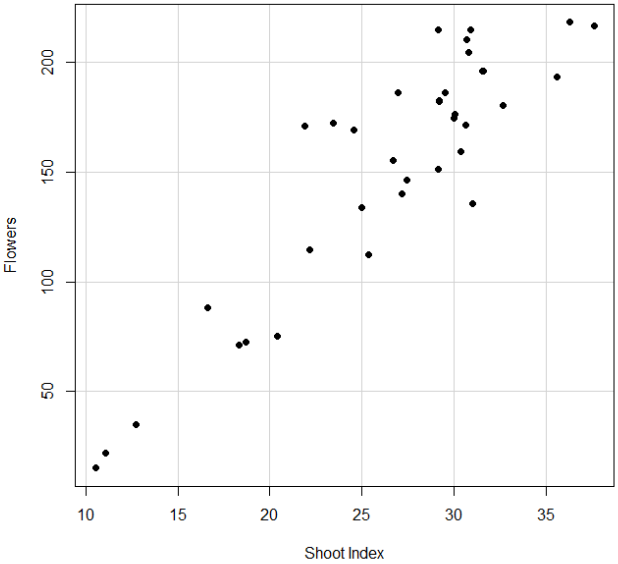


Figure 68. Flowers as a function of shoot index in treatments. Petunias from both application rates. Adjusted r^2: 0.82, p-value: < 0.001

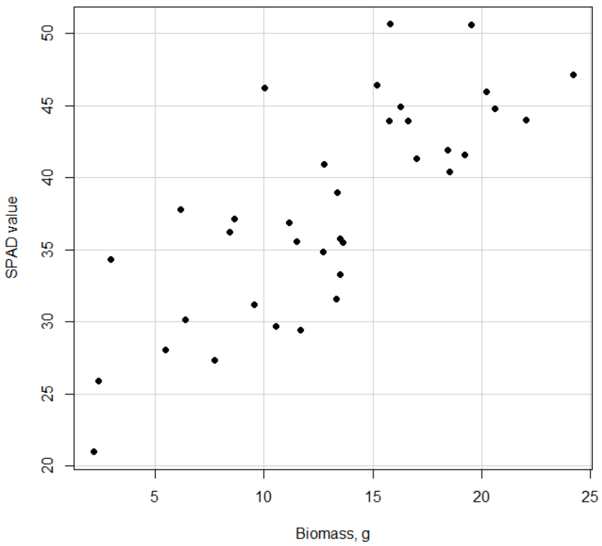


Figure 69. SPAD measure of chlorophyll content as a function of dry biomass in treatments. Petunias from both application rates. Adjusted r^2: 0.59, p-value: <0.001

The SPAD chlorophyll measurements were not as closely correlated with the other measurements of plant performance, although the correlation was still highly significant at $p<0.001$ (Figure 69). The chlorophyll measurements also did not show very distinct differences between treatments. In the petunias grown in half sand and half blend for example, there was no statistically significant difference in measures of chlorophyll between any treatment. Furthermore, chlorophyll measures of unhealthy plants grown in the almond fines blend (AF) were inaccurate. The SPAD meter sometimes gave exceedingly high values or was unable to take a reading. Table 20 displays the correlation coefficients between these different measurements of plant performance.

Table 20. Correlation coefficients between different measurements of plant performance in treatments. *** p<0.001.

	Flowers	Biomass	Spad measurement	Shoot index
Flowers	-			
Biomass	0.93***	-		
Spad measurement	0.69***	0.77***	-	
Shoot index	0.91***	0.89***	0.75***	-

5.4.16 Insights from petunia growth trials

Due to the heterogeneity of the treatments, it was difficult to develop a single model which explained plant performance based on the properties of the blend. Treatments could suppress growth for a variety of reasons. One treatment might have microbial respiration within an acceptable range but excessively alkaline pH, while another treatment had acceptable pH but excessively high microbial activity. This reduced the ability for statistical analysis to demonstrate meaningful trends. Stepwise regression found that C:N ratio and total N content together better explained flower production in the full blend scenario than either variable alone ($p=0.04$) and as mentioned earlier, ammonium and manganese better explained biomass production in the full blend scenario than a quadratic function of ammonium alone. Other than this there were no meaningful trends with multiple variables which explain variation better than single variables. Despite the difficulty finding a single model to explain variation in yields, it was still possible to draw several conclusions from the petunia growth study. Blends with respiration rates above 8 mg CO_2-C gOM^{-1} day^{-1} produced phytotoxic conditions in both the full blend and half blend + half sand trials due to VOA production or O_2 depletion. Plants grown in blends with pH above 8 and EC_5 higher than 6 dS m^{-1} performed poorly in both trials. The highest yielding blends had a C:N ratio within the range of 10:1-25:1. Similar to C:N ratio, there was an ideal range for ammonium levels, with levels above this range possibly resulting in ammonium toxicity and levels below this range resulting in N deficiency. One hypothesis for why the highest yielding blends performed so well was reduced levels of ammonium in solution either by microbial immobilization, transformations or sorption.

It is important to note that these findings are for a specific plant species grown at two specific application rates. Different species would respond differently and could either be more productive or more sensitive to conditions in the blends. Different end uses also have different requirements. The use of unblended biosolids has a long history of successful use in agriculture, silviculture and reclamation even though when unblended biosolids are used to grow petunias at the application rates in this study, they do not perform well.

The application rates used in this study were intentionally high in order to find potential phytotoxicity as well as to assess their use as a soil amendment for a home gardener who might use the amendment at high application rates. The causes of phytotoxicity found in the blends in these petunia growth trials will be less impactful if materials were to be used as a topdressing rather than as a potting soil. This is already evident in this study when reducing the application rate so that plants are grown in 50% blend + 50% sand. However, the mechanisms of phytotoxicity such as high EC and high rates of decomposition could still reduce yield even at lower application rates.

Treatments which were found to be nutrient deficient in this trial would likely be even less effective at lower application rates, while treatments with what appeared to be excessive levels of plant available N would perform better when used as a top dressing for soils rather than as a substitute for soils. As noted earlier, for blends which were phytotoxic to some degree, there was an improvement in yield at the lower application rate of the half blend + half sand scenario. However, the blends which performed very well at the high application rate of the full blend scenario (YF 100, YF, BC, YLF 100, YLF) were still the highest performing blends at the lower application rate. Moving to even lower application rates, such as ¼ blend + ¾ sand possibly would have seen these top performers replaced with blends which had appeared to have excessive ammonium at the full blend application rate. Yet given that the blends were all created with relatively similar amounts of biosolids and therefore have comparable levels of organic N, having higher rates of available inorganic N does not necessarily make a blend more effective at lower application rates. In systems with high levels of labile organic C and N, relationships develop between plants and microbial activity which creates a “tightly-coupled” N cycle where plant yield is high despite low overall levels of inorganic N (Bowles et al. 2015). Therefore, it is conceivable that even at much lower application rates, the blends which performed best at the full blend and half blend scenarios would still outperform the blends which see yield improvements with reduction in application rate.

To enter into new markets, a biosolids soil amendment product have to be adaptable for a range of end uses and be user friendly in that it did not easily create phytotoxic conditions. The high application rates used in this study account for potential end uses which could involve heavy applications of a soil amendment, or which could involve particularly sensitive plants. Marketing products which require careful attention to application rates to avoid plant toxicity is certainly possible as synthetic N fertilizers are widely available for purchase in the US. Products which were not phytotoxic at high application rates and still effective at low application rates are be ideal though – as this broadens the range of uses possible for the product and limit negative user experiences.

In terms of the criteria this project set for a successful biosolids soil amendment product, germination in the blend should be above 80% compared to controls (which in this case had 100% germination success), and plant growth should be improved in a manner similar to or better than controls (Table 21).

As seen in Table 21, the majority of blends created by this project performed similar to or better than the biosolids soil amendment control at improving petunia growth. The almond fines and walnut shell char blend (AF, WSC) were the only biosolids blends which yielded significantly lower quantities of flowers and biomass than controls ($p<0.05$). While this means all other blends performed reasonably well at improving petunia plant growth, there were certain blends which excelled and had few unsightly foliar symptoms of nutrient imbalances, namely the yard waste fines, yard waste fines without sand, biochar, yard/lumber fines, yard lumber fines without sand, and walnut shell blends (YF, YF 100, BC, YLF,

YLF 100, WS). When considering the germination criteria, the biochar, gypsum board, almond fines and walnut shell char are all below the 80% germination success threshold. Given that the biochar blend (BC) performed well in odor trials and in petunia growth trials, a reduction in the amount of biochar used in the blend could help retain the positive qualities of the blend while making it less phytotoxic to germination of salt sensitive crops. The biochar feedstock was also the most expensive material by far at $90/CY and any full scale production of a biosolids soil amendment would only be able to incorporate small amounts of biochar due to cost considerations.

Table 21. Treatment performance on project criteria for plant response. Similar or better than control is defined as biomass and flower yields being statistically similar or greater to Tagro Mix at $p<0.05$. Germination success is defined as ≥80%. Cells highlighted in red are a failure to meet criteria. *Peat was not used at the half blend application rate. **Comparisons are made to this treatment.

Treatment	**Similar or better than control at full amendment application rate**	**Similar or better than control at half amendment application rate**	**Cucumber germination success ≥ 80%**	**Radish germination success ≥ 80%**
af	no	no	0	0
bc	yes	yes	80	20
cg	yes	no	100	100
gb	yes	yes	60	60
lf	yes	yes	90	95
lf 100	yes	yes	95	95
p	no	n/a*	100	100
rs	yes	yes	95	85
rsd	yes	yes	80	95
sf	no	yes	80	90
tm	n/a**	n/a**	80	95
tp	yes	yes	100	95
ws	yes	yes	80	80
wsc	no	no	0	0
yf	yes	yes	90	95
yf 100	yes	yes	80	95
ylf	yes	yes	100	85
ylf 100	yes	yes	90	80

5.5 Goals for a blended biosolids soil product

To determine whether the blended biosolids soil amendments created in this project were viable products, a set of criteria was created based on common specifications for compost, performance in odor and appearance trials, and performance in plant response trials. Three biosolids blends, lumber fines without sand, yard waste fines without sand and yard waste/lumber fines without sand (LF 100, YF

100, YLF 100) met all the criteria. However, the petunia growth trials showed that specification ranges for % OM were not possible for blends with sand to meet and more importantly plant response was not negatively affected when % OM dropped below 30%. Therefore, blends which did not meet common compost specifications for % OM were still considered as potentially viable products. In Table 22, where blends fail to meet specification criteria solely because of low % OM cells are highlighted in yellow. Where blends meet criteria cells are highlighted in green. Failure to meet criteria are highlighted in red. Allowing exceptions for meeting % OM specification criteria, there are 5 blends which meet all sets of criteria: the lumber fines without sand, yard waste fines, yard waste fines without sand, yard waste/lumber fines without sand, and yard waste/lumber fines blends (LF 100, YF, YF 100, YLF 100, YLF).

Table 22. Treatment performance on overall criteria. Criteria explained on pg. 38-39. Cells highlighted in red are a failure to meet criteria and reasons for failing to meet criteria are written in each cell. Cells highlighted in green meet criteria. Where treatments fell outside of a specification range that was not shown to greatly affect plant performance, cells have been highlighted in yellow.

Treatment	**Meets specification criteria**	**Meets odor and appearance criteria**	**Meets plant trial criteria**
af	% OM, C:N, CO_2 evolution	odor	petunia yield, germination
bc	EC	yes	germination
gb	% OM	appearance	germination
lf	% OM	appearance	yes
lf 100	yes	yes	yes
rs	% OM	appearance	yes
rsd	% OM	appearance	yes
sf	EC, C:N	odor, appearance	petunia yield
ws	pH, C:N	odor, appearance	yes
wsc	EC, pH	odor, appearance	petunia yield, germination
yf	% OM	yes	yes
yf 100	yes	yes	yes
ylf	% OM	yes	yes
ylf 100	yes	yes	yes

As mentioned earlier blends will perform differently based on application rate, plant species, and how a product is being used (potting soil versus topdressing). The biochar blend (BC) for example, works very well at improving petunia growth, however its EC is too high for the germination of radish. This blend could work well as a product which was marketed specifically as a topdressing which should be incorporated into soil or surface applied at a lower application rate. Similarly, odor and appearance will have different levels of importance depending on the end user, with users more familiar with odors associated with agriculture, landscaping and wastewater treatment being accepting of a wider range of odors and appearance than end users such as homeowners. As with public acceptability and plant performance, the importance of blends being able to meet common compost specifications will vary based on their intended end use. In this very project for example, the % OM ranges called for by specifications were found to exclude blends which still performed well at improving plant growth.

A blend can fail to meet criteria but still be useful for certain applications. That said, the set of criteria created for this project were meant to find products that are appropriate for use by a wide range of end users in a wide range of applications, similar to how a basic compost is used. Blend performance in regard to these criteria is therefore helpful in predicting whether the blend would be successful if marketed to the general public and private enterprises as a soil amendment.

6. Conclusion

By blending biosolids with organic and inorganic feedstocks it was possible to create novel soil amendment products. The final properties in the blended soil amendments were explained by the initial properties of blend ingredients and the ratios the ingredients are mixed at as well as by microbial activity. Certain of these blended soil amendments were found to address the issues that prevent unblended biosolids from being adopted in a wider range of applications.

The majority of blended biosolids soil amendment products were found to have a more acceptable odor and appearance than unblended biosolids. In blends that had more offensive odors than unblended biosolids, high levels of microbial activity and high pH that caused ammonia volatilization were at fault. Sorption of odors, reduction of ammonia volatilization, and the dilution of biosolids were responsible for a reduction of odor in blends which had less offensive odors than biosolids. While it was difficult to explain why certain blends performed better in the aesthetics survey using measured variables, consistent particle size, absence of sand, and similarity in appearance to soil seemed to be important attributes for blends which had an acceptable appearance.

The majority of blended soil amendments were also found to have higher petunia biomass and flower yields than unblended biosolids. For blends with yields lower than unblended biosolids, excessive microbial activity, excessive alkalinity and excessive EC were responsible. Foliar symptoms of nutrient imbalances, possibly symptomatic of excess ammonium, were visible in many blends. The blends with the highest biomass and flower yields also showed few foliar symptoms of nutrient imbalances and possibly had reduced levels of ammonium in solution due to sorption and microbial immobilization. Blends which performed poorly in germination assays had excessive microbial activity, high pH, and high EC. Plant tissue analysis to test hypotheses about nutrient imbalances would be informative if further work were done on biosolids soil amendments used at high application rates.

While blended soil amendments were able to meet some common compost specifications that unblended biosolids were not, blends created in this project had difficulty meeting specifications requirements for % OM. Plant trials showed that blends which did not meet the % OM requirements still had high yields of biomass and flowers. Meeting specification requirements for C:N ratio, microbial respiration, and EC were more important for achieving high petunia biomass and flower yields.

The addition of sand appears to be unnecessary based on the parameters measured in this study. It does not appear to play a role in reducing odor, meeting specifications, or improving yield and seemed to reduce acceptability of blend appearance. However, it is possible that sand could improve some unmeasured aspects of the blends such as mixability during the production of blends or ease of handling.

This study was designed to evaluate a large number of potential ingredients for a blended soil amendment rather than elucidate a single mechanism behind odor, or plant response. In order to clearly identify these mechanisms, focusing on a single variable and eliminating variation in all other variables in blends would be helpful.

Based on the criteria this project established for a successful blended biosolids soil amendment, the following blends in Table 23 are viable products:

Table 23. Viable blends for a successful blended biosolids soil amendment based on project criteria.

Treatment	Volumetric proportions
LF 100	50% Lumber fines, 50% biosolids
YF	40% Yard Waste fines, 40% biosolids, 20% sand
YF 100	50% Yard waste fines, 50% biosolids
YLF	40% Lumber/Yard waste fines, 40% biosolids, 20% sand
YLF 100	50% Lumber/Yard waste fines, 50% biosolids

This project has shown that it is possible to achieve a wide range of properties in blended biosolids soil amendments depending on what feedstocks are used and how microbial activity modifies these materials. If a different set of criteria than used in this project were established for a specific end use, it would most likely be possible to develop blended biosolids soil amendments which met those criteria and were effective in that end use.

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8. Appendix A

Image results for petunia growth trials

Treatments are in order of biomass yield from petunias grown in 50% treatment + 50% sand. All four replicates of each trial for a treatment are displayed on the first page of photos for a treatment. One close up photo of a plant grown in 100% of treatment is on the first page followed on the second page by one close up photo of a plant grown in 100% treatment and two close up photos of plants grown in 50% treatment + 50% blend. Plants grown in 50% treatment + 50% blend are denoted by the letters "HLF" next to the treatment abbreviation. Foliar abnormalities seen in the two application rates are noted on the first page.

Yard waste fines blend without sand (YF 100)

Blend Ratio: 50% yard waste fines, 50% biosolids

Grown in 100% yard waste fines blend without sand (YF 100)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
19.51	1.14	193.3	7.59	50.6	1.89

Grown in 50% yard waste fines blend without sand, 50% sand (YF 100 HLF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
22.05	0.80	218.3	12.61	43.96	1.25

Biochar blend properties:

EC_5	3.4 dS/m	NH_4^+	1606 ppm
pH	5.84	P	967 ppm
OM	56%	K	1774 ppm
C:N	13.0:1	Ca	3348 ppm
Total N	2.21%	S	1945 ppm
Respiration	5.2 mg CO2-C/g OM/day	Mg	1553 ppm
Bulk density	0.20 g/cm^3	Na	394 ppm

Detail photo YF 100 2:

Notes: Very faint interveinal chlorosis on young leaves of both YF 100 and YF 100 HLF

Yard waste fines blend without sand (YF 100)

Blend Ratio: 50% yard waste fines, 50% biosolids

YF 100

YF 100 HLF

YF 100 HLF

Biochar blend (BC)

Blend Ratio: 25% biochar, 25% yard waste fines, 50% biosolids

Grown in 100% biochar blend (BC)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
20.21	1.50	216.5	6.29	45.9	2.56

Grown in 50% biochar blend, 50% sand (BC HLF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
20.63	1.30	196	5.48	44.8	1.89

Biochar blend properties:

EC_5	5.6 dS/m	NH_4^+	2283 ppm
pH	6.86	P	447 ppm
OM	59%	K	2187 ppm
C:N	11.3:1	Ca	7736 ppm
Total N	2.58%	S	572 ppm
Respiration	4.0 mg CO2-C/g OM/day	Mg	1559 ppm
Bulk density	0.17 g/cm^3	Na	571 ppm

Detail photo: BC 1

Notes: No signs of nutrient deficiencies or chlorosis visible on BC HLF. Very slight interveinal chlorosis of new growth on BC.

Biochar blend (BC)

Blend Ratio: 25% biochar, 25% yard waste fines, 50% biosolids

Additional pictures:

BC

BC HLF

BC HLF

Yard waste fines blend (YF)

Blend Ratio: 40% yard waste fines, 40% biosolids, 20% sand

Grown in 100% yard waste fines blend (YF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
16.27	0.37	180.5	6.99	44.93	2.82

Grown in 50% yard waste fines blend, 50% sand (YF HLF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
19.21	1.30	210.5	10.34	41.56	1.29

Biochar blend properties:

EC_5	1.3 dS/m	NH_4^+	704 ppm
pH	6.05	P	991 ppm
OM	21%	K	690 ppm
C:N	12.3:1	Ca	2033 ppm
Total N	0.81%	S	916 ppm
Respiration	5.2 mg CO2-C/g OM/day	Mg	1122 ppm
Bulk density	0.43 g/cm^3	Na	232 ppm

Detail photo YF 2:

Notes: Vague interveinal chlorosis on young leaves, some speckled browning of leaves on YF. Some chlorosis and browning of lower leaves on YF HLF.

Yard waste fines blend (YF)

Blend Ratio: 40% yard waste fines, 40% biosolids, 20% sand

YF

YF HLF

YF HLF

TAGRO Potting Soil (TP)

Blend Ratio: 62% aged bark, 31% sawdust, 7% Tacoma biosolids

Grown in 100% TAGRO potting soil TP

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
24.2	1.15	204.8	6.29	47.1	2.96

Grown in 50% TAGRO potting soil, 50% sand TP HLF

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
18.44	0.80	196.3	7.26	41.9	2.80

Biochar blend properties:

EC_5	1.9 dS/m	NH_4^+	958 ppm
pH	4.91	P	634 ppm
OM	50%	K	1493 ppm
C:N	17.5:1	Ca	3073 ppm
Total N	1.16%	S	818 ppm
Respiration	2.3 mg CO2-C/g OM/day	Mg	889 ppm
Bulk density	0.28 g/cm^3	Na	185 ppm

Detail photo TP1:

Notes: Dark green leaves, slight thin whitening of some leave edges on TP. Some chlorosis of lower leaves on TP HLF.

TAGRO Potting Soil (TP)

Blend Ratio: 62% aged bark, 31% sawdust, 7% Tacoma biosolids

TP

TP HLF

TP HLF

Yard waste/lumber fines blend without sand (YLF 100)

Blend Ratio: 50% yard waste/lumber fines, 50% biosolids

Grown in 100% yard waste/lumber fines blend without sand (YLF 100)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
15.78	1.25	171.25	13.25	50.6	2.98

Grown in 50% yard waste/lumber fines blend without sand, 50% sand (YLF 100 HLF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
17.02	0.92	215	8.81	41.3	1.47

Biochar blend properties:

EC_5	4.4 dS/m	NH_4^+	2482 ppm
pH	6.19	P	915 ppm
OM	58%	K	820 ppm
C:N	14.9:1	Ca	6395 ppm
Total N	1.77%	S	3005 ppm
Respiration	3.2 mg CO2-C/g OM/day	Mg	1157 ppm
Bulk density	0.19 g/cm^3	Na	1406 ppm

Detail photo ZLF 100 3:

Notes: Small amounts of chlorosis and browning on older leaves in ZLF 100. Some interveinal chlorosis of younger leaves, chlorosis and browning of older leaves on ZLF 100 HLF.

Yard waste/lumber fines blend without sand (YLF 100)

Blend Ratio: 50% yard waste/lumber fines, 50% biosolids

YLF 100

YLF 100 HLF

YLF 100 HLF

TAGRO mix (TM)

Blend Ratio: 40% sawdust, 40% Tacoma biosolids, 20% sand

Grown in 100% TAGRO mix (TM)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
10.05	1.18	140	13.73	46.2	1.61

Grown in 50% TARGO mix, 50% sand (TM HLF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
16.63	0.50	186	16.75	43.95	3.39

Biochar blend properties:

EC_5	1.0 dS/m	NH_4^+	723 ppm
pH	6.57	P	661 ppm
OM	16%	K	354 ppm
C:N	10.9:1	Ca	1594 ppm
Total N	0.64%	S	619 ppm
Respiration	5.0 mg CO2-C/g OM/day	Mg	482 ppm
Bulk density	0.39 g/cm^3	Na	246 ppm

Detail photo TM 1:

Notes: Light interveinal chlorosis on young leaves, light chlorosis with some browning of older leaves on TM. Interveinal chlorosis on TM HLF although less than on TM. Chlorosis and browning of older leaves on TM HLF.

TAGRO mix (TM)

Blend Ratio: 40% sawdust, 40% Tacoma biosolids, 20% sand

TM

TM HLF

TM HLF

Yard waste/lumber fines blend (YLF)

Blend Ratio: 40% yard waste/lumber fines, 40% biosolids, 20% sand

Grown in 100% yard waste/lumber fines blend (YLF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
18.55	1.02	215	4.12	40.4	2.06

Grown in 50% yard waste/lumber fines blend, 50% sand (YLF HLF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
15.77	0.38	176.5	5.12	43.96	3.50

Biochar blend properties:

EC_5	1.4 dS/m	NH_4^+	865 ppm
pH	6.42	P	848 ppm
OM	20%	K	317 ppm
C:N	13.1:1	Ca	2986 ppm
Total N	0.82%	S	1244 ppm
Respiration	3.2 mg CO2-C/g OM/day	Mg	842 ppm
Bulk density	0.43 g/cm^3	Na	712 ppm

Detail photo ZLF 3:

Notes: Some chlorosis and browning of older leaves on ZLF. Some chlorosis of older leaves on ZLF HLF.

Yard waste/lumber fines blend (YLF)

Blend Ratio: 40% yard waste/lumber fines, 40% biosolids, 20% sand

YLF

YLF HLF

YLF HLF

Lumber fines blend (LF)

Blend Ratio: 40% lumber fines, 40% biosolids, 20% sand

Grown in 100% lumber fines blend (LF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
11.52	1.55	155.5	5.85	35.6	2.85

Grown in 50% lumber fines blend, 50% sand (LF HLF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
13.64	0.67	182.5	20.12	35.5	2.82

Biochar blend properties:

EC_5	1.4 dS/m	NH_4^+	934 ppm
pH	5.76	P	841 ppm
OM	21%	K	258 ppm
C:N	11.8:1	Ca	1571 ppm
Total N	0.72%	S	865 ppm
Respiration	3.5 mg CO2-C/g OM/day	Mg	828 ppm
Bulk density	0.41 g/cm^3	Na	479 ppm

Detail photo VLF 4:

Notes: Interveinal chlorosis of younger leaves, chlorosis and browning of older leaves on VLF. Some interveinal chlorosis of younger leaves, chlorosis and browning of older leaves with some speckling on VLF HLF.

Lumber fines blend (LF)

Blend Ratio: 40% lumber fines, 40% biosolids, 20% sand

LF

LF HLF

LF HLF

Redwood shavings blend (RS)

Blend Ratio: 40% redwood shavings, 40% biosolids, 20% sand

Grown in 100% redwood shavings blend (RS)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
10.54	0.89	146.5	4.79	33.3	3.91

Grown in 50% redwood shavings blend, 50% sand (RS HLF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
13.51	0.70	171	9.00	36.91	4.99

Redwood shavings blend properties:

EC_5	1.7 dS/m	NH_4^+	945 ppm
pH	5.69	P	803 ppm
OM	18%	K	182 ppm
C:N	10.1:1	Ca	1382 ppm
Total N	0.55%	S	781 ppm
Respiration	2.9 mg CO2-C/g OM/day	Mg	792 ppm
Bulk density	0.37 g/cm^3	Na	123 ppm

Detail photo: RS 4

Notes: Interveinal chlorosis on young leaves and chlorosis and browning of older leaves on RS. Faint interveinal chlorosis on young leaves, chlorosis and browning of older leaves on RS HLF.

Redwood shavings blend (RS)

Blend Ratio: 40% redwood shavings, 40% biosolids, 20% sand

RS

RS HLF

RS HLF

Vision lumber fines without sand (LF 100)

Blend Ratio: 50% lumber fines, 50% biosolids

Grown in 100% Vision lumber fines without sand (LF 100)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
8.44	0.41	114.5	14.89	36.21	2.67

Grown in 50% vision lumber fines without sand, 50% sand (LF 100 HLF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
13.50	0.36	186.25	8.51	35.78	0.85

Biochar blend properties:

EC_5	4.1 dS/m	NH_4^+	3113 ppm
pH	5.72	P	1026 ppm
OM	66%	K	758 ppm
C:N	11.0:1	Ca	3582ppm
Total N	2.90%	S	2875 ppm
Respiration	2.9 mg CO2-C/g OM/day	Mg	1508 ppm
Bulk density	0.16 g/cm^3	Na	962 ppm

Detail photo VLF 100 2:

Notes: Interveinal chlorosis of younger leaves, chlorosis and browning of older leaves with some speckling on VLF 100. Interveinal chlorosis of younger leaves, chlorosis and browning of older leaves VLF 100 HLF.

Vision lumber fines without sand (LF 100)

Blend Ratio: 50% lumber fines, 50% biosolids

LF 100

LF 100 HLF

LF 100 HLF

Gypsum board fines blend (GB)

Blend Ratio: 40% gypsum board fines, 40% biosolids, 20% sand

Grown in 100% gypsum board fines blend (GB)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
8.64	1.28	112.5	17.80	37.18	1.06

Grown in 50% gypsum board fines blend, 50% sand (GB)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
23.37	1.02	159.25	7.41	38.98	2.21

Biochar blend properties:

EC_5	2.3 dS/m	NH_4^+	558 ppm
pH	7.34	P	256 ppm
OM	13%	K	255 ppm
C:N	12.7:1	Ca	12349 ppm
Total N	0.40%	S	5651 ppm
Respiration	3.5 mg CO2-C/g OM/day	Mg	610 ppm
Bulk density	0.57 g/cm^3	Na	651 ppm

Detail photo GB 3:

Notes: Leaf edge whitened on old leaves in ZPF. Pronounced lead edge whitening on old leaves in ZPF HLF.

Gypsum board fines blend (GB)

Blend Ratio: 40% gypsum board fines, 40% biosolids, 20% sand

GB

GB HLF

GB HLF

Redwood sawdust blend (RSD)

Blend Ratio: 40% redwood sawdust, 40% biosolids, 50% sand

Grown in 100% redwood sawdust blend (RSD)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
11.17	0.30	169.3	10.65	36.9	4.99

Grown in 50% redwood sawdust blend, 50% sand (RSD HLF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
13.31	1.00	182.3	13.57	31.6	2.91

Redwood sawdust blend properties:

EC_5	1.3 dS/m	NH_4^+	985 ppm
pH	6.04	P	814 ppm
OM	20%	K	258 ppm
C:N	17.2:1	Ca	1538 ppm
Total N	0.71%	S	956 ppm
Respiration	1.7 mg CO2-C/g OM/day	Mg	880 ppm
Bulk density	0.39 g/cm^3	Na	276 ppm

Detail photo: RSD 1

Notes: Interveinal chlorosis of young leaves and chlorosis and browning on older leaves on both RSD and RSD HLF.

Redwood sawdust blend (RSD)

Blend Ratio: 40% redwood sawdust, 40% biosolids, 50% sand

RSD

RSD HLF

RSD HLF

Walnut shell blend (WS)

Blend Ratio: 40% Walnut shells, 40% biosolids, 20% sand

Grown in 100% walnut shell blend (WS)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
15.18	0.57	174.5	13.07	46.44	1.24

Grown in 50% walnut shell blend, 50% sand (WS HLF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
12.76	0.36	151.3	12.10	40.94	2.08

Biochar blend properties:

EC_5	0.9 dS/m	NH_4^+	575 ppm
pH	5.57	P	1270 ppm
OM	36%	K	11811 ppm
C:N	29.0:1	Ca	4192 ppm
Total N	0.52%	S	1335 ppm
Respiration	1.1 mg CO2-C/g OM/day	Mg	1674 ppm
Bulk density	0.49 g/cm^3	Na	355 ppm

Detail photo WS 2:

Notes: Very thin whitening of leave edges similar to Tagro Potting Soil (TP) in WS HLF.

Walnut shell blend (WS)

Blend Ratio: 40% Walnut shells, 40% biosolids, 20% sand

WS

WS HLF

WS HLF

San Francisco Biosolids (SF)

Blend Ratio: 100% Oceanside treatment plant biosolids

Grown in 100% biosolids (SF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
6.19	0.50	71	6.86	36.9	4.99

Grown in 50% biosolids, 50% sand (SF HLF)

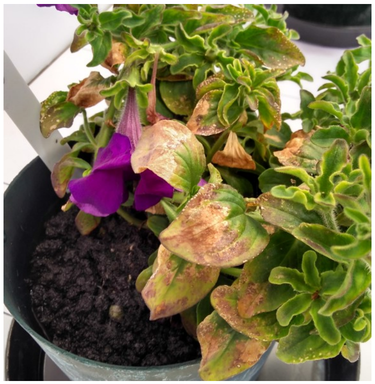
Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
12.70	1.09	172.5	13.22	31.63	2.91

Biosoldis properties:

EC_5	7.2 dS/m	NH_4^+	5271 ppm
pH	6.23	P	1118 ppm
OM	53%	K	703 ppm
C:N	6.6:1	Ca	3480 ppm
Total N	3.73%	S	3473 ppm
Respiration	3.7 mg CO2-C/g OM/day	Mg	1609 ppm
Bulk density	0.20 g/cm^3	Na	558 ppm

Detail photo:

SF 3



Notes: Purple lesions and speckling on leaves of SF. Interveinal chlorosis of young leaves, chlorosis and browning on older leaves and purple lesions and speckling on all leaves in SF HLF.

San Francisco Biosolids (SF)

Blend Ratio: 100% Oceanside treatment plant biosolids

SF

SF HLF

SF HLF

Walnut shell char blend (WSC)

Blend Ratio: 25% walnut shell char, 25% yard waste fines, 50% biosolids

Grown in 100% walnut shell char blend (WSC)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
20.21	1.50	216.5	6.29	45.9	2.56

Grown in 50% walnut shell char, 50% sand (WSC HLF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
20.63	1.30	196	5.48	44.8	1.89

Biochar blend properties:

EC_5	13.6 dS/m	NH_4^+	472 ppm
pH	10.09	P	822 ppm
OM	44%	K	564 ppm
C:N	15.5:1	Ca	1235 ppm
Total N	2.31%	S	460 ppm
Respiration	2.6 mg CO2-C/g OM/day	Mg	678 ppm
Bulk density	0.21 g/cm^3	Na	116 ppm

Detail photo WSC 4:

Notes: Chlorosis of new leaves and purple lesions on WSC. Foliage pale green, chlorosis of new leaves on WSC HLF.

Walnut shell char blend (WSC)

Blend Ratio: 25% walnut shell char, 25% yard waste fines, 50% biosolids

WSC

WSC HLF

WSC HLF

Almond fines blend (AF)

Blend Ratio: 40% almond fines, 40% SF biosolids, 20% sand

Grown in 100% almond fines blend (AF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
2.17	1.04	15	8.66	21.0	12.26

Grown in 50% almond fines blend, 50% sand (AF HLF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
7.73	3.99	88	51.26	27.4	15.98

Almond fines blend properties:

EC_5	1.6 dS/m	NH_4^+	1966 ppm
pH	6.49	P	862 ppm
OM	27%	K	3430 ppm
C:N	9.1:1	Ca	1073 ppm
Total N	1.75%	S	649 ppm
Respiration	8.6 mg CO2-C/g OM/day	Mg	1005 ppm
Bulk density	0.52 g/cm^3	Na	ND

Detail photo of AF 2

Notes: Severe stunting and death in both AF and AF HLF. After several weeks of stunted growth, normal growth started in 2 plants in AF and 2 plants in AF HLF. No signs of chlorosis were visible in these plants.

Almond fines blend (AF)

Blend Ratio: 40% almond fines, 40% SF biosolids, 20% sand

Additional pictures:

AF

AF HLF

AF HLF

Cedar Grove compost (CG)

Blend Ratio: 100% Cedar Grove compost

Grown in 100% Cedar Grove compost (CG)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
11.68	0.45	135.8	8.72	29.45	2.11

Grown in 50% Cedar Grove compost, 50% sand (CG HLF)

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
5.48	0.41	75	5.57	28.1	1.71

Compost properties:

EC_5	2.2 dS/m	NH_4^+	27 ppm
pH	7.15	P	315 ppm
OM	55%	K	4131 ppm
C:N	16.3:1	Ca	5533 ppm
Total N	1.67%	S	69 ppm
Respiration	1.4 mg CO2-C/g OM/day	Mg	1135 ppm
Bulk density	0.25 g/cm^3	Na	2475 ppm

Detail photo: CG3

Notes: CG had chlorosis of lower leaves and pale green foliage. CG HLF had chlorosis of bracts and foliage was pale green. Note the low SPADS numbers for both treatments. The majority of available N in the blend was in nitrate form, with 357 ppm NO_3^-.

Cedar Grove compost (CG)

Blend Ratio: 100% Cedar Grove compost

Additional pictures:

CG

CG HLF

CG HLF

Peat growing medium (P)

Blend Ratio: 100% Sunshine #4 Peat growing medium

Grown in 100% peat growing medium

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
6.41	0.51	72.5	10.69	30.2	2.11

Peat growing medium properties:

EC_5	1.2 dS/m	NH_4^+	57 ppm
pH	5.07	P	137 ppm
OM	65%	K	1393 ppm
C:N	40.8:1	Ca	5825ppm
Total N	0.77%	S	1619 ppm
Respiration	2.01 mg CO2-C/g OM/day	Mg	3128 ppm
Bulk density	0.10 g/cm^3	Na	161 ppm

Detail photo: P3

Notes: Pale green foliage and chlorosis of bracts.

Additional photo:

Sand (S)

Blend Ratio: 100% Sand

Grown in 100% Sand

Dry Biomass (g)	SE	Flower Count	SE	SPADS	SE
2.39	0.25	34.8	4.46	25.9	1.89

Sand properties:

EC_5	0.03 dS/m
pH	7.42
OM	1%
C/N	
Total N	
Respiration	
Bulk density	1.38 g/cm^3

Detail photo S2:

Notes: Entire plant pale green, note low SPADS value. Chlorosis of lower leaves and bracts.

Additional photo: