## **Comprehensive Simulation Parameters for Project Chimera v**1.2

This document outlines potential parameters for the simulation mechanics of Project Chimera, drawing upon extensive research into Cannabis sativa L. biology, cultivation, genetics, and industry practices, significantly enhanced with details from cultivator discussions as recorded in "transcriptss.pdf" (hereafter cited as "Transcript P.[PageNumber]").

### **1. Cannabis Biology and Characteristics Parameters (Part 1: Botanical & Chemical)**

This section details fundamental biological parameters of the Cannabis sativa L. plant, its morphology, chemistry, and inherent characteristics related to its interaction with the environment and biological threats.

#### **1.1 Botanical Features Parameters**

Parameters defining the physical structure, classification, and life cycle stages of the cannabis plant.

* **Taxonomy and Classification:**
  + Species: *Cannabis sativa L.* [1]
  + Subspecies/Varieties: *sativa*, *indica*, *ruderalis*.
    - Note: Traditional classifications may not correlate perfectly with genetic structure [2, 3]. Cultivator experience suggests that even within these, traits like stretch and nutrient preference can vary significantly (Transcript P.114, P.196). For example, some OG cuts have minimal lateral branching (Transcript P.182-183).
  + Hemp vs. Drug-type distinction: Based on THC content (e.g., <0.3% Δ⁹-THC for hemp) [1]. This is a critical botanical and regulatory parameter [1] (Transcript P.2, P.276-277).
    - Range: % Δ⁹-THC can range from negligible (<0.1%) in some hemp varieties to over 30% in high-potency drug-type cultivars [4-6]. Some cultivars test around 15-19% THC, while others can reach 28-35% THC (Transcript P.187, P.197). THCA flower is also a market factor under hemp regulations (Transcript P.276-279).
  + Chemovars: Classification based on cannabinoid profile [7, 8] (e.g., Type I: THC-dominant, Type II: THC/CBD mixed, Type III: CBD-dominant, Type IV: CBG-dominant, Type V: negligible cannabinoids) [2].
    - Game should support differentiation based on chemical profile rather than just traditional labels [2]. Consumer markets show preferences for different profiles; e.g., some European markets value specific terpene expressions over pure THC content (Transcript P.192).
* **Morphology:** Parameters defining the physical structure and form of the plant.
  + Plant Height: Potential range (e.g., 0.2m to >12m cultivated) [1]. Influenced by genetics and environment [1].
    - Hemp types tend to be taller and less branched, drug-types bushier [1, 9].
    - Range: Dwarf varieties can be 0.2m [1]. Fiber hemp can exceed 12m [1].
    - Drug types typically range from 0.5m to over 3m. Some strains can stretch significantly, e.g., a 12-inch plant stretching to 5 feet (Transcript P.114). Sherb Banger 22 known for a 4-week stretch period (Transcript P.114-115).
  + Stem Structure: Erect, furrows, branching patterns, woody interior, hollow internodes [1].
    - Stem diameter can range from 1-3cm in mature plants, influenced by genetics and vigor [13].
    - Base can become very big and thick [14].
    - Branching Pattern: Influenced by genetics and environment (e.g., apical dominant, lateral spread, balanced) [15]. Sativa-like strains tend to have more lateral branching. Some OG cuts show minimal lateral branching without topping (Transcript P.182-183). HLVd infection can cause abnormal, horizontal branching (Transcript P.80).
    - Sativas tend to have more lanky branches, Indicas more compact [16-18].
  + Leaf Morphology: Compound leaves with leaflets radiating from the petiole end [1].
    - Leaflet Number: Number of leaflets (e.g., 3-13) [1].
    - Developmental sequence: 1 (seedlings/stressed), 3, 5, 7, 9, then potentially more (up to 13+) on robust mature plants, decreasing later [19].
    - Leaflet Shape: Lanceolate, ovoid, oblanceolate [1]. Influenced by genetics (e.g., broad in Indica types, narrow in Sativa types) [19].
    - Serrated margins [1].
    - Leaf Size: Broad (Indica) vs. long/slender (Sativa) [19].
    - Changes throughout lifecycle, peaking around the 12th node [19].
    - Leaf Angle/Droop: Angle relative to stem, turgidity.
      * Heavily influenced by hydration (underwatered-drooping) [13, 20]. Genetics may influence baseline angle [13]. Hybrids show a spectrum [13]. HLVd may cause leaves to curl or appear malformed (Transcript P.80).
    - Diagnostic Leaf Venation [1].
  + Leaf Arrangement: Opposite (lower nodes) to alternate (main stem) [1, 19].
    - Phyllotaxy shift typically occurs around the 12th node [19].
  + Bud/Flower Structure: Shape (e.g., conical, spear, round, "golf balls" (Transcript P.181), foxtail), density (airy, medium, compact, "rock-hard" under LEDs (Transcript P.202)), leaf-to-calyx ratio [15].
    - Indica types tend to have dense, compact buds, Sativa types longer, airy buds [11, 16].
    - Foxtailing can occur, sometimes accelerating towards harvest [21]. Some strains exhibit foxtailing as a genetic trait, not necessarily negative (Transcript P.120).
    - HLVd can cause "dudding" or significantly reduced bud development and trichome production (Transcript P.80, P.171).
  + Pistil Color (Mature): Colors such as orange-red, pink-purple, brown [15].
  + Trichome Density: Potential levels (low, medium, high) [15].
    - A key visual quality indicator (frostiness, resin) [15, 22, 23]. Influenced by genetics and environment [15, 24, 25]. Some strains are known for high resin production suitable for hash (Transcript P.9, P.21).
    - Can vary dramatically between strains [24]. Use of products like Athena Stack can visually increase trichome production (Transcript P.160).
  + Trichome Appearance: Transition in color (clear to milky to brown/amber) indicates maturity [15, 22, 26].
    - Visual cues for resin and ripeness [15, 22, 26]. Trichomes contain cannabinoids [24]. For hash production, plants might be harvested earlier when trichomes are optimal for separation (e.g., day 40 for a 70-day flower strain) (Transcript P.197).
  + Trichome Degradation: Can be induced by experiments [27]. Poor storage can lead to reduced trichome vibrancy [28, 29]. Improper drying/curing can lead to terpene loss (Transcript P.179).
  + Root System: Adaptable taproot with lateral branching [1].
    - Can reach up to 2.5m deep in soil depending on soil/water [1, 30].
    - Root health and development influenced by growing media [30, 31]. HLVd can be present in roots (Transcript P.83). Fusarium also infects through roots (Transcript P.84).
    - Plants from seed have a strong, deep taproot; cloned plants typically have weaker, more lateral, not as deep roots [32].
    - Rootbound plants stress plant if left untreated [33].
    - Root restriction (small containers) stunts growth, limits nutrient/water uptake, alters structure [30, 34, 35]. Smaller pots (e.g., 1-2 gallons) preferred by some for more control with frequent irrigations (Transcript P.127).
  + Visual Representation: Potential for root system visualization showing medium, water, nutrient response [36].
  + Fruit (Achene)/Seed: <3.8mm length, often in persistent perianth (mottled/marbled) [1]. Seed production can yield 5,000 to over 20,000 seeds per light depending on cultivation methods and nutrient lines (Transcript P.309). Shipping seeds is generally legal, but banking for seed sales can be problematic (Transcript P.2). Cuttings/clones shipping legality is evolving, based on <0.3% THC in the cutting itself (Transcript P.1-2, P.276-277).
* **Sex Determination:**
  + Predominantly dioecious (separate male (XY)/female (XX) plants) [1, 37]. Females are valued for cannabinoids in inflorescences [37].
  + Monoecious/Hermaphroditic forms: Can occur naturally (stress-induced, e.g., light leaks, temperature swings (Transcript P.158, P.171)) or be chemically induced (e.g., silver thiosulfate, STS (Transcript P.169)) for breeding [37].
    - Hermaphroditism involves producing both male and female flowers on the same plant, leading to "seeded" crops [38, 39]. Some strains have a higher genetic predisposition to herm under stress (e.g., Dante's Inferno #6) (Transcript P.152). Sterility of pollen from hermaphroditic plants can vary (Transcript P.152).
* **Growth Stages:**
  + Germination: First physiological stage [40].
    - Requires proper medium temperature (8-10°C average daily minimum for outdoor sowing, or specific ranges for in vitro/controlled) [41, 42].
    - Light not required [42]. Influenced by genetics, physical factors (medium composition, env conditions) [40].
    - Optimal conditions and quality seeds yield 80-100% germination [43]. Poor germination rates can be associated with bad genetics [44] or old seeds (Transcript P.168).
    - Range/Likely Level: Germination rate can be affected by genotype, medium composition, and environmental conditions [40, 43]. Reputable breeders aim for near 100% [43].
  + Seedling: Early growth [45, 46].
    - Typically single leaflet leaves initially, progressing to 3, then 5 [19]. Sensitive stage [47].
  + Vegetative: Rapid growth stage, building root system and stems, then foliage [46, 48].
    - Needs high nitrogen [46, 49]. Fairly tough during this stage [50]. Environmental conditions like temp/humidity deviations impact growth speed [51]. Optimal VPD is crucial (Transcript P.235). Low light (e.g. 200s PPFD) can be sufficient if DLI is met (Transcript P.161). Veg duration varies (e.g., 10-18 days for some commercial setups (Transcript P.176, P.217), up to 5-6 weeks for others (Transcript P.200)).
    - Problems often begin to show here [52]. Duration modeled as 50 days in one facility example [53].
  + Flowering: Stage where inflorescences develop [45, 46].
    - Requires lower humidity (especially late flower, e.g. 40-50% RH, though some run higher at 60-65% with LEDs (Transcript P.161)) and specific light spectrum/intensity [47]. Needs higher phosphorus/potassium [45, 49]. Light cycle typically 12/12, but some manipulate to 11/13 to finish plants or influence expression (Transcript P.115).
    - Longest stage in one model (57 days) [53]. Can range from 7 weeks (e.g., Rainbow Belts, Zkittlez crosses (Transcript P.115)) to 10+ weeks (e.g., Haze varieties, some OGs (Transcript P.115, P.169, P.308)) depending on genetics. Stretch period (first 1-4 weeks of flower) can last 3-4 weeks for some strains (e.g., Sherb Banger 22 (Transcript P.114-115)).
  + Maturation: Buds thicken, trichomes mature [21, 27].
    - Harvest timing determined by trichome appearance (clear to milky to amber) and yield/chemistry correlation [54]. Cannabinoid and terpene profiles change during maturation (Transcript P.8, P.172). Some harvest earlier for specific products like hash (Transcript P.197).
  + Harvest: Physical removal of plants/flowers [55]. Timing crucial for potency/quality [54, 56].
* **Phenotypic Plasticity:** The ability of a plant with a specific genotype to exhibit different phenotypes in different environments [38, 57-60].
  + This is a fundamental concept for GxE modeling [38, 57-60]. Environment (light, temp, nutrients, stress) heavily influences expression of genetic potential (Transcript P.187, P.200-207).
  + Clones with identical genotype can show different phenotypes with varied conditions [3, 58].

#### **1.2 Chemical Profile Parameters**

Parameters defining the chemical composition of the cannabis plant, particularly secondary metabolites produced primarily in glandular trichomes [4, 24, 61].

* **Cannabinoids:** (>140 identified) [62].
  + Major Cannabinoids:
    - Δ⁹-tetrahydrocannabinol (THC): Psychoactive compound [63].
      * Potency often measured as % DW [64]. Levels up to 25-30% of floral dry weight achieved [4]. Some cultivars testing at 28-35% THC reported (Transcript P.187). Others may test lower (e.g. 12-19%) but still be desirable (Transcript P.170, P.197). Moisture content at testing significantly impacts reported THC % (Transcript P.12, P.22).
      * Can reach 30% in some plants [5].
      * Likely Levels: High THC strains can exceed 20%, some even reaching 30% [4-6]. Cultivator discussions mention THC levels from 12% to 35%+ (Transcript P.13, P.170, P.187, P.197).
      * Traditional hemp is <0.3% [1]. THCA flower market exists under hemp definition (Transcript P.276-279).
    - Cannabidiol (CBD): Non-psychoactive, therapeutic potential [63, 65].
      * Potency often measured as % DW [64].
      * Likely Levels: High CBD strains can exceed 15-20%. Many hybrids have mixed ratios.
    - Cannabigerol (CBG): Precursor to other cannabinoids [63]. Increasing interest in breeding [66].
    - Cannabinol (CBN): Sedative effects [63]. Accumulates with degradation/aging [63].
  + Minor Cannabinoids: Growing interest (distinct therapeutic benefits) [66].
    - Δ⁹-tetrahydrocannabivarin (THCV): Investigating production genetics crucial [66].
    - Cannabidivarin (CBDV): Investigating production genetics crucial [66].
    - Cannabichromene (CBC): Investigating production genetics crucial [66].
    - Cannabichromenevarin (CBCV) [63].
    - Cannabigerovarin (CBGV) [63].
    - Delta-8 THC [63], Delta-10 THC [63], HHC [63]: Novel cannabinoids often in legal grey areas, facing evolving scrutiny [67]. Delta-8 can be synthesized from CBD (Transcript P.279-281).
    - THCP, THCB [63].
  + Cannabinoid Acids: Biosynthetic precursors, convert to neutral form via decarboxylation (heat, aging) [63, 68, 69].
    - THCA (tetrahydrocannabinolic acid) [63]. THCA flower being sold under hemp regulations is a major market factor (Transcript P.276-279).
    - CBDA (cannabidiolic acid) [63].
    - CBGA (cannabigerolic acid) [63].
  + Total Cannabinoids (e.g., Total THC: THCA \* 0.877 + THC, Total CBD: CBDA \* 0.877 + CBD) [63].
    - Critical quality parameters [68]. Content variability in plant material is an issue for consistency [68].
    - Can reach 25-30% of floral dry weight [4]. Potency is a key driver in many markets, though this is being questioned by connoisseurs (Transcript P.170, P.197, P.239). Moisture content at testing significantly impacts reported THC % (Transcript P.12, P.22). Using products like "Fade" can increase THC by 2-6% absolute (Transcript P.13).
* **Terpenes:** (>120 identified) [62].
  + Aromatic compounds contributing to aroma, flavor, and potential effects (entourage effect) [63, 65, 70]. Produced in glandular trichomes [61]. Critical for consumer preference, especially in connoisseur markets (Transcript P.8, P.152, P.179, P.192).
  + Concentration influenced by genetics, environment, post-harvest handling [71]. Late-stage nutrient protocols (like "Fade") can enhance terpene expression (Transcript P.8-9). Drying and curing are critical for terpene preservation (Transcript P.179, P.298-299).
  + Dominant Terpenes: Myrcene, Limonene, Caryophyllene, Pinene, Ocimene, Terpinolene [63].
  + Other Terpenes: Humulene, Linalool, Bisabolol, Nerolidol, Geraniol, Borneol, Fenchol, Cineole, Camphor, Phellandrene, Terpineol, Carene, Farnesene, Phytol, Carvacrol, Aromadendrene, Eudesmol [63].
  + Terpene Profiles: Concentrations and ratios of individual terpenes [64, 65, 71]. Contributes to market demand [71]. Breeding for unique terpene profiles is a major goal for some (Transcript P.152, P.172).
  + System for classification (e.g., Cream/Cake/Cookies/Candy, Fruity, Herbal, Pine, Skunk, Spicy, Sweet, Tropical, Woody/Earth) [72]. The "candy" profile (e.g., from Dante's Inferno #6) is currently popular (Transcript P.152, P.172). "Gas" is another popular profile (Transcript P.187).
  + Total Terpenes [63]. High terpene content is desirable but can be diluted by excessive yield focus ("yield dilution") (Transcript P.62).
  + Volatilization: Terpenes can volatilize, especially during drying/curing at warmer temperatures [73].
    - Proper drying/curing crucial for retention [25, 54, 73]. Target 7-10 days dry time, 60F/60%RH environment (Transcript P.298-299).
* **Flavonoids:** Contribute to pigmentation and aroma/flavor [8, 63].
  + Cannflavins [63]. Anthocyanins responsible for purple colors, influenced by genetics and cold temperatures (Transcript P.14-15).
* **Volatile Sulfur Compounds (VSCs):** Contribute to pungent/characteristic notes like "gas" or "skunk" [63]. Unstable over time [63].
* **Esters:** Contribute sweet/fruity notes [63].
* **Other Constituents:** Hydrocarbons, phenolics, sugars [63].
* **Entourage Effect:** Synergistic interaction between cannabinoids, terpenes, and other compounds influencing effects and therapeutic potential [8, 63].

#### **1.3 Physiological Processes Parameters (Continuation)**

Parameters governing the internal functions and responses of the cannabis plant, building on the initial photosynthesis, transpiration, nutrient uptake, and biosynthesis parameters.

* **Water Relations:** Beyond basic transpiration.
  + Water Uptake Rate: Influenced by root system size/health, substrate moisture content, substrate type (e.g., coir's high water retention vs. rockwool's quick dry down) [1-3]. VPD heavily influences uptake (Transcript P.125, P.235).
  + Aquaporin activity (e.g., PIP aquaporins) may play a role at a molecular level [2].
  + Leaf Water Potential: Measure of plant water stress. Influenced by substrate moisture, humidity, airflow, transpiration rate.
  + Stomatal Response: Opening and closing of stomata to regulate gas exchange and water loss.
    - Influenced by light intensity, CO2 levels, humidity, wind. Can be reduced in later maturation stages [4]. Far-red light at end of day can influence stomatal closure and plant sleep cycles (Transcript P.203).
* **Carbon Metabolism:**
  + Carbon Fixation Rate: Directly related to photosynthetic rate.
  + Photoassimilate Production: Synthesis of sugars.
  + Photoassimilate Partitioning: Allocation of sugars to different plant parts (roots, shoots, leaves, flowers).
    - Influenced by growth stage, nutrient availability (e.g., Nitrogen for vegetative growth vs. Phosphorus for flowering/bud development) [5]. Late flower N restriction (e.g., using "Fade") encourages resource allocation to flowers (Transcript P.7-9, P.15).
* **Hormonal Regulation:** Internal plant hormones (phytohormones) play crucial roles in growth, development, and responses to environment and stress.
  + Auxins: Involved in root development, apical dominance, vegetative growth. Auxin activity typically decreases during flowering transition [6].
  + Cytokinins: Promote cell division, shoot development. Certain cytokinins increase during flowering transition [6].
    - Meta-topolin (mT), a natural cytokinin, is effective for shoot proliferation in tissue culture [7].
  + Gibberellins: Involved in stem elongation (e.g., "stretch" at flowering onset) [6].
  + Abscisic Acid (ABA): Stress hormone, involved in stomatal closure and dormancy. Increases under drought stress. Drought stress (generative steering) is a key crop steering technique (Transcript P.122-123).
  + Ethylene: Involved in senescence, ripening, stress responses.
  + Brassinosteroids: Promote growth and stress tolerance.
  + Phytohormone Balance: The relative levels and interactions of these hormones regulate developmental transitions (e.g., vegetative to flowering, re-vegetation) [6, 8].
    - Mother plants in long-term vegetative state may experience subtle changes in hormonal balance [4].
* **Nutrient Mobility and Translocation:** Movement of absorbed nutrients within the plant (e.g., from older leaves to new growth/flowers).
  + Efficiency may diminish with physiological age [4]. Nitrogen is highly mobile and translocated from fan leaves during late flower if root zone N is restricted (e.g. when using "Fade") (Transcript P.8, P.15). Calcium is immobile; deficiencies (e.g., from flushing with straight RO water or pulling Core too early) can lead to issues like bud rot (Transcript P.7-8, P.12).
* **Resource Remobilization:** Breakdown of macromolecules (proteins, lipids, nucleic acids) in senescing tissues and transport of resulting nutrients to other parts of the plant [9].
  + Occurs in older leaves even in vegetative mothers [4]. Crucial for reproductive success in nature [9]. This is a key mechanism during "Fade" or flushing (Transcript P.8, P.15).
* **Developmental Plasticity:** Ability to alter growth patterns in response to environmental cues (e.g., branching patterns influenced by light distribution, nutrient availability) [10].
* **Circadian Rhythms:** Internal biological clock regulating daily physiological processes (e.g., photosynthesis, transpiration, flowering time). Interacts with photoperiod. Use of far-red light to signal end-of-day can influence these rhythms (Transcript P.203).

#### **1.4 Stress Responses Parameters**

Parameters defining how the cannabis plant reacts to and is affected by various abiotic and biotic stressors, and its ability to tolerate them. Stress can impact yield, quality, and even chemotype. Strategic stress (e.g., controlled drought, specific nutrient withdrawal like "Fade") can enhance desired traits like terpene and cannabinoid production (Transcript P.8, P.122-124).

* **Abiotic Stress Responses:** Responses to non-living environmental factors.
  + **Drought Stress:** (Intentional for generative steering)
    - Physiological Effects: Reduced stomatal conductance, decreased photosynthesis, wilting, reduced transpiration.
    - Can induce changes in leaf water potential [11]. Induces hormonal responses for survival and reproduction (Transcript P.122).
    - Growth/Yield Effects: Stunted growth, reduced biomass, lower flower yield.
    - Controlled drought stress in flowering stage can increase inflorescence dry weight and cannabinoid content [12]. Key part of "generative steering" by manipulating drybacks (Transcript P.11, P.122-123).
    - Chemotype Effects: May increase cannabinoid/terpene concentration (due to reduced biomass/water content or stress-induced synthesis) or decrease total production (due to reduced metabolic activity) [11, 13]. (Transcript P.8, P.124).
    - Stress-induced synthesis vs. dilution [13].
  + **Heat Stress:**
    - Physiological Effects: Denaturation of enzymes, impaired photosynthesis, increased respiration, heat shock protein production.
    - Can cause managing temperature to be critical for quality [14]. Excessive heat can stress plants, leading to reduced quality or hermaphroditism (Transcript P.158, P.171).
    - Growth/Yield Effects: Stunted growth, reduced flower development, wilting, leaf damage.
    - Chemotype Effects: Can degrade cannabinoids (e.g., THC) and volatilize terpenes, reducing overall potency and aroma profile [14].
  + **Cold Stress:**
    - Physiological Effects: Reduced enzymatic activity, membrane damage, impaired nutrient uptake.
    - Growth/Yield Effects: Stunted growth, leaf damage, reduced yield.
    - Chemotype Effects: Can impact cannabinoid/terpene synthesis.
    - Some varieties may show color changes (e.g., purple hues) in response to cold [15]. This is a common technique to enhance "bag appeal" (Transcript P.14-15). Colder water at end of flower can also induce color (Transcript P.14).
  + **Light Stress (Too High/Low Intensity):**
    - Physiological Effects: Photoinhibition (damage to photosynthetic apparatus) from excessive light [16].
    - Reduced photosynthesis from insufficient light. Plants growing into lights will burn (Transcript P.114).
    - Growth/Yield Effects: Leaf burn, stunted growth, reduced yield from excessive light.
    - Leggy growth, low yield from insufficient light.
    - Chemotype Effects: Optimal light intensity and spectrum are crucial for cannabinoid and terpene production [17-19]. Some genetics are more sensitive to high PPFD than others (e.g., old Indicas) (Transcript P.116).
    - UV light can stimulate cannabinoid production (protective mechanism) [20, 21], but excessive UV can be damaging.
    - Different light spectra affect morphological, physiological, and chemical parameters [17, 22]. Far-red can influence flowering time and stretch (Transcript P.203). Mixed HPS/LED can give unique expressions (Transcript P.202-207).
  + **Nutrient Deficiency/Toxicity:**
    - Physiological Effects: Impaired metabolic processes, reduced photosynthesis, visible symptoms (e.g., leaf yellowing from N deficiency, brown spots from P deficiency/toxicity, leaf burn from nutrient excess/toxicity) [23, 24]. Calcium deficiency in late flower can lead to bud rot (Transcript P.7-8).
    - Can trigger/accelerate senescence [25]. Removing core nutrients (e.g., Athena ProLine Core) too early or using straight RO water can cause deficiencies (Transcript P.8, P.12).
    - Growth/Yield Effects: Stunted growth, reduced biomass, lower yield [5, 23, 24].
    - Nutrient imbalance can restrict development [26]. Overwatering can lead to nutrient lockout or root issues mistaken for deficiencies (Transcript P.11).
    - Chemotype Effects: Nutrient availability significantly impacts cannabinoid and terpene biosynthesis and concentration [18, 27, 28].
    - High Nitrogen can decrease cannabinoid/terpene concentration while increasing biomass (dilution effect) [5, 29]. This is a reason for products like "Fade" (Transcript P.7-9).
    - Phosphorus is conventionally supplied at high amounts for optimal function and yield, but deficiency at vegetative stage impacts functional phenotyping and ionome [30].
  + **Waterlogged Soil/Root Zone Hypoxia:**
    - Physiological Effects: Root damage, impaired nutrient/water uptake, reduced oxygen availability to roots. Increased risk with overwatering, especially in dense media like coco if not managed (Transcript P.11, P.126).
    - Growth/Yield Effects: Wilting, stunted growth, root rot susceptibility [31], reduced yield.
    - Chemotype Effects: Reduced plant health negatively impacts secondary metabolite production.
  + **Salinity Stress:** Accumulation of soluble salts in the root zone, particularly in hydroponics/soilless media [26]. High EC in media due to insufficient runoff or excessive drybacks (Transcript P.123, P.158).
    - Physiological Effects: Impaired water uptake, ion toxicity.
    - Growth/Yield Effects: Stunted growth, reduced yield. Lockout of other nutrients.
    - Chemotype Effects: Can impact metabolite profiles. Extreme EC can burn plants.
* **Biotic Stress Responses:** Responses to living organisms.
  + **Pest Infestation:** (See also 1.6 Pest/Disease Resistance Parameters)
    - Damage Types: Feeding damage (leaf loss, tissue damage), disease transmission, growth hindrance [32, 33]. Thrips, mites mentioned as common problems (Transcript P.80, P.179).
    - Physiological Effects: Allocation of resources to defense mechanisms (e.g., production of defensive compounds).
    - Growth/Yield Effects: Reduced vigor, stunted growth, significant yield loss [32, 33].
    - Trichome damage/loss can directly reduce cannabinoid/terpene yield [34].
  + **Pathogen Infection:** (See also 1.6 Pest/Disease Resistance Parameters)
    - Damage Types: Tissue damage, impaired physiological function (e.g., nutrient/water transport, photosynthesis), systemic infection [32, 35]. Bud rot (Botrytis) is a major concern, linked to calcium deficiency and high humidity (Transcript P.7-8, P.15). Fusarium is a root pathogen, no cure, spreads via water (Transcript P.84). HLVd causes stunting, dudding, reduced quality (Transcript P.3, P.16, P.80, P.171).
    - Physiological Effects: Activation of plant immune response, production of defense compounds.
    - Older mothers may have potentially weakened immune response or chronic stress leading to higher susceptibility [34].
    - Growth/Yield Effects: Reduced vigor, stunted growth, wilting, necrosis, significant yield loss [32, 35]. HLVd can devastate crops (Transcript P.3, P.16-17).
    - Can be mistaken for age-related decline [34]. Systemic pathogens like HLVd cause stunting and reduced trichome production/yields [34].
  + **Competition (Light, Nutrients, Water, Space):** Competition from other cannabis plants or companion plants [36].
    - Physiological Effects: Altered growth patterns (e.g., reaching for light), reduced resource uptake efficiency.
    - Growth/Yield Effects: Reduced individual plant yield. Plant spacing is important for maximizing yield per area [37, 38]. Density of 1.6 plants/sq ft mentioned (Transcript P.183).
  + **Stress-Induced Senescence:** Premature aging and death of plant tissues or the whole plant due to severe or prolonged stress [9]. Can be desirable at end of flower (e.g., with "Fade") but problematic if premature (Transcript P.8).

#### **1.5 Strain-Specific Optimal Conditions and Characteristics Parameters**

Parameters defining the variations in optimal growth conditions, growth habits, and other characteristics between different cannabis genotypes (strains/cultivars). Cultivars show wide variation in response to environment and inputs (Transcript P.114, P.163, P.187, P.200).

* **Optimal Environmental Ranges:** Genotype-dependent ideal ranges for:
  + Temperature: Specific optimal temperature ranges for vegetative and flowering stages [39]. Some strains are more sensitive to temperature swings (Transcript P.15, P.158). Some growers run 73-76F even in late flower with "Fade" (Transcript P.15).
  + Humidity: Specific optimal humidity ranges for vegetative and flowering stages [39]. Some strains are more prone to mold in high humidity (Transcript P.15). Some run 60-65% RH with LEDs in flower (Transcript P.161).
  + Light Intensity (PPFD): Different strains may utilize light more or less efficiently and have different saturation points. Some strains are sensitive to high PPFD (e.g. old indicas) (Transcript P.116).
  + Light Spectrum: Different strains may respond differently to specific light wavelengths [17, 22, 39]. Some strains show better color or terpene expression under specific spectra (e.g. mixed HPS/LED, or specific LED spectra like ThinkGrow vs. Luxx) (Transcript P.202-207, P.113, P.160). Far-red for end-of-day signal (Transcript P.203).
  + CO2 Concentration: Optimal CO2 levels for different strains, especially in CEA [39-41]. Typically 1500ppm in flower (Transcript P.161).
  + Airflow/Ventilation: Specific needs for different growth structures and densities to prevent mold/pests [42]. Dense bud structures require more airflow (Transcript P.15).
  + Substrate Moisture Content: Optimal levels and tolerance for drying out or waterlogging vary [1-3]. Some strains prefer larger drybacks than others (Transcript P.11, P.124). Rockwool vs. Coco drydown characteristics (Transcript P.113, P.180).
  + Nutrient Solution pH: Optimal pH range for nutrient uptake can vary slightly by strain and substrate [16, 43, 44]. Some growers maintain a consistent pH (e.g. 6.0-6.2) for all strains in coco (Transcript P.158). Monosilicic acid can affect pH in rockwool (Transcript P.11).
  + Nutrient Concentrations (EC/PPM): Optimal nutrient strength varies by strain and growth stage [27, 43, 45]. Some strains are heavy feeders, others sensitive (e.g., OGs might prefer lower EC than Runtz; Runtz sensitive to high EC, Pie Hoe can take very high EC) (Transcript P.196). Some run 3.0 EC all the way through with Athena ProLine (Transcript P.12, P.15).
  + Specific Nutrient Ratios (NPK, Ca:Mg, etc.): Optimal ratios can be strain-specific and outcome-specific (e.g., maximizing yield vs. maximizing cannabinoid concentration) [13, 27, 45].
* **Growth Habits and Morphology:** Genotype-dependent traits:
  + Plant Height and Structure: Tall/thin (sativa-like) vs. short/bushy (indica-like) [10, 47, 48]. Some strains have significant stretch (e.g. Sherb Banger 22, 4-week stretch from 12" to 5ft (Transcript P.114-115)) while others are short (e.g. Rainbow Belts, Zkittlez finishing in 7 weeks (Transcript P.115)).
  + Branching patterns (apical dominant vs. lateral spread, OG minimal lateral without topping) [10] (Transcript P.182-183). Untopped plants develop a main cola with lateral branches reaching near the top (Transcript P.183).
  + Internodal spacing [49].
  + Leaf Morphology: Leaflet number and width (narrow-leaf vs. broad-leaf) [49, 50].
  + Flower Structure: Shape, density, leaf-to-calyx ratio [10, 51]. Some genetics known for specific structures (e.g. "golf balls" (Transcript P.181)). Some LED-grown flower can be rock-hard (Transcript P.202).
  + Root System Development: Efficiency and structure of the root system can be strain-specific [3]. Cloned plants have weaker, more lateral roots than seed plants (Transcript P.32).
* **Life Cycle and Flowering Time:** Genotype-dependent duration of growth stages:
  + Seedling Stage Duration [10, 54].
  + Vegetative Stage Duration: Ability to remain vegetative under specific photoperiods [10, 55, 56]. Commercial grows may have veg times from 10-18 days (Transcript P.176, P.217) to several weeks (Transcript P.200).
  + Flowering Time/Duration: Crucial parameter for breeding and cultivation planning [10, 39, 57, 58]. Ranges from 7 weeks (e.g. some Zkittlez crosses (Transcript P.115)) to 10+ weeks (e.g. Haze varieties, some OGs (Transcript P.115, P.169, P.308)).
  + Sativa varieties typically have longer flowering times (10-16 weeks) than indica (6-10 weeks) [10, 57]. Photoperiod-dependent flowering vs. autoflowering [59-61]. Use of far-red light can shorten flowering time by a week or more (Transcript P.204).
  + Semi-full-term/fast-flowering strains [62, 63].
  + Maturation Indicators: Visual cues (pistil color, trichome appearance) indicating peak ripeness can vary slightly by strain [10, 64-66].
  + Trichome gland head phenotypes change over the flowering period [67]. Optimal harvest timing varies by strain [68]. For hash production, plants might be harvested earlier (e.g. day 40 for a 70-day flower strain) (Transcript P.197).
  + Re-vegetation Potential: Ability to revert to vegetative growth after flowering can be strain-dependent [6, 69].
  + Older plants may struggle more [69].
* **Yield Potential:** Genotype-dependent inherent capacity for biomass and flower production under optimal conditions.
  + Measured in grams per plant or grams per square foot [65]. Can be influenced by substrate choice [1, 3]. Yields of 2.5-4 lbs per light reported by cultivators (Transcript P.116, P.204). Some strains are known low yielders (e.g. cookies, lcg) but high value (Transcript P.116, P.241). Under canopy lighting can increase yield by 20-50% (Transcript P.225). Hash yields also vary (e.g., 3% vs 4-5.5% with Fade) (Transcript P.9).
* **Chemical Profile (Chemovar):** Genotype-dependent production of specific cannabinoids, terpenes, and other compounds, defining the chemovar [70-73]. Huge driver of market value (Transcript P.152, P.170).
  + Major Cannabinoid Ratios (THC:CBD, THC:CBG, CBD:CBG, etc.) [28, 74].
  + Controlled by alleles at cannabinoid synthase loci [74, 75]. Breeding can target specific ratios [76, 77].
  + Minor Cannabinoid Production (THCV, CBDV, CBG, CBC, CBN, etc.) [72, 78, 79]. Genetics control production [76, 77].
  + Terpene Profile: Specific terpenes produced and their relative concentrations [72, 73, 78, 80, 81]. Unique terpene profiles are highly sought after (e.g. Dante's Inferno #6 cherry candy (Transcript P.152, P.172)).
  + Genetics are foundational, but expression influenced by environment and post-harvest [82]. Terpene synthase (TPS) genes are involved [45, 79].
  + Unique flavor/aroma profiles are strain-defining [58, 80, 83]. "Gas" and "candy" profiles are popular (Transcript P.172, P.187).
  + Flavonoid Production (Cannflavins, Anthocyanins for color) [78, 84] (Transcript P.14-15).
  + Total Cannabinoid Potency (% DW) [71, 74, 78]. THC levels are often a primary market driver, but this is shifting (Transcript P.170, P.197, P.239).
  + Total Terpene Content [78].
  + Stability of Chemical Profile: Consistency across different grows/environments (less plastic chemotypes) [85, 86].
  + Desirable for medicinal/commercial purposes [18, 71, 85, 87]. Influenced by genetic stability and environmental control [71, 88].
* **Propagation Characteristics:**
  + Seed Germination Rate and Speed [10, 89, 90]. Old seeds may have poor germination (Transcript P.168).
  + Cloning Success Rate: Ease of rooting cuttings, influenced by genetics and mother plant health [25, 91]. Some strains are notoriously difficult to clone.
  + Tissue Culture Recalcitrance: Difficulty of in vitro regeneration and transformation for certain genotypes [48, 92, 93].
  + Genotype-dependent HLVd eradication success in meristem culture [94]. (Transcript P.17-18, P.81).
  + Doubled Haploid (DH) Production Recalcitrance: Difficulty in generating homozygous lines rapidly [41, 93].
* **Responses to Cultivation Techniques:** Different strains may respond better or worse to specific methods.
  + Pruning and Training (e.g., Topping, LST, ScrOG, SOG): Effectiveness for yield and structure optimization can be strain-dependent [91, 95-98]. Some growers prefer no topping to encourage a dominant main cola and specific canopy structures (Transcript P.182-183). Stretch characteristics heavily influence training needs (Transcript P.114). Defoliation timing and extent interact with nutrient strategies like "Fade" (Transcript P.12, P.15-16).
  + Fertigation/Nutrient Management: Optimal nutrient timing, strength, and ratios may differ [13, 26, 27, 43, 45]. Some strains (e.g. Runtz) are sensitive to high EC, while others (e.g. Pie Hoe) can take very high EC (Transcript P.196). OGs might prefer lower EC (Transcript P.196).
  + Nutrient Use Efficiency (NUE) varies [45, 99].
  + Substrate Suitability: Performance can vary significantly across different substrates (soil, coco coir, peat mixes, rockwool, hydroponics) and may be genotype-specific [2, 3, 31]. Some strains might prefer the buffering of coco over the rapid changes in rockwool (Transcript P.116, P.180).
* **Desired Effects/Applications:** While influenced by environment and post-harvest, the genetic chemotype provides the basis for different effects and applications [72, 86, 100-103].
  + Recreational Effects: Energetic/cerebral (sativa-like) vs. relaxing/sedative (indica-like) [47, 102].
  + While traditional Sativa/Indica labels are not fully reliable for genetic structure [59, 104, 105], market categorizations persist based on perceived effects [47, 102].
  + Entourage effect plays a role [78, 106-109].
  + Medical Applications: Specific cannabinoid/terpene profiles are sought for therapeutic outcomes (e.g., high CBD for certain conditions) [85, 101, 110].
  + Tailored chemotypes for medicinal needs [111].

#### **1.6 Pest/Disease Resistance Parameters**

Parameters defining a strain's inherent ability to resist common pests and diseases.

* **Resistance Levels:** Genotype-dependent inherent resistance or susceptibility to:
  + Fungal Diseases (e.g., Powdery Mildew (PM), Bud Rots like Botrytis, Root/Crown Rots like Fusarium/Pythium) [32, 33, 112, 113]. Botrytis is a significant issue, especially with dense buds or under LED lights if humidity is not managed. Calcium deficiency can exacerbate botrytis (Transcript P.7-8, P.15). Fusarium is a concern in hydroponic/recirculating systems, no cure, spreads via water (Transcript P.84). PM resistance is a highly desirable trait (Transcript P.79).
  + Mold resistance is a crucial agronomic trait [114]. Strains from humid regions may have higher mold resistance [58].
  + Bacterial Diseases [32, 33].
  + Viral Pathogens (e.g., Hop Latent Viroid - HLVd) [32, 33]. HLVd resistance varies by genotype [94]. Some strains may be asymptomatic carriers (Transcript P.80-81). Symptoms include stunting, dudding, brittle stems, abnormal branching, reduced trichomes/yield/quality (Transcript P.3, P.16, P.80, P.171). Spreads via mechanical damage (tools, hands) (Transcript P.80). Present in roots (Transcript P.83). Can be in seeds (unconfirmed for cannabis, Tumi studying) (Transcript P.17, P.81).
  + Nematode Infestations (e.g., Root-knot nematodes) [115].
  + Insect Pests (e.g., Spider Mites, Aphids, Whiteflies, Thrips, Fungus Gnats) [32, 33, 113, 116]. Thrips and mites are common (Transcript P.80, P.179).
* **Mechanism of Resistance:** May involve structural defenses, production of defensive compounds (e.g., secondary metabolites like cannabinoids and terpenes can act as deterrents/protectants) [20, 21, 117], or activation of immune pathways. Plant polycultures may attract beneficial organisms for natural pest/disease control [118].
* **Stress-Induced Susceptibility:** Stress (abiotic or biotic) can weaken a plant's defenses and increase susceptibility to pests and diseases [34, 119]. Older mother plants may be more susceptible [34]. Stress can also cause HLVd to express symptoms in previously asymptomatic plants (Transcript P.17).
* **Impact on Yield/Quality:** Resistance (or lack thereof) directly impacts yield quantity and quality by minimizing (or maximizing) damage and systemic infection [32, 33, 113]. HLVd can devastate crops (Transcript P.3, P.16-17).

## Comprehensive Simulation Parameters for Project Chimera

**This document outlines potential parameters for the simulation mechanics of Project Chimera, drawing upon extensive research into Cannabis sativa L. biology, cultivation, genetics, and industry practices, significantly enhanced with details from cultivator discussions as recorded in "transcriptss.pdf" (hereafter cited as "Transcript P.[PageNumber]").**

### 1. Cannabis Biology and Characteristics Parameters (Part 1: Botanical & Chemical)

**This section details fundamental biological parameters of the Cannabis sativa L. plant, its morphology, chemistry, and inherent characteristics related to its interaction with the environment and biological threats.**

#### 1.1 Botanical Features Parameters

**Parameters defining the physical structure, classification, and life cycle stages of the cannabis plant.**

* **Taxonomy and Classification:**
  + **Species: *Cannabis sativa L.* [1]**
  + **Subspecies/Varieties: *sativa*, *indica*, *ruderalis*.**
    - **Note: Traditional classifications may not correlate perfectly with genetic structure [2, 3]. Cultivator experience suggests that even within these, traits like stretch and nutrient preference can vary significantly (Transcript P.114, P.196). For example, some OG cuts have minimal lateral branching (Transcript P.182-183).**
  + **Hemp vs. Drug-type distinction: Based on THC content (e.g., <0.3% Δ⁹-THC for hemp) [1]. This is a critical botanical and regulatory parameter [1] (Transcript P.2, P.276-277).**
    - **Range: % Δ⁹-THC can range from negligible (<0.1%) in some hemp varieties to over 30% in high-potency drug-type cultivars [4-6]. Some cultivars test around 15-19% THC, while others can reach 28-35% THC (Transcript P.187, P.197). THCA flower is also a market factor under hemp regulations (Transcript P.276-279).**
  + **Chemovars: Classification based on cannabinoid profile [7, 8] (e.g., Type I: THC-dominant, Type II: THC/CBD mixed, Type III: CBD-dominant, Type IV: CBG-dominant, Type V: negligible cannabinoids) [2].**
    - **Game should support differentiation based on chemical profile rather than just traditional labels [2]. Consumer markets show preferences for different profiles; e.g., some European markets value specific terpene expressions over pure THC content (Transcript P.192).**
* **Morphology: Parameters defining the physical structure and form of the plant.**
  + **Plant Height: Potential range (e.g., 0.2m to >12m cultivated) [1]. Influenced by genetics and environment [1].**
    - **Hemp types tend to be taller and less branched, drug-types bushier [1, 9].**
    - **Range: Dwarf varieties can be 0.2m [1]. Fiber hemp can exceed 12m [1].**
    - **Drug types typically range from 0.5m to over 3m. Some strains can stretch significantly, e.g., a 12-inch plant stretching to 5 feet (Transcript P.114). Sherb Banger 22 known for a 4-week stretch period (Transcript P.114-115).**
  + **Stem Structure: Erect, furrows, branching patterns, woody interior, hollow internodes [1].**
    - **Stem diameter can range from 1-3cm in mature plants, influenced by genetics and vigor [13].**
    - **Base can become very big and thick [14].**
    - **Branching Pattern: Influenced by genetics and environment (e.g., apical dominant, lateral spread, balanced) [15]. Sativa-like strains tend to have more lateral branching. Some OG cuts show minimal lateral branching without topping (Transcript P.182-183). HLVd infection can cause abnormal, horizontal branching (Transcript P.80).**
    - **Sativas tend to have more lanky branches, Indicas more compact [16-18].**
  + **Leaf Morphology: Compound leaves with leaflets radiating from the petiole end [1].**
    - **Leaflet Number: Number of leaflets (e.g., 3-13) [1].**
    - **Developmental sequence: 1 (seedlings/stressed), 3, 5, 7, 9, then potentially more (up to 13+) on robust mature plants, decreasing later [19].**
    - **Leaflet Shape: Lanceolate, ovoid, oblanceolate [1]. Influenced by genetics (e.g., broad in Indica types, narrow in Sativa types) [19].**
    - **Serrated margins [1].**
    - **Leaf Size: Broad (Indica) vs. long/slender (Sativa) [19].**
    - **Changes throughout lifecycle, peaking around the 12th node [19].**
    - **Leaf Angle/Droop: Angle relative to stem, turgidity.**
      * **Heavily influenced by hydration (underwatered-drooping) [13, 20]. Genetics may influence baseline angle [13]. Hybrids show a spectrum [13]. HLVd may cause leaves to curl or appear malformed (Transcript P.80).**
    - **Diagnostic Leaf Venation [1].**
  + **Leaf Arrangement: Opposite (lower nodes) to alternate (main stem) [1, 19].**
    - **Phyllotaxy shift typically occurs around the 12th node [19].**
  + **Bud/Flower Structure: Shape (e.g., conical, spear, round, "golf balls" (Transcript P.181), foxtail), density (airy, medium, compact, "rock-hard" under LEDs (Transcript P.202)), leaf-to-calyx ratio [15].**
    - **Indica types tend to have dense, compact buds, Sativa types longer, airy buds [11, 16].**
    - **Foxtailing can occur, sometimes accelerating towards harvest [21]. Some strains exhibit foxtailing as a genetic trait, not necessarily negative (Transcript P.120).**
    - **HLVd can cause "dudding" or significantly reduced bud development and trichome production (Transcript P.80, P.171).**
  + **Pistil Color (Mature): Colors such as orange-red, pink-purple, brown [15].**
  + **Trichome Density: Potential levels (low, medium, high) [15].**
    - **A key visual quality indicator (frostiness, resin) [15, 22, 23]. Influenced by genetics and environment [15, 24, 25]. Some strains are known for high resin production suitable for hash (Transcript P.9, P.21).**
    - **Can vary dramatically between strains [24]. Use of products like Athena Stack can visually increase trichome production (Transcript P.160).**
  + **Trichome Appearance: Transition in color (clear to milky to brown/amber) indicates maturity [15, 22, 26].**
    - **Visual cues for resin and ripeness [15, 22, 26]. Trichomes contain cannabinoids [24]. For hash production, plants might be harvested earlier when trichomes are optimal for separation (e.g., day 40 for a 70-day flower strain) (Transcript P.197).**
  + **Trichome Degradation: Can be induced by experiments [27]. Poor storage can lead to reduced trichome vibrancy [28, 29]. Improper drying/curing can lead to terpene loss (Transcript P.179).**
  + **Root System: Adaptable taproot with lateral branching [1].**
    - **Can reach up to 2.5m deep in soil depending on soil/water [1, 30].**
    - **Root health and development influenced by growing media [30, 31]. HLVd can be present in roots (Transcript P.83). Fusarium also infects through roots (Transcript P.84).**
    - **Plants from seed have a strong, deep taproot; cloned plants typically have weaker, more lateral, not as deep roots [32].**
    - **Rootbound plants stress plant if left untreated [33].**
    - **Root restriction (small containers) stunts growth, limits nutrient/water uptake, alters structure [30, 34, 35]. Smaller pots (e.g., 1-2 gallons) preferred by some for more control with frequent irrigations (Transcript P.127).**
  + **Visual Representation: Potential for root system visualization showing medium, water, nutrient response [36].**
  + **Fruit (Achene)/Seed: <3.8mm length, often in persistent perianth (mottled/marbled) [1]. Seed production can yield 5,000 to over 20,000 seeds per light depending on cultivation methods and nutrient lines (Transcript P.309). Shipping seeds is generally legal (DEA rescheduled, Transcript P.2), but banking for seed sales can be problematic (Transcript P.2). Cuttings/clones shipping legality is evolving, based on <0.3% THC in the cutting itself (Transcript P.1-2, P.276-277).**
* **Sex Determination:**
  + **Predominantly dioecious (separate male (XY)/female (XX) plants) [1, 37]. Females are valued for cannabinoids in inflorescences [37].**
  + **Monoecious/Hermaphroditic forms: Can occur naturally (stress-induced, e.g., light leaks, temperature swings (Transcript P.158, P.171)) or be chemically induced (e.g., silver thiosulfate, STS (Transcript P.169)) for breeding [37].**
    - **Hermaphroditism involves producing both male and female flowers on the same plant, leading to "seeded" crops [38, 39]. Some strains have a higher genetic predisposition to herm under stress (e.g., Dante's Inferno #6) (Transcript P.152). Sterility of pollen from hermaphroditic plants can vary (Transcript P.152).**
* **Growth Stages:**
  + **Germination: First physiological stage [40].**
    - **Requires proper medium temperature (8-10°C average daily minimum for outdoor sowing, or specific ranges for in vitro/controlled) [41, 42].**
    - **Light not required [42]. Influenced by genetics, physical factors (medium composition, env conditions) [40].**
    - **Optimal conditions and quality seeds yield 80-100% germination [43]. Poor germination rates can be associated with bad genetics [44] or old seeds (Transcript P.168).**
    - **Range/Likely Level: Germination rate can be affected by genotype, medium composition, and environmental conditions [40, 43]. Reputable breeders aim for near 100% [43].**
  + **Seedling: Early growth [45, 46].**
    - **Typically single leaflet leaves initially, progressing to 3, then 5 [19]. Sensitive stage [47].**
  + **Vegetative: Rapid growth stage, building root system and stems, then foliage [46, 48].**
    - **Needs high nitrogen [46, 49]. Fairly tough during this stage [50]. Environmental conditions like temp/humidity deviations impact growth speed [51]. Optimal VPD is crucial (Transcript P.235). Low light (e.g. 200s PPFD) can be sufficient if DLI is met (Transcript P.161). Veg duration varies (e.g., 10-18 days for some commercial setups (Transcript P.176, P.217), up to 5-6 weeks for others (Transcript P.200)).**
    - **Problems often begin to show here [52]. Duration modeled as 50 days in one facility example [53].**
  + **Flowering: Stage where inflorescences develop [45, 46].**
    - **Requires lower humidity (especially late flower, e.g. 40-50% RH, though some run higher at 60-65% with LEDs (Transcript P.161)) and specific light spectrum/intensity [47]. Needs higher phosphorus/potassium [45, 49]. Light cycle typically 12/12, but some manipulate to 11/13 to finish plants or influence expression (Transcript P.115).**
    - **Longest stage in one model (57 days) [53]. Can range from 7 weeks (e.g., Rainbow Belts, Zkittlez crosses (Transcript P.115)) to 10+ weeks (e.g., Haze varieties, some OGs (Transcript P.115, P.169, P.308)) depending on genetics. Stretch period (first 1-4 weeks of flower) can last 3-4 weeks for some strains (e.g., Sherb Banger 22 (Transcript P.114-115)).**
  + **Maturation: Buds thicken, trichomes mature [21, 27].**
    - **Harvest timing determined by trichome appearance (clear to milky to amber) and yield/chemistry correlation [54]. Cannabinoid and terpene profiles change during maturation (Transcript P.8, P.172). Some harvest earlier for specific products like hash (Transcript P.197).**
  + **Harvest: Physical removal of plants/flowers [55]. Timing crucial for potency/quality [54, 56].**
* **Phenotypic Plasticity: The ability of a plant with a specific genotype to exhibit different phenotypes in different environments [38, 57-60].**
  + **This is a fundamental concept for GxE modeling [38, 57-60]. Environment (light, temp, nutrients, stress) heavily influences expression of genetic potential (Transcript P.187, P.200-207).**
  + **Clones with identical genotype can show different phenotypes with varied conditions [3, 58].**

#### 1.2 Chemical Profile Parameters

**Parameters defining the chemical composition of the cannabis plant, particularly secondary metabolites produced primarily in glandular trichomes [4, 24, 61].**

* **Cannabinoids: (>140 identified) [62].**
  + **Major Cannabinoids:**
    - **Δ⁹-tetrahydrocannabinol (THC): Psychoactive compound [63].**
      * **Potency often measured as % DW [64]. Levels up to 25-30% of floral dry weight achieved [4]. Some cultivars testing at 28-35% THC reported (Transcript P.187). Others may test lower (e.g. 12-19%) but still be desirable (Transcript P.170, P.197). Moisture content at testing significantly impacts reported THC % (Transcript P.12, P.22).**
      * **Can reach 30% in some plants [5].**
      * **Likely Levels: High THC strains can exceed 20%, some even reaching 30% [4-6]. Cultivator discussions mention THC levels from 12% to 35%+ (Transcript P.13, P.170, P.187, P.197).**
      * **Traditional hemp is <0.3% [1]. THCA flower market exists under hemp definition (Transcript P.276-279).**
    - **Cannabidiol (CBD): Non-psychoactive, therapeutic potential [63, 65].**
      * **Potency often measured as % DW [64].**
      * **Likely Levels: High CBD strains can exceed 15-20%. Many hybrids have mixed ratios.**
    - **Cannabigerol (CBG): Precursor to other cannabinoids [63]. Increasing interest in breeding [66].**
    - **Cannabinol (CBN): Sedative effects [63]. Accumulates with degradation/aging [63].**
  + **Minor Cannabinoids: Growing interest (distinct therapeutic benefits) [66].**
    - **Δ⁹-tetrahydrocannabivarin (THCV): Investigating production genetics crucial [66].**
    - **Cannabidivarin (CBDV): Investigating production genetics crucial [66].**
    - **Cannabichromene (CBC): Investigating production genetics crucial [66].**
    - **Cannabichromenevarin (CBCV) [63].**
    - **Cannabigerovarin (CBGV) [63].**
    - **Delta-8 THC [63], Delta-10 THC [63], HHC [63]: Novel cannabinoids often in legal grey areas, facing evolving scrutiny [67]. Delta-8 can be synthesized from CBD (Transcript P.279-281).**
    - **THCP, THCB [63].**
  + **Cannabinoid Acids: Biosynthetic precursors, convert to neutral form via decarboxylation (heat, aging) [63, 68, 69].**
    - **THCA (tetrahydrocannabinolic acid) [63]. THCA flower being sold under hemp regulations is a major market factor (Transcript P.276-279).**
    - **CBDA (cannabidiolic acid) [63].**
    - **CBGA (cannabigerolic acid) [63].**
  + **Total Cannabinoids (e.g., Total THC: THCA \* 0.877 + THC, Total CBD: CBDA \* 0.877 + CBD) [63].**
    - **Critical quality parameters [68]. Content variability in plant material is an issue for consistency [68].**
    - **Can reach 25-30% of floral dry weight [4]. Potency is a key driver in many markets, though this is being questioned by connoisseurs (Transcript P.170, P.197, P.239). Moisture content at testing significantly impacts reported THC % (Transcript P.12, P.22). Using products like "Fade" can increase THC by 2-6% absolute (Transcript P.13).**
* **Terpenes: (>120 identified) [62].**
  + **Aromatic compounds contributing to aroma, flavor, and potential effects (entourage effect) [63, 65, 70]. Produced in glandular trichomes [61]. Critical for consumer preference, especially in connoisseur markets (Transcript P.8, P.152, P.179, P.192).**
  + **Concentration influenced by genetics, environment, post-harvest handling [71]. Late-stage nutrient protocols (like "Fade") can enhance terpene expression (Transcript P.8-9). Drying and curing are critical for terpene preservation (Transcript P.179, P.298-299).**
  + **Dominant Terpenes: Myrcene, Limonene, Caryophyllene, Pinene, Ocimene, Terpinolene [63].**
  + **Other Terpenes: Humulene, Linalool, Bisabolol, Nerolidol, Geraniol, Borneol, Fenchol, Cineole, Camphor, Phellandrene, Terpineol, Carene, Farnesene, Phytol, Carvacrol, Aromadendrene, Eudesmol [63].**
  + **Terpene Profiles: Concentrations and ratios of individual terpenes [64, 65, 71]. Contributes to market demand [71]. Breeding for unique terpene profiles is a major goal for some (Transcript P.152, P.172).**
  + **System for classification (e.g., Cream/Cake/Cookies/Candy, Fruity, Herbal, Pine, Skunk, Spicy, Sweet, Tropical, Woody/Earth) [72]. The "candy" profile (e.g., from Dante's Inferno #6) is currently popular (Transcript P.152, P.172). "Gas" is another popular profile (Transcript P.187).**
  + **Total Terpenes [63]. High terpene content is desirable but can be diluted by excessive yield focus ("yield dilution") (Transcript P.62).**
  + **Volatilization: Terpenes can volatilize, especially during drying/curing at warmer temperatures [73].**
    - **Proper drying/curing crucial for retention [25, 54, 73]. Target 7-10 days dry time, 60F/60%RH environment (Transcript P.298-299).**
* **Flavonoids: Contribute to pigmentation and aroma/flavor [8, 63].**
  + **Cannflavins [63]. Anthocyanins responsible for purple colors, influenced by genetics and cold temperatures (Transcript P.14-15).**
* **Volatile Sulfur Compounds (VSCs): Contribute to pungent/characteristic notes like "gas" or "skunk" [63]. Unstable over time [63].**
* **Esters: Contribute sweet/fruity notes [63].**
* **Other Constituents: Hydrocarbons, phenolics, sugars [63].**
* **Entourage Effect: Synergistic interaction between cannabinoids, terpenes, and other compounds influencing effects and therapeutic potential [8, 63].**

#### 1.3 Physiological Processes Parameters (Continuation)

**Parameters governing the internal functions and responses of the cannabis plant, building on the initial photosynthesis, transpiration, nutrient uptake, and biosynthesis parameters.**

* **Water Relations: Beyond basic transpiration.**
  + **Water Uptake Rate: Influenced by root system size/health, substrate moisture content, substrate type (e.g., coir's high water retention vs. rockwool's quick dry down) [1-3]. VPD heavily influences uptake (Transcript P.125, P.235).**
  + **Aquaporin activity (e.g., PIP aquaporins) may play a role at a molecular level [2].**
  + **Leaf Water Potential: Measure of plant water stress. Influenced by substrate moisture, humidity, airflow, transpiration rate.**
  + **Stomatal Response: Opening and closing of stomata to regulate gas exchange and water loss.**
    - **Influenced by light intensity, CO2 levels, humidity, wind. Can be reduced in later maturation stages [4]. Far-red light at end of day can influence stomatal closure and plant sleep cycles (Transcript P.203).**
* **Carbon Metabolism:**
  + **Carbon Fixation Rate: Directly related to photosynthetic rate.**
  + **Photoassimilate Production: Synthesis of sugars.**
  + **Photoassimilate Partitioning: Allocation of sugars to different plant parts (roots, shoots, leaves, flowers).**
    - **Influenced by growth stage, nutrient availability (e.g., Nitrogen for vegetative growth vs. Phosphorus for flowering/bud development) [5]. Late flower N restriction (e.g., using "Fade") encourages resource allocation to flowers (Transcript P.7-9, P.15).**
* **Hormonal Regulation: Internal plant hormones (phytohormones) play crucial roles in growth, development, and responses to environment and stress.**
  + **Auxins: Involved in root development, apical dominance, vegetative growth. Auxin activity typically decreases during flowering transition [6].**
  + **Cytokinins: Promote cell division, shoot development. Certain cytokinins increase during flowering transition [6].**
    - **Meta-topolin (mT), a natural cytokinin, is effective for shoot proliferation in tissue culture [7].**
  + **Gibberellins: Involved in stem elongation (e.g., "stretch" at flowering onset) [6].**
  + **Abscisic Acid (ABA): Stress hormone, involved in stomatal closure and dormancy. Increases under drought stress. Drought stress (generative steering) is a key crop steering technique (Transcript P.122-123).**
  + **Ethylene: Involved in senescence, ripening, stress responses.**
  + **Brassinosteroids: Promote growth and stress tolerance.**
  + **Phytohormone Balance: The relative levels and interactions of these hormones regulate developmental transitions (e.g., vegetative to flowering, re-vegetation) [6, 8].**
    - **Mother plants in long-term vegetative state may experience subtle changes in hormonal balance [4].**
* **Nutrient Mobility and Translocation: Movement of absorbed nutrients within the plant (e.g., from older leaves to new growth/flowers).**
  + **Efficiency may diminish with physiological age [4]. Nitrogen is highly mobile and translocated from fan leaves during late flower if root zone N is restricted (e.g. when using "Fade") (Transcript P.8, P.15). Calcium is immobile; deficiencies (e.g., from flushing with straight RO water or pulling Core too early) can lead to issues like bud rot (Transcript P.7-8, P.12).**
* **Resource Remobilization: Breakdown of macromolecules (proteins, lipids, nucleic acids) in senescing tissues and transport of resulting nutrients to other parts of the plant [9].**
  + **Occurs in older leaves even in vegetative mothers [4]. Crucial for reproductive success in nature [9]. This is a key mechanism during "Fade" or flushing (Transcript P.8, P.15).**
* **Developmental Plasticity: Ability to alter growth patterns in response to environmental cues (e.g., branching patterns influenced by light distribution, nutrient availability) [10].**
* **Circadian Rhythms: Internal biological clock regulating daily physiological processes (e.g., photosynthesis, transpiration, flowering time). Interacts with photoperiod. Use of far-red light to signal end-of-day can influence these rhythms (Transcript P.203).**

#### 1.4 Stress Responses Parameters

**Parameters defining how the cannabis plant reacts to and is affected by various abiotic and biotic stressors, and its ability to tolerate them. Stress can impact yield, quality, and even chemotype. Strategic stress (e.g., controlled drought, specific nutrient withdrawal like "Fade") can enhance desired traits like terpene and cannabinoid production (Transcript P.8, P.122-124).**

* **Abiotic Stress Responses: Responses to non-living environmental factors.**
  + **Drought Stress: (Intentional for generative steering)**
    - **Physiological Effects: Reduced stomatal conductance, decreased photosynthesis, wilting, reduced transpiration.**
    - **Can induce changes in leaf water potential [11]. Induces hormonal responses for survival and reproduction (Transcript P.122).**
    - **Growth/Yield Effects: Stunted growth, reduced biomass, lower flower yield.**
    - **Controlled drought stress in flowering stage can increase inflorescence dry weight and cannabinoid content [12]. Key part of "generative steering" by manipulating drybacks (Transcript P.11, P.122-123).**
    - **Chemotype Effects: May increase cannabinoid/terpene concentration (due to reduced biomass/water content or stress-induced synthesis) or decrease total production (due to reduced metabolic activity) [11, 13]. (Transcript P.8, P.124).**
    - **Stress-induced synthesis vs. dilution [13].**
  + **Heat Stress:**
    - **Physiological Effects: Denaturation of enzymes, impaired photosynthesis, increased respiration, heat shock protein production.**
    - **Can cause managing temperature to be critical for quality [14]. Excessive heat can stress plants, leading to reduced quality or hermaphroditism (Transcript P.158, P.171).**
    - **Growth/Yield Effects: Stunted growth, reduced flower development, wilting, leaf damage.**
    - **Chemotype Effects: Can degrade cannabinoids (e.g., THC) and volatilize terpenes, reducing overall potency and aroma profile [14].**
  + **Cold Stress:**
    - **Physiological Effects: Reduced enzymatic activity, membrane damage, impaired nutrient uptake.**
    - **Growth/Yield Effects: Stunted growth, leaf damage, reduced yield.**
    - **Chemotype Effects: Can impact cannabinoid/terpene synthesis.**
    - **Some varieties may show color changes (e.g., purple hues) in response to cold [15]. This is a common technique to enhance "bag appeal" (Transcript P.14-15). Colder water at end of flower can also induce color (Transcript P.14).**
  + **Light Stress (Too High/Low Intensity):**
    - **Physiological Effects: Photoinhibition (damage to photosynthetic apparatus) from excessive light [16].**
    - **Reduced photosynthesis from insufficient light. Plants growing into lights will burn (Transcript P.114).**
    - **Growth/Yield Effects: Leaf burn, stunted growth, reduced yield from excessive light.**
    - **Leggy growth, low yield from insufficient light.**
    - **Chemotype Effects: Optimal light intensity and spectrum are crucial for cannabinoid and terpene production [17-19]. Some genetics are more sensitive to high PPFD than others (e.g., old Indicas) (Transcript P.116).**
    - **UV light can stimulate cannabinoid production (protective mechanism) [20, 21], but excessive UV can be damaging.**
    - **Different light spectra affect morphological, physiological, and chemical parameters [17, 22]. Far-red can influence flowering time and stretch (Transcript P.203). Mixed HPS/LED can give unique expressions (Transcript P.202-207).**
  + **Nutrient Deficiency/Toxicity:**
    - **Physiological Effects: Impaired metabolic processes, reduced photosynthesis, visible symptoms (e.g., leaf yellowing from N deficiency, brown spots from P deficiency/toxicity, leaf burn from nutrient excess/toxicity) [23, 24]. Calcium deficiency in late flower can lead to bud rot (Transcript P.7-8).**
    - **Can trigger/accelerate senescence [25]. Removing core nutrients (e.g., Athena ProLine Core) too early or using straight RO water can cause deficiencies (Transcript P.8, P.12).**
    - **Growth/Yield Effects: Stunted growth, reduced biomass, lower yield [5, 23, 24].**
    - **Nutrient imbalance can restrict development [26]. Overwatering can lead to nutrient lockout or root issues mistaken for deficiencies (Transcript P.11).**
    - **Chemotype Effects: Nutrient availability significantly impacts cannabinoid and terpene biosynthesis and concentration [18, 27, 28].**
    - **High Nitrogen can decrease cannabinoid/terpene concentration while increasing biomass (dilution effect) [5, 29]. This is a reason for products like "Fade" (Transcript P.7-9).**
    - **Phosphorus is conventionally supplied at high amounts for optimal function and yield, but deficiency at vegetative stage impacts functional phenotyping and ionome [30].**
  + **Waterlogged Soil/Root Zone Hypoxia:**
    - **Physiological Effects: Root damage, impaired nutrient/water uptake, reduced oxygen availability to roots. Increased risk with overwatering, especially in dense media like coco if not managed (Transcript P.11, P.126).**
    - **Growth/Yield Effects: Wilting, stunted growth, root rot susceptibility [31], reduced yield.**
    - **Chemotype Effects: Reduced plant health negatively impacts secondary metabolite production.**
  + **Salinity Stress: Accumulation of soluble salts in the root zone, particularly in hydroponics/soilless media [26]. High EC in media due to insufficient runoff or excessive drybacks (Transcript P.123, P.158).**
    - **Physiological Effects: Impaired water uptake, ion toxicity.**
    - **Growth/Yield Effects: Stunted growth, reduced yield. Lockout of other nutrients.**
    - **Chemotype Effects: Can impact metabolite profiles. Extreme EC can burn plants.**
* **Biotic Stress Responses: Responses to living organisms.**
  + **Pest Infestation: (See also 1.6 Pest/Disease Resistance Parameters)**
    - **Damage Types: Feeding damage (leaf loss, tissue damage), disease transmission, growth hindrance [32, 33]. Thrips, mites mentioned as common problems (Transcript P.80, P.179).**
    - **Physiological Effects: Allocation of resources to defense mechanisms (e.g., production of defensive compounds).**
    - **Growth/Yield Effects: Reduced vigor, stunted growth, significant yield loss [32, 33].**
    - **Trichome damage/loss can directly reduce cannabinoid/terpene yield [34].**
  + **Pathogen Infection: (See also 1.6 Pest/Disease Resistance Parameters)**
    - **Damage Types: Tissue damage, impaired physiological function (e.g., nutrient/water transport, photosynthesis), systemic infection [32, 35]. Bud rot (Botrytis) is a major concern, linked to calcium deficiency and high humidity (Transcript P.7-8, P.15). Fusarium is a root pathogen, no cure, spreads via water (Transcript P.84). HLVd causes stunting, dudding, reduced quality (Transcript P.3, P.16, P.80, P.171).**
    - **Physiological Effects: Activation of plant immune response, production of defense compounds.**
    - **Older mothers may have potentially weakened immune response or chronic stress leading to higher susceptibility [34].**
    - **Growth/Yield Effects: Reduced vigor, stunted growth, wilting, necrosis, significant yield loss [32, 35]. HLVd can devastate crops (Transcript P.3, P.16-17).**
    - **Can be mistaken for age-related decline [34]. Systemic pathogens like HLVd cause stunting and reduced trichome production/yields [34].**
  + **Competition (Light, Nutrients, Water, Space): Competition from other cannabis plants or companion plants [36].**
    - **Physiological Effects: Altered growth patterns (e.g., reaching for light), reduced resource uptake efficiency.**
    - **Growth/Yield Effects: Reduced individual plant yield. Plant spacing is important for maximizing yield per area [37, 38]. Density of 1.6 plants/sq ft mentioned (Transcript P.183).**
  + **Stress-Induced Senescence: Premature aging and death of plant tissues or the whole plant due to severe or prolonged stress [9]. Can be desirable at end of flower (e.g., with "Fade") but problematic if premature (Transcript P.8).**

#### 1.5 Strain-Specific Optimal Conditions and Characteristics Parameters

**Parameters defining the variations in optimal growth conditions, growth habits, and other characteristics between different cannabis genotypes (strains/cultivars). Cultivars show wide variation in response to environment and inputs (Transcript P.114, P.163, P.187, P.200).**

* **Optimal Environmental Ranges: Genotype-dependent ideal ranges for:**
  + **Temperature: Specific optimal temperature ranges for vegetative and flowering stages [39]. Some strains are more sensitive to temperature swings (Transcript P.15, P.158). Some growers run 73-76F even in late flower with "Fade" (Transcript P.15).**
  + **Humidity: Specific optimal humidity ranges for vegetative and flowering stages [39]. Some strains are more prone to mold in high humidity (Transcript P.15). Some run 60-65% RH with LEDs in flower (Transcript P.161).**
  + **Light Intensity (PPFD): Different strains may utilize light more or less efficiently and have different saturation points. Some strains are sensitive to high PPFD (e.g. old indicas) (Transcript P.116).**
  + **Light Spectrum: Different strains may respond differently to specific light wavelengths [17, 22, 39]. Some strains show better color or terpene expression under specific spectra (e.g. mixed HPS/LED, or specific LED spectra like ThinkGrow vs. Luxx) (Transcript P.202-207, P.113, P.160). Far-red for end-of-day signal (Transcript P.203).**
  + **CO2 Concentration: Optimal CO2 levels for different strains, especially in CEA [39-41]. Typically 1500ppm in flower (Transcript P.161).**
  + **Airflow/Ventilation: Specific needs for different growth structures and densities to prevent mold/pests [42]. Dense bud structures require more airflow (Transcript P.15).**
  + **Substrate Moisture Content: Optimal levels and tolerance for drying out or waterlogging vary [1-3]. Some strains prefer larger drybacks than others (Transcript P.11, P.124). Rockwool vs. Coco drydown characteristics (Transcript P.113, P.180).**
  + **Nutrient Solution pH: Optimal pH range for nutrient uptake can vary slightly by strain and substrate [16, 43, 44]. Some growers maintain a consistent pH (e.g. 6.0-6.2) for all strains in coco (Transcript P.158). Monosilicic acid can affect pH in rockwool (Transcript P.11).**
  + **Nutrient Concentrations (EC/PPM): Optimal nutrient strength varies by strain and growth stage [27, 43, 45]. Some strains are heavy feeders, others sensitive (e.g., OGs might prefer lower EC than Runtz; Runtz sensitive to high EC, Pie Hoe can take very high EC) (Transcript P.196). Some run 3.0 EC all the way through with Athena ProLine (Transcript P.12, P.15).**
  + **Specific Nutrient Ratios (NPK, Ca:Mg, etc.): Optimal ratios can be strain-specific and outcome-specific (e.g., maximizing yield vs. maximizing cannabinoid concentration) [13, 27, 45].**
* **Growth Habits and Morphology: Genotype-dependent traits:**
  + **Plant Height and Structure: Tall/thin (sativa-like) vs. short/bushy (indica-like) [10, 47, 48]. Some strains have significant stretch (e.g. Sherb Banger 22, 4-week stretch from 12" to 5ft (Transcript P.114-115)) while others are short (e.g. Rainbow Belts, Zkittlez finishing in 7 weeks (Transcript P.115)).**
  + **Branching patterns (apical dominant vs. lateral spread, OG minimal lateral without topping) [10] (Transcript P.182-183). Untopped plants develop a main cola with lateral branches reaching near the top (Transcript P.183).**
  + **Internodal spacing [49].**
  + **Leaf Morphology: Leaflet number and width (narrow-leaf vs. broad-leaf) [49, 50].**
  + **Flower Structure: Shape, density, leaf-to-calyx ratio [10, 51]. Some genetics known for specific structures (e.g. "golf balls" (Transcript P.181)). Some LED-grown flower can be rock-hard (Transcript P.202).**
  + **Root System Development: Efficiency and structure of the root system can be strain-specific [3]. Cloned plants have weaker, more lateral roots than seed plants (Transcript P.32).**
* **Life Cycle and Flowering Time: Genotype-dependent duration of growth stages:**
  + **Seedling Stage Duration [10, 54].**
  + **Vegetative Stage Duration: Ability to remain vegetative under specific photoperiods [10, 55, 56]. Commercial grows may have veg times from 10-18 days (Transcript P.176, P.217) to several weeks (Transcript P.200).**
  + **Flowering Time/Duration: Crucial parameter for breeding and cultivation planning [10, 39, 57, 58]. Ranges from 7 weeks (e.g. some Zkittlez crosses (Transcript P.115)) to 10+ weeks (e.g. Haze varieties, some OGs (Transcript P.115, P.169, P.308)).**
  + **Sativa varieties typically have longer flowering times (10-16 weeks) than indica (6-10 weeks) [10, 57]. Photoperiod-dependent flowering vs. autoflowering [59-61]. Use of far-red light can shorten flowering time by a week or more (Transcript P.204).**
  + **Semi-full-term/fast-flowering strains [62, 63].**
  + **Maturation Indicators: Visual cues (pistil color, trichome appearance) indicating peak ripeness can vary slightly by strain [10, 64-66].**
  + **Trichome gland head phenotypes change over the flowering period [67]. Optimal harvest timing varies by strain [68]. For hash production, plants might be harvested earlier (e.g. day 40 for a 70-day flower strain) (Transcript P.197).**
  + **Re-vegetation Potential: Ability to revert to vegetative growth after flowering can be strain-dependent [6, 69].**
  + **Older plants may struggle more [69].**
* **Yield Potential: Genotype-dependent inherent capacity for biomass and flower production under optimal conditions.**
  + **Measured in grams per plant or grams per square foot [65]. Can be influenced by substrate choice [1, 3]. Yields of 2.5-4 lbs per light reported by cultivators (Transcript P.116, P.204). Some strains are known low yielders (e.g. cookies, lcg) but high value (Transcript P.116, P.241). Under canopy lighting can increase yield by 20-50% (Transcript P.225). Hash yields also vary (e.g., 3% vs 4-5.5% with Fade) (Transcript P.9).**
* **Chemical Profile (Chemovar): Genotype-dependent production of specific cannabinoids, terpenes, and other compounds, defining the chemovar [70-73]. Huge driver of market value (Transcript P.152, P.170).**
  + **Major Cannabinoid Ratios (THC:CBD, THC:CBG, CBD:CBG, etc.) [28, 74].**
  + **Controlled by alleles at cannabinoid synthase loci [74, 75]. Breeding can target specific ratios [76, 77].**
  + **Minor Cannabinoid Production (THCV, CBDV, CBG, CBC, CBN, etc.) [72, 78, 79]. Genetics control production [76, 77].**
  + **Terpene Profile: Specific terpenes produced and their relative concentrations [72, 73, 78, 80, 81]. Unique terpene profiles are highly sought after (e.g. Dante's Inferno #6 cherry candy (Transcript P.152, P.172)).**
  + **Genetics are foundational, but expression influenced by environment and post-harvest [82]. Terpene synthase (TPS) genes are involved [45, 79].**
  + **Unique flavor/aroma profiles are strain-defining [58, 80, 83]. "Gas" and "candy" profiles are popular (Transcript P.172, P.187).**
  + **Flavonoid Production (Cannflavins, Anthocyanins for color) [78, 84] (Transcript P.14-15).**
  + **Total Cannabinoid Potency (% DW) [71, 74, 78]. THC levels are often a primary market driver, but this is shifting (Transcript P.170, P.197, P.239).**
  + **Total Terpene Content [78].**
  + **Stability of Chemical Profile: Consistency across different grows/environments (less plastic chemotypes) [85, 86].**
  + **Desirable for medicinal/commercial purposes [18, 71, 85, 87]. Influenced by genetic stability and environmental control [71, 88].**
* **Propagation Characteristics:**
  + **Seed Germination Rate and Speed [10, 89, 90]. Old seeds may have poor germination (Transcript P.168).**
  + **Cloning Success Rate: Ease of rooting cuttings, influenced by genetics and mother plant health [25, 91]. Some strains are notoriously difficult to clone.**
  + **Tissue Culture Recalcitrance: Difficulty of in vitro regeneration and transformation for certain genotypes [48, 92, 93].**
  + **Genotype-dependent HLVd eradication success in meristem culture [94]. (Transcript P.17-18, P.81).**
  + **Doubled Haploid (DH) Production Recalcitrance: Difficulty in generating homozygous lines rapidly [41, 93].**
* **Responses to Cultivation Techniques: Different strains may respond better or worse to specific methods.**
  + **Pruning and Training (e.g., Topping, LST, ScrOG, SOG): Effectiveness for yield and structure optimization can be strain-dependent [91, 95-98]. Some growers prefer no topping to encourage a dominant main cola and specific canopy structures (Transcript P.182-183). Stretch characteristics heavily influence training needs (Transcript P.114). Defoliation timing and extent interact with nutrient strategies like "Fade" (Transcript P.12, P.15-16).**
  + **Fertigation/Nutrient Management: Optimal nutrient timing, strength, and ratios may differ [13, 26, 27, 43, 45]. Some strains (e.g. Runtz) are sensitive to high EC, while others (e.g. Pie Hoe) can take very high EC (Transcript P.196). OGs might prefer lower EC (Transcript P.196).**
  + **Nutrient Use Efficiency (NUE) varies [45, 99].**
  + **Substrate Suitability: Performance can vary significantly across different substrates (soil, coco coir, peat mixes, rockwool, hydroponics) and may be genotype-specific [2, 3, 31]. Some strains might prefer the buffering of coco over the rapid changes in rockwool (Transcript P.116, P.180).**
* **Desired Effects/Applications: While influenced by environment and post-harvest, the genetic chemotype provides the basis for different effects and applications [72, 86, 100-103].**
  + **Recreational Effects: Energetic/cerebral (sativa-like) vs. relaxing/sedative (indica-like) [47, 102].**
  + **While traditional Sativa/Indica labels are not fully reliable for genetic structure [59, 104, 105], market categorizations persist based on perceived effects [47, 102].**
  + **Entourage effect plays a role [78, 106-109].**
  + **Medical Applications: Specific cannabinoid/terpene profiles are sought for therapeutic outcomes (e.g., high CBD for certain conditions) [85, 101, 110].**
  + **Tailored chemotypes for medicinal needs [111].**

#### 1.6 Pest/Disease Resistance Parameters

**Parameters defining a strain's inherent ability to resist common pests and diseases.**

* **Resistance Levels: Genotype-dependent inherent resistance or susceptibility to:**
  + **Fungal Diseases (e.g., Powdery Mildew (PM), Bud Rots like Botrytis, Root/Crown Rots like Fusarium/Pythium) [32, 33, 112, 113]. Botrytis is a significant issue, especially with dense buds or under LED lights if humidity is not managed. Calcium deficiency can exacerbate botrytis (Transcript P.7-8, P.15). Fusarium is a concern in hydroponic/recirculating systems, no cure, spreads via water (Transcript P.84). PM resistance is a highly desirable trait (Transcript P.79).**
  + **Mold resistance is a crucial agronomic trait [114]. Strains from humid regions may have higher mold resistance [58].**
  + **Bacterial Diseases [32, 33].**
  + **Viral Pathogens (e.g., Hop Latent Viroid - HLVd) [32, 33]. HLVd resistance varies by genotype [94]. Some strains may be asymptomatic carriers (Transcript P.80-81). Symptoms include stunting, dudding, brittle stems, abnormal branching, reduced trichomes/yield/quality (Transcript P.3, P.16, P.80, P.171). Spreads via mechanical damage (tools, hands) (Transcript P.80). Present in roots (Transcript P.83). Can be in seeds (unconfirmed for cannabis, Tumi studying) (Transcript P.17, P.81).**
  + **Nematode Infestations (e.g., Root-knot nematodes) [115].**
  + **Insect Pests (e.g., Spider Mites, Aphids, Whiteflies, Thrips, Fungus Gnats) [32, 33, 113, 116]. Thrips and mites are common (Transcript P.80, P.179).**
* **Mechanism of Resistance: May involve structural defenses, production of defensive compounds (e.g., secondary metabolites like cannabinoids and terpenes can act as deterrents/protectants) [20, 21, 117], or activation of immune pathways. Plant polycultures may attract beneficial organisms for natural pest/disease control [118].**
* **Stress-Induced Susceptibility: Stress (abiotic or biotic) can weaken a plant's defenses and increase susceptibility to pests and diseases [34, 119]. Older mother plants may be more susceptible [34]. Stress can also cause HLVd to express symptoms in previously asymptomatic plants (Transcript P.17).**
* **Impact on Yield/Quality: Resistance (or lack thereof) directly impacts yield quantity and quality by minimizing (or maximizing) damage and systemic infection [32, 33, 113]. HLVd can devastate crops (Transcript P.3, P.16-17).**

### 2. Cannabis Breeding and Genetics Parameters

**This section outlines the parameters governing the inheritance of traits, breeding methodologies, genetic management, and related analytical and simulation considerations within the Cannabis sativa L. breeding context. This is a core area for the simulation, driving strain development and player progression. Breeding for specific terpene profiles (e.g., "candy," "gas") and unique genetic expressions is a primary goal (Transcript P.152, P.172, P.187). The philosophy of finding "keepers" through pheno hunting is central (Transcript P.150, P.154).**

#### 2.1 Foundational Genetic Parameters

**Parameters defining the basic mechanisms of inheritance and genome structure in cannabis.**

* **2.1.1 Genome Structure**
  + **Ploidy Level: Diploid (2n=20) [1, 2]. Simulation models diploid genetics as default.**
  + **Chromosome Number: 9 pairs of autosomes and XY sex chromosomes [1, 2].**
  + **Genome Size: Approximately 818 Mb (XX) to 843 Mb (XY) [1]. Influences data for genomic analysis. Cannabis genome still being fully mapped (Transcript P.78).**
  + **Chloroplast Genome: Parameter for maternal lineage or plastid traits (e.g., Yunma 7 approx. 153,899 bp) [3].**
  + **Mitochondrial Genome: Parameter for specific research paths, less critical for core breeding [4].**
* **2.1.2 Inheritance Models**
  + **Mendelian Inheritance: For traits controlled by single genes with dominant/recessive or co-dominant alleles [5-8].**
    - **Alleles: Different forms of a gene.**
    - **Genotype: The genetic makeup (e.g., BB, Bb, bb).**
    - **Phenotype: Observable characteristics from genotype and environment (e.g., Silver Bud vs. Golden Bud) [1].**
    - **Homozygous: Two identical alleles (e.g., BB, bb) [2, 3].**
    - **Heterozygous: Two different alleles (e.g., Bb) [4].**
    - **Dominance: One allele masks another's effect [5, 19].**
    - **Recessiveness: The masked allele [5].**
    - **Co-dominance: Both alleles contribute to the phenotype [6].**
  + **Polygenic Inheritance: For traits controlled by multiple genes (e.g., yield, potency, flowering time, disease resistance) [6, 7, 9-11].**
    - **Quantitative Trait Loci (QTLs): Genomic regions influencing quantitative traits [6, 8-10, 12-17]. Simulation models cumulative effect.**
    - **Additive Gene Action/Effects: Multiple genes contribute cumulatively [8, 21].**
    - **Dominance Effects: Interactions between alleles at the same locus [8].**
    - **Epistasis: Interactions between genes at different loci influencing expression [6, 8-10, 18-20]. Crucial for complex traits.**
  + **Pleiotropy: A single gene/QTL affecting multiple traits [6, 9, 10, 18].**
  + **Gene Linkage: Genes close on the same chromosome are often inherited together [6, 8, 10].**
    - **Recombination/Crossing Over: Process shuffling genetic material; frequency depends on gene distance [8-10, 21, 22].**
    - **Genetic Maps: Represent gene order based on recombination frequency [8, 22].**
    - **Recombination Rate: Frequency of crossing over, influenced by genetic map distances (cM) [21, 22].**
  + **Mutation Rate: Spontaneous DNA sequence change introducing new variation [21, 23, 24]. Parameter for novel trait appearance.**
* **2.1.3 Genetic Variation and Population Genetics**
  + **Genetic Variation: Differences in DNA among individuals.**
  + **Allele Frequency: Proportion of a specific allele in a population.**
  + **Genetic Diversity: Total genetic characteristics in a species; maintaining it is a challenge [7, 11].**
  + **Genetic Erosion: Loss of genetic diversity [11].**
  + **Gene Flow: Transfer of genetic variation between populations [7].**
* **2.1.4 Sex Determination**
  + **XY System: Male (XY), Female (XX) as primary mechanism [1, 25, 26].**
  + **Environmental Influence on Sex Expression: Conditions like light leaks, temperature swings can lead to hermaphroditism [26] (Transcript P.158, P.171).**
  + **Genetic Influence on Sex Expression: Genes on sex chromosomes and autosomes [27]. Sex identification markers (PCR-based) used in reality [28-30]. Some strains have higher genetic predisposition to herm (e.g., Dante's Inferno #6, Transcript P.152).**
  + **Chemically Induced Reversal: Using agents like Silver Thiosulfate (STS) or colloidal silver to induce male flowers on female plants for feminized seed production (Transcript P.169). Pollen viability/sterility from induced males can vary (Transcript P.152).**
* **2.1.5 Genotype-by-Environment Interaction (GxE)**
  + **The effect of an environmental factor on phenotypic expression depends on the genotype [6, 7, 10, 12-14]. Critical for realism. (Transcript P.113, P.116, P.160-161, P.187, P.196, P.200-207).**
  + **Norm of Reaction: Range of phenotypes from one genotype across different environments.**
  + **Different strains perform differently under varying conditions (e.g., indoor vs. outdoor, different nutrient regimes, light spectra - HPS vs LED, specific LED brands like ThinkGrow vs Luxx, under canopy lighting) [15, 16] (Transcript P.113, P.116, P.160-161, P.202-207, P.225). Cold temperatures or "Fade" nutrients can induce purple coloration (Transcript P.14-15).**

#### 2.2 Trait Parameters (Specific to Cannabis)

**Parameters defining the heritable characteristics that breeding programs aim to manipulate.**

* **2.2.1 Agronomic Traits**
  + **Yield Components:**
    - **Flower Biomass (g/plant, g/m²) [11, 19, 22, 30, 31, 58-75]. Influenced by genetics and environment [31, 59]. Can range from low (Cookies, LCG - Transcript P.116, P.241) to high (2.5-4 lbs/light - Transcript P.116, P.204). Under canopy lighting can increase yield by 20-50% (Transcript P.225).**
    - **Bud Density (airy, medium, compact, "rock-hard" under LEDs (Transcript P.202)) [32, 72, 321, 324, 327].**
    - **Harvest Index (ratio of harvestable biomass to total biomass) [31].**
    - **Hash Yield (% return from fresh frozen or dry material). Varies significantly by strain. "Fade" nutrients increased hash yield by 1.3% absolute in one test (Transcript P.9). Some strains are bred/selected specifically as "washers."**
  + **Growth Habit/Architecture:**
    - **Plant Height/Stature (e.g., tall, medium, short, dwarfing) [32, 33, 34, 60, 64, 65, 67, 70, 74, 75, 106, 123, 144, 174, 185, 234, 248, 315, 317, 318, 321-328]. Stretch varies significantly (e.g., Sherb Banger 22: 4-week stretch, 12" to 5ft; Rainbow Belts/Zkittlez: short) (Transcript P.114-115).**
    - **Branching Pattern (e.g., apical dominant, lateral spread, balanced) [32, 42, 322, 329]. Some OGs have minimal lateral branching without topping (Transcript P.182-183). Untopped plants often develop a dominant main cola (Transcript P.183).**
    - **Leaf Morphology (leaflet number, shape, size, margin, color - e.g. black leaves with Fade (Transcript P.14)) [32, 321].**
  + **Flowering Time:**
    - **Photoperiod Response (short-day) [34, 35]. Requires specific light/dark cycle (e.g., 12/12, or 11/13 to push finish - Transcript P.115) [34, 36-38].**
    - **Days to Maturity (after flowering initiation) [2, 6, 25, 31, 33, 34, 37, 39, 40, 60, 63, 65, 66, 68-71, 73, 75, 90, 92, 93, 98, 100, 102, 106, 123, 131, 146, 162, 178, 185, 188, 189, 192, 194, 234, 235, 248, 250, 314-320]. Strain-dependent, from 7 weeks (Zkittlez crosses, Transcript P.115) to 10+ weeks (Hazes, OGs, Transcript P.115, P.169, P.308). Far-red light can shorten by a week+ (Transcript P.204).**
    - **Autoflowering (day-neutral) Trait [13, 25, 32, 35, 41, 42, 53-57]. Flowers based on age, not photoperiod [43, 53]. Controlled by ruderalis genes [13, 41]. Cannot be reverted [53].**
    - **Semi-Full-Term (Quicks): Hybrids flowering 2-3 weeks earlier [44].**
  + **Seed Production Traits:**
    - **Seed Yield (seeds per plant/flower) [31]. Can be 5,000 to 20,000+ per light (Transcript P.309).**
    - **Seed Maturity (timing, hardness, visual cues) [45, 106, 370].**
    - **Seed Viability (% germinating) [46, 47]. Influenced by genetics, storage, maturity. Old seeds may have poor germination (Transcript P.168).**
    - **Germination Rate (speed) [23, 34, 36, 41, 46, 48, 370]. Influenced by genetics, environment, media.**
    - **Seed Characteristics: Natural markings, stripes [23, 36, 41, 106, 370].**
  + **Stress Tolerance (Abiotic):**
    - **Drought Tolerance [49].**
    - **Heat Tolerance [49]. Some strains herm easily with temperature swings (Transcript P.158, P.171).**
    - **Salinity Tolerance [49]. Some strains sensitive to high EC (Runtz), others tolerant (Pie Hoe) (Transcript P.196).**
    - **Temperature Extremes Tolerance [49]. Cold can induce purple colors (Transcript P.14-15).**
    - **Nutrient Deficiency/Toxicity Tolerance [50-52]. Some strains are heavy feeders, others are sensitive (Transcript P.196).**
    - **Light Intensity Tolerance: Some strains sensitive to high PPFD (old Indicas, Transcript P.116).**
  + **Stress Tolerance (Biotic):**
    - **Pest Resistance/Tolerance (e.g., mites, thrips, aphids, fungus gnats) [11, 13, 19, 22, 25, 31, 49, 53, 54, 72, 92, 123, 316, 319, 329, 338-344]. Resistance Level (susceptible, moderate, resistant) [31].**
    - **Disease Resistance/Tolerance (e.g., powdery mildew, botrytis, fusarium, pythium, rust, blights, leaf spots, viruses, HLVd) [11, 13, 16, 19, 22, 25, 31, 49, 54-60, 72, 92, 123, 316, 319, 329, 338-344]. Specific resistance (e.g., Powdery Mildew Resist - Transcript P.79) [31, 319, 329, 343]. HLVd resistance varies; some asymptomatic carriers (Transcript P.17, P.80-81).**
  + **Nutrient Requirements/Use Efficiency (NUE): [19, 22, 31, 61, 62, 76, 345-360]. Strain-dependent [31, 358]. Influence on deficiency/toxicity symptoms [319, 348, 361]. OGs may prefer lower EC (Transcript P.196).**
  + **Water Use Efficiency (WUE): [61-63].**
  + **Recalcitrance to Tissue Culture/Regeneration: Genotype-dependent difficulty [64-69]. HLVd eradication via meristem TC varies by genotype (Transcript P.17-18, P.81).**
  + **Responses to Training Techniques (pruning, topping, LST): [70-72]. Influenced by genetics and growth stage [42, 322, 329]. Some growers prefer no topping (Transcript P.182-183, P.200). Defoliation strategy interacts with nutrient plans like "Fade" (Transcript P.12, P.15-16).**
  + **Root Development: Genetic influence on root structure and vigor [41, 44, 47, 321, 367-369]. Cloned plants have weaker, more lateral roots (Transcript P.32).**
  + **Environmental Adaptation: Suitability for specific environments (indoor, outdoor, greenhouse, climates, altitude) [2, 7, 10, 12, 16, 56, 57, 64, 65, 67, 70, 73-75, 106, 123, 144, 189, 234, 250, 315, 317-319, 322, 324, 325, 362-366]. Michigan's humidity and cold fall temps are challenging for out-of-state genetics (Transcript P.5-6).**
* **2.2.2 Chemotype Traits**
  + **Cannabinoid Profile: Concentrations (% Dry Weight or mg/plant) of major/minor cannabinoids and acidic forms [9, 10, 11, 15, 30, 31, 59, 62, 63, 73-89, 76-89].**
    - **THC/THCA Content: [1, 9, 15, 31, 32, 34, 40, 59, 64, 66, 68, 71-75, 77-81, 87-202]. Influenced by genetics (THCAS locus) [82], environment, maturity [83-85]. Ranges from 12% to 35%+ (Transcript P.13, P.170, P.187, P.197). Moisture content at testing is critical (Transcript P.12, P.22). "Fade" nutrients can increase THC (Transcript P.13).**
    - **CBD/CBDA Content: [1, 9, 15, 25, 31, 62, 63, 69, 73-75, 77, 79-86, 87-89, 121, 122, 129, 133, 136, 139, 143, 147, 149, 152, 154-162, 164-177, 189-192, 196-205]. Influenced by genetics (CBDAS locus) [82], environment, maturity [83-85].**
    - **CBG/CBGA Content: [15, 73-75, 77]. Precursor [73]. Influenced by genetics (CBGAS locus) [82], maturity [77]. CBGA-predominant chemotype [87, 88].**
    - **CBC/CBCA Content: [15, 73-75, 77]. Influenced by genetics (CBCAS locus) [82].**
    - **THCV/THCVA Content: [15, 73, 74, 77]. Propyl cannabinoid [89]. Influenced by genetics (e.g., stacking Apr alleles) [89].**
    - **CBDV/CBDVA Content: [15, 73, 74, 77]. Propyl cannabinoid [89].**
    - **CBN/CBNA Content: [73, 74, 77, 90]. Degradation product of THC/THCA [90]. Increases with oxidation, heat, aging [90].**
    - **Minor Cannabinoids (Delta-8/10 THC, HHC, THCP, THCB, etc.): [12, 31, 62, 73, 76-89, 206]. Potential for breeding for high levels [30, 83]. Delta-8 can be synthesized from CBD (Transcript P.279-281).**
    - **Cannabinoid Purity: Proportion of target cannabinoid relative to total [77]. Key for medicinal cultivars [76, 91].**
    - **Total Cannabinoids: Sum of quantified cannabinoids [77].**
  + **Terpene Profile: Concentrations and ratios of individual terpenes [9, 10, 15, 31, 62, 73, 75, 76, 77, 79-82, 85-89, 92, 203, 206-209]. Contributors to aroma, flavor, effects [73, 93, 94]. Influenced by genetics (TPS genes) [61], environment (e.g. "Fade" nutrients, Transcript P.8-9), maturity, drying/curing (Transcript P.179, P.298-299) [75, 94].**
    - **Major/Individual Terpenes: Myrcene, Limonene, Caryophyllene, Pinene, Ocimene, Terpinolene, Humulene, Linalool, Bisabolol, Nerolidol, Geraniol, etc. [73, 76, 81, 207-209].**
    - **Minor Terpenes [73].**
    - **Total Terpenes. "Yield dilution" can reduce total terps if biomass is pushed too hard (Transcript P.62).**
    - **Terpene Ratios [76, 81].**
  + **Aroma and Flavor Descriptors: (e.g., citrus, pine, fuel, earthy, skunky, sweet, spicy, cheese, fruity, "candy" (Transcript P.152, P.172), "gas" (Transcript P.187)) [16, 30, 31, 40, 55, 66, 67, 71, 75, 79-81, 86, 93-103, 105, 107, 111, 113, 115-119, 121, 122, 125, 127-131, 133, 136, 137, 140, 142-151, 153-155, 157-160, 162, 163, 165-179, 181-203, 205-281]. Linked to terpene profiles. Market preference for unique profiles (Transcript P.152, P.170, P.192).**
  + **Flavonoid Content: Contribution to pigmentation (anthocyanins for purples, Transcript P.14-15) and other effects [96, 97].**
  + **Volatile Sulfur Compound (VSC) Content: Contribution to pungent notes ("gas," "skunk") [96].**
  + **Decarboxylation Profile: How readily cannabinoid acids convert to neutral cannabinoids [76-78, 87-89].**
* **2.2.3 Visual/Morphological Quality Traits (Bag Appeal)**
  + **Bud Appearance: Overall shape (e.g., "golf balls" Transcript P.181), trim quality [31, 59, 98-100, 107, 140, 176, 189, 220, 267, 277, 314].**
  + **Bud Density: (airy, medium, compact, "rock-hard" under LEDs Transcript P.202).**
  + **Bud Color: (e.g., green, purple, orange hues) [67, 98, 107, 113, 123, 140, 189, 194, 247, 249, 262, 264, 265, 314, 317, 318, 332]. Often influenced by genetics and temperature (cold for purples, Transcript P.14-15) or "Fade" nutrients (Transcript P.14).**
  + **Trichome Density/Coverage ("frostiness") [34, 49, 55, 59, 66, 71, 75, 93, 101-104, 134, 137, 158, 220, 233, 267, 280, 318, 321, 332-337]. Athena Stack can visually increase (Transcript P.160).**
  + **Trichome Color/Appearance: Clear to milky to amber as maturity indicator [90, 98, 105-109]. Differentiated by fluorescence [107, 110, 111]. Important for hash making timing (Transcript P.197).**
  + **Trichome Characteristics: Type, size [34, 49, 55, 59, 66, 71, 75, 93, 134, 137, 158, 220, 233, 267, 280, 318, 321, 332-337].**
  + **Pistil Color (Mature): Orange-red, pink-purple, brown [90, 98, 105, 220, 321]. Indicator of maturity.**
  + **Leaf-to-Calyx Ratio: Influences trim efficiency [98, 112].**
* **2.2.4 Effect Profile & Other Traits**
  + **Effect Profile: Psychoactive, physical, therapeutic effects [25, 34, 36, 40, 55, 63-66, 68-72, 75, 90, 93-105, 107-110, 112-115, 117, 118, 120-122, 125-137, 139-151, 153-203, 205, 206, 211, 212, 222, 223, 226, 229, 230, 232, 233, 235-246, 248-258, 260-313]. Linked to cannabinoid/terpene profiles (entourage effect) [93, 114]. Categories like "creative focus," "relaxation," "energy" [115, 116, 282, 293]. Market preference shifting from pure THC to overall experience/terps (Transcript P.170, P.192, P.197, P.239).**
  + **Uniformity and Stability: How consistently a trait is expressed [11, 17, 19, 20, 24, 25, 30, 31, 68, 75, 92, 106, 123, 316, 330, 331]. Important for reliable product.**
  + **Sex Expression Tendency: Dioecy, monoecy, hermaphroditism [23, 321]. Genetic predisposition to herm under stress (Dante's Inferno #6, Transcript P.152). Ability to induce for breeding (STS, Transcript P.169) [30, 321].**
  + **Other Morphological Traits: Stem color (e.g., purple stems) [17], foxtailing (genetic in some strains, Transcript P.120) [119, 135, 148, 295, 318, 321].**
  + **Biostimulant/Microbial Response: Genetic variability in response [346].**
  + **Water Activity: For storage and mold prevention [117].**
  + **Shelf Life/Stability: Preservation of cannabinoids/terpenes. Affected by drying/curing (Transcript P.179, P.298-299).**
  + **Nutritional Content (Seeds): Protein, oil, phenolic compounds [119, 120].**

#### 2.3 Breeding Methodologies and Processes Parameters

**Parameters defining the techniques and strategies used to create and manage new cannabis varieties. Breeding philosophy: MHigh Dave emphasizes finding unique terpene profiles and not just chasing hype (Transcript P.150-152); Bean Fiends emphasizes thorough testing before release (Transcript P.187).**

* **2.3.1 Parent Selection**
  + **Based on desired traits (e.g., unique terpenes, vigor, structure, resistance) [5, 7, 10, 17, 45, 132, 135, 142, 176, 202]. (Transcript P.151-152, P.170-171).**
  + **Phenotypic Selection: Based on observable traits [5, 7, 17-20, 127, 145, 173-176]. Critical in pheno hunts.**
  + **Genotypic Selection: Based on genetic information (e.g., from DNA fingerprinting or marker analysis).**
  + **Marker-Assisted Selection (MAS): Using genetic markers linked to traits [7, 8, 11, 13, 16, 21, 22, 131, 198, 203, 225-227]. (e.g., for HLVd resistance, PM resistance genes, Transcript P.79).**
  + **Genomic Selection (GS): Using genome-wide markers to predict breeding value [7, 8, 10, 11, 13, 16, 18, 198, 203, 225, 226, 229]. Higher tier [7, 22].**
  + **Optimal Contribution Selection: Maximize genetic gain, minimize inbreeding [7].**
  + **Male Selection: Crucial. Structure, vigor, stem rubs for aroma, and ultimately, progeny testing (performance of offspring) are key (Symbiotic, Transcript P.170-171).**
* **2.3.2 Mating Designs and Sexual Reproduction**
  + **Generations: Tracking P, F1, F2, F3+ [132, 151-155]. F1s for diversity, later generations for stabilization (Transcript P.168, P.188, P.319).**
  + **Manual Pollination: Player identifies plants, collects/applies pollen [5, 23, 135-137, 145, 146]. Shaking males in a room with females (Symbiotic, Transcript P.170).**
    - **Pollen Collection Rate: Amount of viable pollen [137]. Some reversed females produce little or delayed pollen (Transcript P.169-170).**
    - **Pollination Success Rate: Probability of seed set [47, 147].**
    - **Controlled Environment: Isolated breeding spaces to prevent unwanted pollination [23, 42, 146, 148, 149].**
  + **Natural/Open Pollination: Pollen drift distance parameter [23, 42, 145, 147-150].**
  + **Controlled Crosses: Manually pollinating specific plants [23]. (e.g., Bean Fiends x Symbiotic collabs, Transcript P.318).**
  + **Reciprocal Crosses: A x B and B x A to assess maternal effects [7].**
  + **Diallel Crosses: All possible crosses between a set of parents [7]. For general/specific combining ability.**
* **2.3.3 Asexual Reproduction (Propagation for Preserving Genetics)**
  + **Cloning (Vegetative Cuttings): Genetically identical copies from mother plant [4, 5, 19, 31, 38, 42-48, 121, 133, 156-160]. Preserves phenotype/genotype [19, 31, 38, 49, 138, 163-166]. Standard practice for maintaining "keepers."**
    - **Cutting Success Rate: [133, 159]. Influenced by technique, hormones, environment, mother plant health, genetics [133, 159, 160]. Some strains are hard to clone.**
    - **Rooting Time: [160-162]. Influenced similarly [159, 160].**
    - **Mother Plant Maintenance: Keeping plants in vegetative state [4, 19, 31, 45, 47, 121, 133, 156, 159, 160]. Regular refresh of moms is good practice (e.g., every 6-8 weeks, Transcript P.183). Older moms can decline or accumulate pathogens (Transcript P.34, P.183).**
    - **Cloning from Flowering Plants: Possible, may take longer [157, 162].**
    - **Genetic Stability: Clones are identical; phenotypic differences due to GxE [5, 138, 163-167].**
    - **Clonal Rejuvenation: Tissue culture to restore vigor or clean pathogens [168] (Transcript P.17-18).**
  + **Tissue Culture/Micropropagation: Advanced sterile lab technique [6, 33, 43, 50-52, 56, 59, 64, 66, 138, 165, 169-171].**
    - **Protocol Success Rate: For initiation, multiplication, rooting, acclimatization [56, 69, 138]. Genotype-dependent [33, 56, 67, 69].**
    - **Pathogen Eradication (Meristem Culture): [33, 50, 51, 56, 59, 67, 138]. Especially for HLVd (Transcript P.17-18, P.81). Success varies by genotype and lab skill. Can take multiple attempts (Transcript P.17-18).**
    - **Regeneration Capability: From explants (nodal segments, callus, protoplasts) [64, 67, 68, 138]. Protoplast regeneration is a bottleneck [68].**
    - **Genetic Stability: Assessed with markers (e.g., ISSR) [138, 163, 165]. Generally stable.**
    - **Equipment and Sterile Technique: Required (Laminar flow hood, autoclave, microscope) [169, 170, 172] (Transcript P.18-19). Cost can be $5k-$50k for a lab (Transcript P.18-20).**
    - **Benefits: Cleaning genetics, long-term storage/archiving of genetic libraries, rapid multiplication (Transcript P.17-22).**
* **2.3.4 Population Development and Breeding Strategies/Schemes**
  + **Selective Breeding (Phenotype Selection): [5, 127, 145, 173-176]. Traditional, slower [173]. Still the primary method in pheno hunts (Transcript P.150-155).**
  + **Crossbreeding & Hybridization: Creating hybrids from distinct parents [6, 20, 135, 147, 173, 176, 177]. Creates new combinations, hybrid vigor [6, 20, 173]. (e.g., Symbiotic crossing Purple Punch male with various elite females, Transcript P.167).**
  + **Population Types:**
    - **F1 Hybrid: First generation from distinct parents [5, 11, 19, 25, 30-32, 136, 152, 155, 183, 186, 187]. Often exhibit heterosis. Uniform if parents stable. High diversity for pheno hunting (Transcript P.168, P.188).**
    - **F2 Population: From selfing/intercrossing F1s; segregation occurs [4, 5]. Can reveal recessive traits.**
    - **Recombinant Inbred Lines (RILs): From repeated selfing of F2 individuals [7]. For mapping/gene interaction studies.**
    - **Backcross Populations (BC1, BC2, etc.): [4, 24, 25, 29]. Used to introgress specific traits (Transcript P.319-320, TH Seeds explanation).**
    - **Synthetic Varieties: Intercrossing parental lines, random mating [7].**
    - **Diversity Panels: For association mapping [128].**
  + **Developing True-Breeding Lines (Inbred Lines - IBLs): Mating related individuals for homozygosity/stability [2, 3, 6, 10, 11, 16, 17, 19, 20, 24-27, 30, 31, 34, 136, 151, 153, 178-182]. Breed true [2-4, 29, 151, 180, 182]. Requires many generations [2]. Working lines to F4/F5 for stability (TH Seeds, Transcript P.320).**
    - **Inbreeding: Essential for stable lines [9, 10].**
    - **Inbreeding Depression: Reduced vigor/fertility from deleterious recessives [6, 144, 178, 183, 184].**
    - **Managing Inbreeding: Population size, new genetics, nucleus breeding [144, 178, 185].**
  + **Backcrossing (BX): Crossing hybrid to recurrent parent to transfer specific trait [4, 6, 7, 18, 24-29, 136, 151, 152, 178, 181, 183, 188, 189]. Percentage of recurrent parent genome increases each generation [183, 189]. Used to reinforce traits of a mother plant using new male offspring (TH Seeds, Transcript P.319-320).**
  + **Self-Pollination (Selfing, S1): Crossing plant with itself [6, 18, 190, 191]. Increases homozygosity. Induced chemically [1, 25, 41]. Used to create S1s of elite cuts (e.g., Tear Gas S1, Transcript P.188) for preservation or finding similar phenos.**
  + **Stabilization: Reducing genetic variation for consistent trait expression [2, 11, 19, 20, 24-27, 30, 31, 34]. Goal of many breeding programs.**
  + **Phenotype Hunting (Pheno Hunting): Growing populations (e.g., 100s-1000s of seeds) to identify desirable individuals [6, 11, 35, 202, 204, 205]. (MHigh Dave 400 seeds, Transcript P.154; Highline 5k-10k seeds/year, Transcript P.238). Requires meticulous observation and record keeping. Taking cuts of all plants before flower is a common SOP (Transcript P.154).**
  + **Seed Production Methods:**
    - **Seeds: Generative propagation, introduces variation unless stable lines [23, 31, 36-41].**
    - **Feminized Seeds: Using induced female pollen (from STS/colloidal silver treatment (Transcript P.169)) on females for all-female offspring [25, 31, 41, 192]. Risk of hermaphroditism if unstable genetics [148, 192, 193]. European market demand is high (Transcript P.170). Some reversed females are poor pollen producers or pollen is delayed (Transcript P.169-170).**
    - **Autoflowering Genetics: Breeding with C. ruderalis [53-57].**
    - **Triploid Seeds: Crossing tetraploid (4x) with diploid (2x) for sterile triploid (3x) offspring [11, 150, 194, 195]. Prevents seeding. May have distinct morphology/aromas, not necessarily higher potency [196]. More variation if parents not homozygous [197]. (Post-MVP)**
    - **Developing Semi-Full-Term Varieties (Quicks): Crossing autoflowering and photoperiod parents [44].**
  + **Doubled Haploids (DHs): Homozygous lines in one generation from haploid cells [18, 33, 138, 139]. Accelerates breeding.**
* **2.3.5 Breeding Program Management**
  + **Breeding Goals/Objectives: Defining desired traits (e.g., unique terps, yield, disease resistance, market trends like "candy" or "gas") [198-201] (Transcript P.151-152, P.172, P.187).**
  + **Record Keeping: Pedigree, phenotype, genotype, stock inventory [121, 152, 207]. Crucial for tracking selections.**
  + **Data Collection: Meticulous recording of observations during pheno hunts [45, 121, 134, 202, 206].**
  + **Selection Intensity: Proportion of individuals selected (e.g., finding 9 keepers from 231 seeds - Coffin Candy hunt, Transcript P.305).**
  + **Breeding Cycle/Generation Time: [18, 208, 209]. From seed to tested selection can take a year or more (MHigh Dave, Transcript P.154). Seed production itself is 3-4 months plus testing (Symbiotic, Transcript P.168).**
  + **Resource Constraints: Space (veg space for holding cuts during pheno hunt is critical, Transcript P.186), labor, budget [64, 65, 202, 208, 232, 244]. Pheno hunts are expensive (MHigh Dave $10k-$15k on seeds, Transcript P.150, P.154).**
  + **Testing: Sending selections to multiple testers in varied environments for feedback before release (TH Seeds, Transcript P.320).**

#### 2.4 Genetic Resource Management Parameters

**Parameters related to acquiring, storing, and managing genetic material.**

* **2.4.1 Germplasm Acquisition**
  + **Source: Landraces (diverse, locale-adapted, unique alleles, risk of erosion) [14, 20, 49, 50, 121-127], Feral populations [49, 50], Heirloom varieties [82], Modern cultivars (elite cuts from other breeders/growers, Transcript P.1, P.163, P.165) [14, 122], Breeder collections [128].**
  + **Access Restrictions: Legal/regulatory hurdles [64, 129-131]. DEA rescheduling has eased shipping of seeds and <0.3% THC cuttings (Transcript P.1-2, P.276-277).**
  + **Acquisition Methods: Expeditions, NPC contacts, quests, vendors (e.g., Clone America, Transcript P.1), events [6]. Direct trades/purchases between growers.**
  + **Origin Dossier/Acquisition Report: Source and characteristics info [6]. Verifying authenticity of acquired cuts is a challenge (HLVd risk, mislabeling).**
* **2.4.2 Genetic Material Storage**
  + **Seed Bank: Long-term seed storage [47, 50, 121, 132, 133]. Keeping extensive seed libraries (Highline 5-10k seeds/year hunts, Transcript P.238).**
    - **Storage Conditions: Temperature (-20°C), humidity influence viability [121].**
    - **Inventory Management: Tracking lots, parentage, generation, traits [121, 132-134].**
  + **Pollen Inventory: Storage of collected pollen [132, 135-137]. Fresh pollen preferred by some (Symbiotic, Transcript P.170).**
    - **Storage Conditions: Temperature, humidity influence viability [132]. Freezer storage with desiccant.**
    - **Viability Degradation Rate: Decreases over time [132].**
  + **Tissue Culture Inventory: In vitro storage for preserving "keepers" and mother stock [69, 132, 138] (Transcript P.21-22).**
    - **Storage Methods: Slow growth (short-medium term), Cryopreservation (long-term) [69, 138, 139]. Influence stability/viability [69].**
    - **Passage Number: Subculture count, can influence stability [138].**
    - **Benefit: Massive space saving for large genetic libraries (Jungle Boys 400-500 strains in TC vs. traditional moms, Transcript P.21).**
* **2.4.3 Germplasm Conservation**
  + **Importance: Preserving genetic diversity for future breeding/resilience [20, 49, 50, 124, 127, 134, 140-142]. Preventing loss of valuable cuts (Craft Farmer, Transcript P.21).**
  + **Methods: Genebanks (ex situ via TC or seed banks) [69, 121, 124, 125, 138, 140, 143], On-farm conservation (in situ - maintaining mother plants) [140, 143], Documentation of traditional knowledge [124, 140].**
  + **Effective Population Size (Ne): Maintaining large Ne to slow inbreeding/drift [125, 144].**

#### 2.5 Genetic Analysis and Advanced Breeding Technologies Parameters

**Parameters defining tools for understanding and manipulating genetics at a deeper level.**

* **2.5.1 Genetic Analysis**
  + **DNA Extraction: Obtaining genetic material [210]. (Leaf samples for HLVd/fingerprinting, Transcript P.81, P.332).**
  + **Molecular Markers: Specific DNA sequences (SNPs, SSRs/STRs, ISSRs) for identification/tracking [8, 13, 16, 17, 51, 122, 131, 203, 210, 211].**
    - **STR Analysis: For DNA fingerprinting, relatedness [210-212].**
    - **SNP Analysis: For high-density genotyping, association mapping [13, 16, 17, 121, 122, 203].**
  + **Genotyping: Determining genetic makeup [17, 121, 131, 203, 213].**
  + **Sequencing (DNA/RNA): Determining nucleotide order [14, 16, 17, 121, 122, 130, 214-218]. Cannabis genome still being fully mapped (Transcript P.78).**
    - **Whole Genome Sequencing (WGS) [213, 216].**
    - **Genotyping-by-Sequencing (GBS) [121, 213].**
    - **RNA Sequencing (RNA-seq) for transcriptomics (gene expression) [14, 214, 218-221].**
  + **Bioinformatics Pipelines: Tools for processing and analyzing large genetic/omics datasets [6, 16, 131, 206, 362, 372].**
  + **Genetic Mapping: Determining relative positions of genes/markers [14, 17, 21, 213].**
  + **Association Mapping (GWAS/mGWAS): Identifying genomic regions/genes associated with traits [14, 15, 19, 121, 213, 222, 223]. mGWAS links variation to metabolite profiles [222]. (e.g., finding genes for PM resistance, Transcript P.79).**
  + **QTL Mapping: Identifying QTLs in biparental populations [12, 14-16, 128, 213, 223].**
  + **Parentage Testing: Confirming parentage [210].**
  + **Strain Identification/Authentication: Genetic fingerprinting to verify cultivars (MyFloraDNA CCI, Transcript P.331-334) [82, 134, 224]. Helps combat renaming and ensures consumers get authentic genetics.**
  + **Hemp vs. Drug-Type Differentiation: Genetic/chemical tests [75, 224]. Based on Δ⁹-THC content (Transcript P.2, P.276-277).**
  + **Population Structure and Diversity Analysis: Understanding genetic relationships/diversity [7, 10, 11, 12, 21, 122, 141, 144, 233, 362, 372].**
  + **Fine Mapping and Causal Gene Validation: Identifying specific genes/polymorphisms [21].**
  + **Pathogen Testing: PCR-based tests for HLVd (Tumi Genomics, MyFloraDNA, Transcript P.77, P.81-84, P.327), Fusarium (Transcript P.84), and other viruses/fungi. Importance of regular testing of mother stock (Transcript P.82). Sample pooling for cost efficiency in large scale testing (Transcript P.17).**
  + **Transcriptomics and Proteomics: Studying gene expression and protein production [21, 214, 218-221, 347].**
  + **Metabolomics: Comprehensive analysis of metabolites [12, 21, 79-81, 85, 87-89, 222, 347].**
  + **Epigenetics: Heritable gene expression changes without DNA sequence changes [12, 371].**
* **2.5.2 Advanced Breeding Technologies**
  + **Marker-Assisted Selection (MAS): (Covered in 2.3.1, fundamental to advanced breeding strategies).**
  + **Genomic Selection (GS): (Covered in 2.3.1, fundamental to advanced breeding strategies).**
  + **Genomic Prediction Accuracy: Parameter defining how accurately genetic merit is predicted [7, 9, 10].**
  + **Gene/Genome Editing (CRISPR/Cas9): Precise gene modification [6, 14, 16, 21, 66, 84, 198, 203, 225, 230, 231]. Potential for targeted trait modification (e.g., PM resistance, Transcript P.79) [16, 84, 230]. Requires efficient transformation/regeneration [224]. Subject to regulations [16, 50, 65].**
  + **Genetic Transformation (Introducing foreign DNA): [6, 16, 64, 138].**
  + **Somatic Hybridization (Protoplast Fusion): Fusing cells to create hybrid [68, 138, 139]. Regeneration is a bottleneck [68].**
  + **Doubled Haploid (DH) Production: (Covered in 2.3.4).**
  + **Speed Breeding: Shortening generation time [18, 232].**
  + **Consensus Genetic Maps/Reference Genomes: Integrated data for comprehensive resources [372].**
* **2.5.3 AI Research Lab (In-Game Concept)**
  + **Probabilistic Predictions: For breeding outcomes based on genetic data/AI models [6, 11].**
  + **Genetic Marker Analysis (Simplified): Abstracted MAS/GS for early seedling selection [6, 11, 170, 228].**
  + **AI Model Complexity: Potential for complex models (e.g., small neural networks) [6].**

#### 2.6 Genetic Simulation Parameters (Game Engine Specific)

**Parameters specific to modeling genetic inheritance and population dynamics within the game.**

* **Trait Heritability (h²): Proportion of phenotypic variation due to additive genetic effects [21, 208, 233]. Influences selection effectiveness.**
* **Genetic Correlation: Degree to which two traits are influenced by the same genes [21, 208].**
* **Breeding Value (BV) / Genomic Estimated Breeding Value (GEBV): Estimated genetic merit [208, 229, 233].**
* **Allele Frequencies: Proportion of a specific allele in a population [21, 102, 103, 233, 234].**
* **Linkage Disequilibrium (LD): Non-random association of alleles at different loci [208, 233, 234].**
* **Inbreeding Coefficient (F): Probability of homozygosity by descent [233, 234].**
* **Genetic Diversity Metrics: Quantifying genetic variation (e.g., heterozygosity, alleles per locus, Ne) [122, 141, 144, 233].**
* **Genotype x Environment Interaction (GxE) Modeling: Parameters for how genotypes respond to environmental variations (light, temp, nutrients) [9, 21, 52, 70, 167, 208, 224, 235-238]. (Transcript passim).**
* **Burn-in Phase (Simulated Historical Breeding): Modeling historical selection to create realistic starting LD and diversity [234].**

#### 2.7 Data Management and Visualization Parameters (In-Game)

**Parameters related to handling and displaying genetic and breeding data within the simulation.**

* **Breeding Database: Centralized system for pedigree, phenotype, genotype, environmental, trial metadata [121, 129]. Tracking selections from large pheno hunts (Transcript P.154, P.238).**
* **Trait Library: Player-populated database of known traits and associated markers/genotypes [6, 228].**
* **Pedigree Tracking: Visualizing and managing family trees [6, 134, 152, 239].**
* **Genetic Data Display: Presenting simulated genotype ID, alleles, markers, linked to traits [203, 228, 240]. Displaying CCI from MyFloraDNA (Transcript P.331-332).**
* **Phenotype Observation Data: Recording visual/measured characteristics [5, 202, 241]. Linking observed traits to genetics [5, 241].**
* **Breeding Interface: UI for parent selection, crosses, project management, outcome prediction [118, 132, 203, 228, 239].**
* **Data Visualization: Tables, charts, graphs, visual overlays on plant models [70, 118, 134, 203, 228, 240, 241].**
* **Workflow Management: Tools for outlining/tracking breeding program steps [209, 239]. Managing multiple ongoing hunts and breeding lines.**

#### 2.8 Challenges and Risks Parameters (In-Game)

**Parameters representing potential difficulties and failures in breeding and genetic work.**

* **2.8.1 Biological Challenges**
  + **Tissue Culture Recalcitrance: Genotype-dependent regeneration difficulty [65, 67, 69]. Some strains are very difficult to clean via TC (Transcript P.17-18).**
  + **Genetic Instability: Somaclonal variation, inbreeding depression [138, 144, 163, 178, 183, 184]. Hermaphroditism in feminized lines or due to stress (Transcript P.152, P.169-171).**
  + **Disease/Pest Transmission: Through cloning (HLVd is notorious, Transcript P.17, P.80) or seed (HLVd in seeds being studied, Transcript P.17, P.81) [56, 59, 157, 242].**
  + **Poor Germination: Old seeds or bad genetics (Transcript P.168).**
  + **Low Pollen Production/Viability: In some males or reversed females (Transcript P.152, P.169-170).**
* **2.8.2 Technical Challenges**
  + **Phenotyping Bottlenecks: Difficulty in accurate, high-throughput data collection for large hunts [118, 243]. Subjectivity in selection.**
  + **Data Integration and Management Complexity [19, 129].**
  + **Modeling Complexity: Simulating epistasis, dominance accurately [19].**
  + **HLVd Testing Inconsistencies: Different labs, sample times, or locations within plant can give varied results (Transcript P.17, P.81-82).**
* **2.8.3 Legal and Regulatory Obstacles (Abstracted)**
  + **Licensing, permit requirements for research/access to genetics [16, 21, 50, 64, 66, 129, 130, 227, 243]. Evolving DEA rules on shipping genetics (Transcript P.1-2).**
  + **Banking challenges for cannabis businesses, including seed sales (Transcript P.2).**
* **2.8.4 Resource Constraints**
  + **Limited budget (pheno hunts are expensive - seeds, space, labor, testing, Transcript P.150, P.154), space, equipment, skilled personnel [64, 65, 202, 208, 232, 244].**
* **2.8.5 Ethical Considerations (Abstracted)**
  + **Impacts on genetic diversity, IP (importance of DNA fingerprinting, Transcript P.331-334), access to genetics/technology [140, 142, 245-248]. Misappropriation of genetics/renaming (Transcript P.154, P.313).**
* **2.8.6 Unforeseen Outcomes**
  + **Unexpected trait combinations from recombination/complex interactions [6, 46, 103, 180]. Not all traits fully predictable. Finding no keepers in a large hunt (MHigh Dave, Transcript P.154).**

## Comprehensive Simulation Parameters for Project Chimera

**This document outlines potential parameters for the simulation mechanics of Project Chimera, drawing upon extensive research into Cannabis sativa L. biology, cultivation, genetics, and industry practices, significantly enhanced with details from cultivator discussions as recorded in "transcriptss.pdf" (hereafter cited as "Transcript P.[PageNumber]").**

### 1. Cannabis Biology and Characteristics Parameters (Part 1: Botanical & Chemical)

**This section details fundamental biological parameters of the Cannabis sativa L. plant, its morphology, chemistry, and inherent characteristics related to its interaction with the environment and biological threats.**

#### 1.1 Botanical Features Parameters

**Parameters defining the physical structure, classification, and life cycle stages of the cannabis plant.**

* **Taxonomy and Classification:**
  + **Species: *Cannabis sativa L.* [1]**
  + **Subspecies/Varieties: *sativa*, *indica*, *ruderalis*.**
    - **Note: Traditional classifications may not correlate perfectly with genetic structure [2, 3]. Cultivator experience suggests that even within these, traits like stretch and nutrient preference can vary significantly (Transcript P.114, P.196). For example, some OG cuts have minimal lateral branching (Transcript P.182-183).**
  + **Hemp vs. Drug-type distinction: Based on THC content (e.g., <0.3% Δ⁹-THC for hemp) [1]. This is a critical botanical and regulatory parameter [1] (Transcript P.2, P.276-277).**
    - **Range: % Δ⁹-THC can range from negligible (<0.1%) in some hemp varieties to over 30% in high-potency drug-type cultivars [4-6]. Some cultivars test around 15-19% THC, while others can reach 28-35% THC (Transcript P.187, P.197). THCA flower is also a market factor under hemp regulations (Transcript P.276-279).**
  + **Chemovars: Classification based on cannabinoid profile [7, 8] (e.g., Type I: THC-dominant, Type II: THC/CBD mixed, Type III: CBD-dominant, Type IV: CBG-dominant, Type V: negligible cannabinoids) [2].**
    - **Game should support differentiation based on chemical profile rather than just traditional labels [2]. Consumer markets show preferences for different profiles; e.g., some European markets value specific terpene expressions over pure THC content (Transcript P.192).**
* **Morphology: Parameters defining the physical structure and form of the plant.**
  + **Plant Height: Potential range (e.g., 0.2m to >12m cultivated) [1]. Influenced by genetics and environment [1].**
    - **Hemp types tend to be taller and less branched, drug-types bushier [1, 9].**
    - **Range: Dwarf varieties can be 0.2m [1]. Fiber hemp can exceed 12m [1].**
    - **Drug types typically range from 0.5m to over 3m. Some strains can stretch significantly, e.g., a 12-inch plant stretching to 5 feet (Transcript P.114). Sherb Banger 22 known for a 4-week stretch period (Transcript P.114-115).**
  + **Stem Structure: Erect, furrows, branching patterns, woody interior, hollow internodes [1].**
    - **Stem diameter can range from 1-3cm in mature plants, influenced by genetics and vigor [13].**
    - **Base can become very big and thick [14].**
    - **Branching Pattern: Influenced by genetics and environment (e.g., apical dominant, lateral spread, balanced) [15]. Sativa-like strains tend to have more lateral branching. Some OG cuts show minimal lateral branching without topping (Transcript P.182-183). HLVd infection can cause abnormal, horizontal branching (Transcript P.80).**
    - **Sativas tend to have more lanky branches, Indicas more compact [16-18].**
  + **Leaf Morphology: Compound leaves with leaflets radiating from the petiole end [1].**
    - **Leaflet Number: Number of leaflets (e.g., 3-13) [1].**
    - **Developmental sequence: 1 (seedlings/stressed), 3, 5, 7, 9, then potentially more (up to 13+) on robust mature plants, decreasing later [19].**
    - **Leaflet Shape: Lanceolate, ovoid, oblanceolate [1]. Influenced by genetics (e.g., broad in Indica types, narrow in Sativa types) [19].**
    - **Serrated margins [1].**
    - **Leaf Size: Broad (Indica) vs. long/slender (Sativa) [19].**
    - **Changes throughout lifecycle, peaking around the 12th node [19].**
    - **Leaf Angle/Droop: Angle relative to stem, turgidity.**
      * **Heavily influenced by hydration (underwatered-drooping) [13, 20]. Genetics may influence baseline angle [13]. Hybrids show a spectrum [13]. HLVd may cause leaves to curl or appear malformed (Transcript P.80).**
    - **Diagnostic Leaf Venation [1].**
  + **Leaf Arrangement: Opposite (lower nodes) to alternate (main stem) [1, 19].**
    - **Phyllotaxy shift typically occurs around the 12th node [19].**
  + **Bud/Flower Structure: Shape (e.g., conical, spear, round, "golf balls" (Transcript P.181), foxtail), density (airy, medium, compact, "rock-hard" under LEDs (Transcript P.202)), leaf-to-calyx ratio [15].**
    - **Indica types tend to have dense, compact buds, Sativa types longer, airy buds [11, 16].**
    - **Foxtailing can occur, sometimes accelerating towards harvest [21]. Some strains exhibit foxtailing as a genetic trait, not necessarily negative (Transcript P.120).**
    - **HLVd can cause "dudding" or significantly reduced bud development and trichome production (Transcript P.80, P.171).**
  + **Pistil Color (Mature): Colors such as orange-red, pink-purple, brown [15].**
  + **Trichome Density: Potential levels (low, medium, high) [15].**
    - **A key visual quality indicator (frostiness, resin) [15, 22, 23]. Influenced by genetics and environment [15, 24, 25]. Some strains are known for high resin production suitable for hash (Transcript P.9, P.21).**
    - **Can vary dramatically between strains [24]. Use of products like Athena Stack can visually increase trichome production (Transcript P.160).**
  + **Trichome Appearance: Transition in color (clear to milky to brown/amber) indicates maturity [15, 22, 26].**
    - **Visual cues for resin and ripeness [15, 22, 26]. Trichomes contain cannabinoids [24]. For hash production, plants might be harvested earlier when trichomes are optimal for separation (e.g., day 40 for a 70-day flower strain) (Transcript P.197).**
  + **Trichome Degradation: Can be induced by experiments [27]. Poor storage can lead to reduced trichome vibrancy [28, 29]. Improper drying/curing can lead to terpene loss (Transcript P.179).**
  + **Root System: Adaptable taproot with lateral branching [1].**
    - **Can reach up to 2.5m deep in soil depending on soil/water [1, 30].**
    - **Root health and development influenced by growing media [30, 31]. HLVd can be present in roots (Transcript P.83). Fusarium also infects through roots (Transcript P.84).**
    - **Plants from seed have a strong, deep taproot; cloned plants typically have weaker, more lateral, not as deep roots [32].**
    - **Rootbound plants stress plant if left untreated [33].**
    - **Root restriction (small containers) stunts growth, limits nutrient/water uptake, alters structure [30, 34, 35]. Smaller pots (e.g., 1-2 gallons) preferred by some for more control with frequent irrigations (Transcript P.127).**
  + **Visual Representation: Potential for root system visualization showing medium, water, nutrient response [36].**
  + **Fruit (Achene)/Seed: <3.8mm length, often in persistent perianth (mottled/marbled) [1]. Seed production can yield 5,000 to over 20,000 seeds per light depending on cultivation methods and nutrient lines (Transcript P.309). Shipping seeds is generally legal (DEA rescheduled, Transcript P.2), but banking for seed sales can be problematic (Transcript P.2). Cuttings/clones shipping legality is evolving, based on <0.3% THC in the cutting itself (Transcript P.1-2, P.276-277).**
* **Sex Determination:**
  + **Predominantly dioecious (separate male (XY)/female (XX) plants) [1, 37]. Females are valued for cannabinoids in inflorescences [37].**
  + **Monoecious/Hermaphroditic forms: Can occur naturally (stress-induced, e.g., light leaks, temperature swings (Transcript P.158, P.171)) or be chemically induced (e.g., silver thiosulfate, STS (Transcript P.169)) for breeding [37].**
    - **Hermaphroditism involves producing both male and female flowers on the same plant, leading to "seeded" crops [38, 39]. Some strains have a higher genetic predisposition to herm under stress (e.g., Dante's Inferno #6) (Transcript P.152). Sterility of pollen from hermaphroditic plants can vary (Transcript P.152).**
* **Growth Stages:**
  + **Germination: First physiological stage [40].**
    - **Requires proper medium temperature (8-10°C average daily minimum for outdoor sowing, or specific ranges for in vitro/controlled) [41, 42].**
    - **Light not required [42]. Influenced by genetics, physical factors (medium composition, env conditions) [40].**
    - **Optimal conditions and quality seeds yield 80-100% germination [43]. Poor germination rates can be associated with bad genetics [44] or old seeds (Transcript P.168).**
    - **Range/Likely Level: Germination rate can be affected by genotype, medium composition, and environmental conditions [40, 43]. Reputable breeders aim for near 100% [43].**
  + **Seedling: Early growth [45, 46].**
    - **Typically single leaflet leaves initially, progressing to 3, then 5 [19]. Sensitive stage [47].**
  + **Vegetative: Rapid growth stage, building root system and stems, then foliage [46, 48].**
    - **Needs high nitrogen [46, 49]. Fairly tough during this stage [50]. Environmental conditions like temp/humidity deviations impact growth speed [51]. Optimal VPD is crucial (Transcript P.235). Low light (e.g. 200s PPFD) can be sufficient if DLI is met (Transcript P.161). Veg duration varies (e.g., 10-18 days for some commercial setups (Transcript P.176, P.217), up to 5-6 weeks for others (Transcript P.200)).**
    - **Problems often begin to show here [52]. Duration modeled as 50 days in one facility example [53].**
  + **Flowering: Stage where inflorescences develop [45, 46].**
    - **Requires lower humidity (especially late flower, e.g. 40-50% RH, though some run higher at 60-65% with LEDs (Transcript P.161)) and specific light spectrum/intensity [47]. Needs higher phosphorus/potassium [45, 49]. Light cycle typically 12/12, but some manipulate to 11/13 to finish plants or influence expression (Transcript P.115).**
    - **Longest stage in one model (57 days) [53]. Can range from 7 weeks (e.g., Rainbow Belts, Zkittlez crosses (Transcript P.115)) to 10+ weeks (e.g., Haze varieties, some OGs (Transcript P.115, P.169, P.308)) depending on genetics. Stretch period (first 1-4 weeks of flower) can last 3-4 weeks for some strains (e.g., Sherb Banger 22 (Transcript P.114-115)).**
  + **Maturation: Buds thicken, trichomes mature [21, 27].**
    - **Harvest timing determined by trichome appearance (clear to milky to amber) and yield/chemistry correlation [54]. Cannabinoid and terpene profiles change during maturation (Transcript P.8, P.172). Some harvest earlier for specific products like hash (Transcript P.197).**
  + **Harvest: Physical removal of plants/flowers [55]. Timing crucial for potency/quality [54, 56].**
* **Phenotypic Plasticity: The ability of a plant with a specific genotype to exhibit different phenotypes in different environments [38, 57-60].**
  + **This is a fundamental concept for GxE modeling [38, 57-60]. Environment (light, temp, nutrients, stress) heavily influences expression of genetic potential (Transcript P.187, P.200-207).**
  + **Clones with identical genotype can show different phenotypes with varied conditions [3, 58].**

#### 1.2 Chemical Profile Parameters

**Parameters defining the chemical composition of the cannabis plant, particularly secondary metabolites produced primarily in glandular trichomes [4, 24, 61].**

* **Cannabinoids: (>140 identified) [62].**
  + **Major Cannabinoids:**
    - **Δ⁹-tetrahydrocannabinol (THC): Psychoactive compound [63].**
      * **Potency often measured as % DW [64]. Levels up to 25-30% of floral dry weight achieved [4]. Some cultivars testing at 28-35% THC reported (Transcript P.187). Others may test lower (e.g. 12-19%) but still be desirable (Transcript P.170, P.197). Moisture content at testing significantly impacts reported THC % (Transcript P.12, P.22).**
      * **Can reach 30% in some plants [5].**
      * **Likely Levels: High THC strains can exceed 20%, some even reaching 30% [4-6]. Cultivator discussions mention THC levels from 12% to 35%+ (Transcript P.13, P.170, P.187, P.197).**
      * **Traditional hemp is <0.3% [1]. THCA flower market exists under hemp definition (Transcript P.276-279).**
    - **Cannabidiol (CBD): Non-psychoactive, therapeutic potential [63, 65].**
      * **Potency often measured as % DW [64].**
      * **Likely Levels: High CBD strains can exceed 15-20%. Many hybrids have mixed ratios.**
    - **Cannabigerol (CBG): Precursor to other cannabinoids [63]. Increasing interest in breeding [66].**
    - **Cannabinol (CBN): Sedative effects [63]. Accumulates with degradation/aging [63].**
  + **Minor Cannabinoids: Growing interest (distinct therapeutic benefits) [66].**
    - **Δ⁹-tetrahydrocannabivarin (THCV): Investigating production genetics crucial [66].**
    - **Cannabidivarin (CBDV): Investigating production genetics crucial [66].**
    - **Cannabichromene (CBC): Investigating production genetics crucial [66].**
    - **Cannabichromenevarin (CBCV) [63].**
    - **Cannabigerovarin (CBGV) [63].**
    - **Delta-8 THC [63], Delta-10 THC [63], HHC [63]: Novel cannabinoids often in legal grey areas, facing evolving scrutiny [67]. Delta-8 can be synthesized from CBD (Transcript P.279-281).**
    - **THCP, THCB [63].**
  + **Cannabinoid Acids: Biosynthetic precursors, convert to neutral form via decarboxylation (heat, aging) [63, 68, 69].**
    - **THCA (tetrahydrocannabinolic acid) [63]. THCA flower being sold under hemp regulations is a major market factor (Transcript P.276-279).**
    - **CBDA (cannabidiolic acid) [63].**
    - **CBGA (cannabigerolic acid) [63].**
  + **Total Cannabinoids (e.g., Total THC: THCA \* 0.877 + THC, Total CBD: CBDA \* 0.877 + CBD) [63].**
    - **Critical quality parameters [68]. Content variability in plant material is an issue for consistency [68].**
    - **Can reach 25-30% of floral dry weight [4]. Potency is a key driver in many markets, though this is being questioned by connoisseurs (Transcript P.170, P.197, P.239). Moisture content at testing significantly impacts reported THC % (Transcript P.12, P.22). Using products like "Fade" can increase THC by 2-6% absolute (Transcript P.13).**
* **Terpenes: (>120 identified) [62].**
  + **Aromatic compounds contributing to aroma, flavor, and potential effects (entourage effect) [63, 65, 70]. Produced in glandular trichomes [61]. Critical for consumer preference, especially in connoisseur markets (Transcript P.8, P.152, P.179, P.192).**
  + **Concentration influenced by genetics, environment, post-harvest handling [71]. Late-stage nutrient protocols (like "Fade") can enhance terpene expression (Transcript P.8-9). Drying and curing are critical for terpene preservation (Transcript P.179, P.298-299).**
  + **Dominant Terpenes: Myrcene, Limonene, Caryophyllene, Pinene, Ocimene, Terpinolene [63].**
  + **Other Terpenes: Humulene, Linalool, Bisabolol, Nerolidol, Geraniol, Borneol, Fenchol, Cineole, Camphor, Phellandrene, Terpineol, Carene, Farnesene, Phytol, Carvacrol, Aromadendrene, Eudesmol [63].**
  + **Terpene Profiles: Concentrations and ratios of individual terpenes [64, 65, 71]. Contributes to market demand [71]. Breeding for unique terpene profiles is a major goal for some (Transcript P.152, P.172).**
  + **System for classification (e.g., Cream/Cake/Cookies/Candy, Fruity, Herbal, Pine, Skunk, Spicy, Sweet, Tropical, Woody/Earth) [72]. The "candy" profile (e.g., from Dante's Inferno #6) is currently popular (Transcript P.152, P.172). "Gas" is another popular profile (Transcript P.187).**
  + **Total Terpenes [63]. High terpene content is desirable but can be diluted by excessive yield focus ("yield dilution") (Transcript P.62).**
  + **Volatilization: Terpenes can volatilize, especially during drying/curing at warmer temperatures [73].**
    - **Proper drying/curing crucial for retention [25, 54, 73]. Target 7-10 days dry time, 60F/60%RH environment (Transcript P.298-299).**
* **Flavonoids: Contribute to pigmentation and aroma/flavor [8, 63].**
  + **Cannflavins [63]. Anthocyanins responsible for purple colors, influenced by genetics and cold temperatures (Transcript P.14-15).**
* **Volatile Sulfur Compounds (VSCs): Contribute to pungent/characteristic notes like "gas" or "skunk" [63]. Unstable over time [63].**
* **Esters: Contribute sweet/fruity notes [63].**
* **Other Constituents: Hydrocarbons, phenolics, sugars [63].**
* **Entourage Effect: Synergistic interaction between cannabinoids, terpenes, and other compounds influencing effects and therapeutic potential [8, 63].**

#### 1.3 Physiological Processes Parameters (Continuation)

**Parameters governing the internal functions and responses of the cannabis plant, building on the initial photosynthesis, transpiration, nutrient uptake, and biosynthesis parameters.**

* **Water Relations: Beyond basic transpiration.**
  + **Water Uptake Rate: Influenced by root system size/health, substrate moisture content, substrate type (e.g., coir's high water retention vs. rockwool's quick dry down) [1-3]. VPD heavily influences uptake (Transcript P.125, P.235).**
  + **Aquaporin activity (e.g., PIP aquaporins) may play a role at a molecular level [2].**
  + **Leaf Water Potential: Measure of plant water stress. Influenced by substrate moisture, humidity, airflow, transpiration rate.**
  + **Stomatal Response: Opening and closing of stomata to regulate gas exchange and water loss.**
    - **Influenced by light intensity, CO2 levels, humidity, wind. Can be reduced in later maturation stages [4]. Far-red light at end of day can influence stomatal closure and plant sleep cycles (Transcript P.203).**
* **Carbon Metabolism:**
  + **Carbon Fixation Rate: Directly related to photosynthetic rate.**
  + **Photoassimilate Production: Synthesis of sugars.**
  + **Photoassimilate Partitioning: Allocation of sugars to different plant parts (roots, shoots, leaves, flowers).**
    - **Influenced by growth stage, nutrient availability (e.g., Nitrogen for vegetative growth vs. Phosphorus for flowering/bud development) [5]. Late flower N restriction (e.g., using "Fade") encourages resource allocation to flowers (Transcript P.7-9, P.15).**
* **Hormonal Regulation: Internal plant hormones (phytohormones) play crucial roles in growth, development, and responses to environment and stress.**
  + **Auxins: Involved in root development, apical dominance, vegetative growth. Auxin activity typically decreases during flowering transition [6].**
  + **Cytokinins: Promote cell division, shoot development. Certain cytokinins increase during flowering transition [6].**
    - **Meta-topolin (mT), a natural cytokinin, is effective for shoot proliferation in tissue culture [7].**
  + **Gibberellins: Involved in stem elongation (e.g., "stretch" at flowering onset) [6].**
  + **Abscisic Acid (ABA): Stress hormone, involved in stomatal closure and dormancy. Increases under drought stress. Drought stress (generative steering) is a key crop steering technique (Transcript P.122-123).**
  + **Ethylene: Involved in senescence, ripening, stress responses.**
  + **Brassinosteroids: Promote growth and stress tolerance.**
  + **Phytohormone Balance: The relative levels and interactions of these hormones regulate developmental transitions (e.g., vegetative to flowering, re-vegetation) [6, 8].**
    - **Mother plants in long-term vegetative state may experience subtle changes in hormonal balance [4].**
* **Nutrient Mobility and Translocation: Movement of absorbed nutrients within the plant (e.g., from older leaves to new growth/flowers).**
  + **Efficiency may diminish with physiological age [4]. Nitrogen is highly mobile and translocated from fan leaves during late flower if root zone N is restricted (e.g. when using "Fade") (Transcript P.8, P.15). Calcium is immobile; deficiencies (e.g., from flushing with straight RO water or pulling Core too early) can lead to issues like bud rot (Transcript P.7-8, P.12).**
* **Resource Remobilization: Breakdown of macromolecules (proteins, lipids, nucleic acids) in senescing tissues and transport of resulting nutrients to other parts of the plant [9].**
  + **Occurs in older leaves even in vegetative mothers [4]. Crucial for reproductive success in nature [9]. This is a key mechanism during "Fade" or flushing (Transcript P.8, P.15).**
* **Developmental Plasticity: Ability to alter growth patterns in response to environmental cues (e.g., branching patterns influenced by light distribution, nutrient availability) [10].**
* **Circadian Rhythms: Internal biological clock regulating daily physiological processes (e.g., photosynthesis, transpiration, flowering time). Interacts with photoperiod. Use of far-red light to signal end-of-day can influence these rhythms (Transcript P.203).**

#### 1.4 Stress Responses Parameters

**Parameters defining how the cannabis plant reacts to and is affected by various abiotic and biotic stressors, and its ability to tolerate them. Stress can impact yield, quality, and even chemotype. Strategic stress (e.g., controlled drought, specific nutrient withdrawal like "Fade") can enhance desired traits like terpene and cannabinoid production (Transcript P.8, P.122-124).**

* **Abiotic Stress Responses: Responses to non-living environmental factors.**
  + **Drought Stress: (Intentional for generative steering)**
    - **Physiological Effects: Reduced stomatal conductance, decreased photosynthesis, wilting, reduced transpiration.**
    - **Can induce changes in leaf water potential [11]. Induces hormonal responses for survival and reproduction (Transcript P.122).**
    - **Growth/Yield Effects: Stunted growth, reduced biomass, lower flower yield.**
    - **Controlled drought stress in flowering stage can increase inflorescence dry weight and cannabinoid content [12]. Key part of "generative steering" by manipulating drybacks (Transcript P.11, P.122-123).**
    - **Chemotype Effects: May increase cannabinoid/terpene concentration (due to reduced biomass/water content or stress-induced synthesis) or decrease total production (due to reduced metabolic activity) [11, 13]. (Transcript P.8, P.124).**
    - **Stress-induced synthesis vs. dilution [13].**
  + **Heat Stress:**
    - **Physiological Effects: Denaturation of enzymes, impaired photosynthesis, increased respiration, heat shock protein production.**
    - **Can cause managing temperature to be critical for quality [14]. Excessive heat can stress plants, leading to reduced quality or hermaphroditism (Transcript P.158, P.171).**
    - **Growth/Yield Effects: Stunted growth, reduced flower development, wilting, leaf damage.**
    - **Chemotype Effects: Can degrade cannabinoids (e.g., THC) and volatilize terpenes, reducing overall potency and aroma profile [14].**
  + **Cold Stress:**
    - **Physiological Effects: Reduced enzymatic activity, membrane damage, impaired nutrient uptake.**
    - **Growth/Yield Effects: Stunted growth, leaf damage, reduced yield.**
    - **Chemotype Effects: Can impact cannabinoid/terpene synthesis.**
    - **Some varieties may show color changes (e.g., purple hues) in response to cold [15]. This is a common technique to enhance "bag appeal" (Transcript P.14-15). Colder water at end of flower can also induce color (Transcript P.14).**
  + **Light Stress (Too High/Low Intensity):**
    - **Physiological Effects: Photoinhibition (damage to photosynthetic apparatus) from excessive light [16].**
    - **Reduced photosynthesis from insufficient light. Plants growing into lights will burn (Transcript P.114).**
    - **Growth/Yield Effects: Leaf burn, stunted growth, reduced yield from excessive light.**
    - **Leggy growth, low yield from insufficient light.**
    - **Chemotype Effects: Optimal light intensity and spectrum are crucial for cannabinoid and terpene production [17-19]. Some genetics are more sensitive to high PPFD than others (e.g., old Indicas) (Transcript P.116).**
    - **UV light can stimulate cannabinoid production (protective mechanism) [20, 21], but excessive UV can be damaging.**
    - **Different light spectra affect morphological, physiological, and chemical parameters [17, 22]. Far-red can influence flowering time and stretch (Transcript P.203). Mixed HPS/LED can give unique expressions (Transcript P.202-207).**
  + **Nutrient Deficiency/Toxicity:**
    - **Physiological Effects: Impaired metabolic processes, reduced photosynthesis, visible symptoms (e.g., leaf yellowing from N deficiency, brown spots from P deficiency/toxicity, leaf burn from nutrient excess/toxicity) [23, 24]. Calcium deficiency in late flower can lead to bud rot (Transcript P.7-8).**
    - **Can trigger/accelerate senescence [25]. Removing core nutrients (e.g., Athena ProLine Core) too early or using straight RO water can cause deficiencies (Transcript P.8, P.12).**
    - **Growth/Yield Effects: Stunted growth, reduced biomass, lower yield [5, 23, 24].**
    - **Nutrient imbalance can restrict development [26]. Overwatering can lead to nutrient lockout or root issues mistaken for deficiencies (Transcript P.11).**
    - **Chemotype Effects: Nutrient availability significantly impacts cannabinoid and terpene biosynthesis and concentration [18, 27, 28].**
    - **High Nitrogen can decrease cannabinoid/terpene concentration while increasing biomass (dilution effect) [5, 29]. This is a reason for products like "Fade" (Transcript P.7-9).**
    - **Phosphorus is conventionally supplied at high amounts for optimal function and yield, but deficiency at vegetative stage impacts functional phenotyping and ionome [30].**
  + **Waterlogged Soil/Root Zone Hypoxia:**
    - **Physiological Effects: Root damage, impaired nutrient/water uptake, reduced oxygen availability to roots. Increased risk with overwatering, especially in dense media like coco if not managed (Transcript P.11, P.126).**
    - **Growth/Yield Effects: Wilting, stunted growth, root rot susceptibility [31], reduced yield.**
    - **Chemotype Effects: Reduced plant health negatively impacts secondary metabolite production.**
  + **Salinity Stress: Accumulation of soluble salts in the root zone, particularly in hydroponics/soilless media [26]. High EC in media due to insufficient runoff or excessive drybacks (Transcript P.123, P.158).**
    - **Physiological Effects: Impaired water uptake, ion toxicity.**
    - **Growth/Yield Effects: Stunted growth, reduced yield. Lockout of other nutrients.**
    - **Chemotype Effects: Can impact metabolite profiles. Extreme EC can burn plants.**
* **Biotic Stress Responses: Responses to living organisms.**
  + **Pest Infestation: (See also 1.6 Pest/Disease Resistance Parameters)**
    - **Damage Types: Feeding damage (leaf loss, tissue damage), disease transmission, growth hindrance [32, 33]. Thrips, mites mentioned as common problems (Transcript P.80, P.179).**
    - **Physiological Effects: Allocation of resources to defense mechanisms (e.g., production of defensive compounds).**
    - **Growth/Yield Effects: Reduced vigor, stunted growth, significant yield loss [32, 33].**
    - **Trichome damage/loss can directly reduce cannabinoid/terpene yield [34].**
  + **Pathogen Infection: (See also 1.6 Pest/Disease Resistance Parameters)**
    - **Damage Types: Tissue damage, impaired physiological function (e.g., nutrient/water transport, photosynthesis), systemic infection [32, 35]. Bud rot (Botrytis) is a major concern, linked to calcium deficiency and high humidity (Transcript P.7-8, P.15). Fusarium is a root pathogen, no cure, spreads via water (Transcript P.84). HLVd causes stunting, dudding, reduced quality (Transcript P.3, P.16, P.80, P.171).**
    - **Physiological Effects: Activation of plant immune response, production of defense compounds.**
    - **Older mothers may have potentially weakened immune response or chronic stress leading to higher susceptibility [34].**
    - **Growth/Yield Effects: Reduced vigor, stunted growth, wilting, necrosis, significant yield loss [32, 35]. HLVd can devastate crops (Transcript P.3, P.16-17).**
    - **Can be mistaken for age-related decline [34]. Systemic pathogens like HLVd cause stunting and reduced trichome production/yields [34].**
  + **Competition (Light, Nutrients, Water, Space): Competition from other cannabis plants or companion plants [36].**
    - **Physiological Effects: Altered growth patterns (e.g., reaching for light), reduced resource uptake efficiency.**
    - **Growth/Yield Effects: Reduced individual plant yield. Plant spacing is important for maximizing yield per area [37, 38]. Density of 1.6 plants/sq ft mentioned (Transcript P.183).**
  + **Stress-Induced Senescence: Premature aging and death of plant tissues or the whole plant due to severe or prolonged stress [9]. Can be desirable at end of flower (e.g., with "Fade") but problematic if premature (Transcript P.8).**

#### 1.5 Strain-Specific Optimal Conditions and Characteristics Parameters

**Parameters defining the variations in optimal growth conditions, growth habits, and other characteristics between different cannabis genotypes (strains/cultivars). Cultivars show wide variation in response to environment and inputs (Transcript P.114, P.163, P.187, P.200).**

* **Optimal Environmental Ranges: Genotype-dependent ideal ranges for:**
  + **Temperature: Specific optimal temperature ranges for vegetative and flowering stages [39]. Some strains are more sensitive to temperature swings (Transcript P.15, P.158). Some growers run 73-76F even in late flower with "Fade" (Transcript P.15).**
  + **Humidity: Specific optimal humidity ranges for vegetative and flowering stages [39]. Some strains are more prone to mold in high humidity (Transcript P.15). Some run 60-65% RH with LEDs in flower (Transcript P.161).**
  + **Light Intensity (PPFD): Different strains may utilize light more or less efficiently and have different saturation points. Some strains are sensitive to high PPFD (e.g. old indicas) (Transcript P.116).**
  + **Light Spectrum: Different strains may respond differently to specific light wavelengths [17, 22, 39]. Some strains show better color or terpene expression under specific spectra (e.g. mixed HPS/LED, or specific LED spectra like ThinkGrow vs. Luxx) (Transcript P.202-207, P.113, P.160). Far-red for end-of-day signal (Transcript P.203).**
  + **CO2 Concentration: Optimal CO2 levels for different strains, especially in CEA [39-41]. Typically 1500ppm in flower (Transcript P.161).**
  + **Airflow/Ventilation: Specific needs for different growth structures and densities to prevent mold/pests [42]. Dense bud structures require more airflow (Transcript P.15).**
  + **Substrate Moisture Content: Optimal levels and tolerance for drying out or waterlogging vary [1-3]. Some strains prefer larger drybacks than others (Transcript P.11, P.124). Rockwool vs. Coco drydown characteristics (Transcript P.113, P.180).**
  + **Nutrient Solution pH: Optimal pH range for nutrient uptake can vary slightly by strain and substrate [16, 43, 44]. Some growers maintain a consistent pH (e.g. 6.0-6.2) for all strains in coco (Transcript P.158). Monosilicic acid can affect pH in rockwool (Transcript P.11).**
  + **Nutrient Concentrations (EC/PPM): Optimal nutrient strength varies by strain and growth stage [27, 43, 45]. Some strains are heavy feeders, others sensitive (e.g., OGs might prefer lower EC than Runtz; Runtz sensitive to high EC, Pie Hoe can take very high EC) (Transcript P.196). Some run 3.0 EC all the way through with Athena ProLine (Transcript P.12, P.15).**
  + **Specific Nutrient Ratios (NPK, Ca:Mg, etc.): Optimal ratios can be strain-specific and outcome-specific (e.g., maximizing yield vs. maximizing cannabinoid concentration) [13, 27, 45].**
* **Growth Habits and Morphology: Genotype-dependent traits:**
  + **Plant Height and Structure: Tall/thin (sativa-like) vs. short/bushy (indica-like) [10, 47, 48]. Some strains have significant stretch (e.g. Sherb Banger 22, 4-week stretch from 12" to 5ft (Transcript P.114-115)) while others are short (e.g. Rainbow Belts, Zkittlez finishing in 7 weeks (Transcript P.115)).**
  + **Branching patterns (apical dominant vs. lateral spread, OG minimal lateral without topping) [10] (Transcript P.182-183). Untopped plants develop a main cola with lateral branches reaching near the top (Transcript P.183).**
  + **Internodal spacing [49].**
  + **Leaf Morphology: Leaflet number and width (narrow-leaf vs. broad-leaf) [49, 50].**
  + **Flower Structure: Shape, density, leaf-to-calyx ratio [10, 51]. Some genetics known for specific structures (e.g. "golf balls" (Transcript P.181)). Some LED-grown flower can be rock-hard (Transcript P.202).**
  + **Root System Development: Efficiency and structure of the root system can be strain-specific [3]. Cloned plants have weaker, more lateral roots than seed plants (Transcript P.32).**
* **Life Cycle and Flowering Time: Genotype-dependent duration of growth stages:**
  + **Seedling Stage Duration [10, 54].**
  + **Vegetative Stage Duration: Ability to remain vegetative under specific photoperiods [10, 55, 56]. Commercial grows may have veg times from 10-18 days (Transcript P.176, P.217) to several weeks (Transcript P.200).**
  + **Flowering Time/Duration: Crucial parameter for breeding and cultivation planning [10, 39, 57, 58]. Ranges from 7 weeks (e.g. some Zkittlez crosses (Transcript P.115)) to 10+ weeks (e.g. Haze varieties, some OGs (Transcript P.115, P.169, P.308)).**
  + **Sativa varieties typically have longer flowering times (10-16 weeks) than indica (6-10 weeks) [10, 57]. Photoperiod-dependent flowering vs. autoflowering [59-61]. Use of far-red light can shorten flowering time by a week or more (Transcript P.204).**
  + **Semi-full-term/fast-flowering strains [62, 63].**
  + **Maturation Indicators: Visual cues (pistil color, trichome appearance) indicating peak ripeness can vary slightly by strain [10, 64-66].**
  + **Trichome gland head phenotypes change over the flowering period [67]. Optimal harvest timing varies by strain [68]. For hash production, plants might be harvested earlier (e.g. day 40 for a 70-day flower strain) (Transcript P.197).**
  + **Re-vegetation Potential: Ability to revert to vegetative growth after flowering can be strain-dependent [6, 69].**
  + **Older plants may struggle more [69].**
* **Yield Potential: Genotype-dependent inherent capacity for biomass and flower production under optimal conditions.**
  + **Measured in grams per plant or grams per square foot [65]. Can be influenced by substrate choice [1, 3]. Yields of 2.5-4 lbs per light reported by cultivators (Transcript P.116, P.204). Some strains are known low yielders (e.g. cookies, lcg) but high value (Transcript P.116, P.241). Under canopy lighting can increase yield by 20-50% (Transcript P.225). Hash yields also vary (e.g., 3% vs 4-5.5% with Fade) (Transcript P.9).**
* **Chemical Profile (Chemovar): Genotype-dependent production of specific cannabinoids, terpenes, and other compounds, defining the chemovar [70-73]. Huge driver of market value (Transcript P.152, P.170).**
  + **Major Cannabinoid Ratios (THC:CBD, THC:CBG, CBD:CBG, etc.) [28, 74].**
  + **Controlled by alleles at cannabinoid synthase loci [74, 75]. Breeding can target specific ratios [76, 77].**
  + **Minor Cannabinoid Production (THCV, CBDV, CBG, CBC, CBN, etc.) [72, 78, 79]. Genetics control production [76, 77].**
  + **Terpene Profile: Specific terpenes produced and their relative concentrations [72, 73, 78, 80, 81]. Unique terpene profiles are highly sought after (e.g. Dante's Inferno #6 cherry candy (Transcript P.152, P.172)).**
  + **Genetics are foundational, but expression influenced by environment and post-harvest [82]. Terpene synthase (TPS) genes are involved [45, 79].**
  + **Unique flavor/aroma profiles are strain-defining [58, 80, 83]. "Gas" and "candy" profiles are popular (Transcript P.172, P.187).**
  + **Flavonoid Production (Cannflavins, Anthocyanins for color) [78, 84] (Transcript P.14-15).**
  + **Total Cannabinoid Potency (% DW) [71, 74, 78]. THC levels are often a primary market driver, but this is shifting (Transcript P.170, P.197, P.239).**
  + **Total Terpene Content [78].**
  + **Stability of Chemical Profile: Consistency across different grows/environments (less plastic chemotypes) [85, 86].**
  + **Desirable for medicinal/commercial purposes [18, 71, 85, 87]. Influenced by genetic stability and environmental control [71, 88].**
* **Propagation Characteristics:**
  + **Seed Germination Rate and Speed [10, 89, 90]. Old seeds may have poor germination (Transcript P.168).**
  + **Cloning Success Rate: Ease of rooting cuttings, influenced by genetics and mother plant health [25, 91]. Some strains are notoriously difficult to clone.**
  + **Tissue Culture Recalcitrance: Difficulty of in vitro regeneration and transformation for certain genotypes [48, 92, 93].**
  + **Genotype-dependent HLVd eradication success in meristem culture [94]. (Transcript P.17-18, P.81).**
  + **Doubled Haploid (DH) Production Recalcitrance: Difficulty in generating homozygous lines rapidly [41, 93].**
* **Responses to Cultivation Techniques: Different strains may respond better or worse to specific methods.**
  + **Pruning and Training (e.g., Topping, LST, ScrOG, SOG): Effectiveness for yield and structure optimization can be strain-dependent [91, 95-98]. Some growers prefer no topping to encourage a dominant main cola and specific canopy structures (Transcript P.182-183). Stretch characteristics heavily influence training needs (Transcript P.114). Defoliation timing and extent interact with nutrient strategies like "Fade" (Transcript P.12, P.15-16).**
  + **Fertigation/Nutrient Management: Optimal nutrient timing, strength, and ratios may differ [13, 26, 27, 43, 45]. Some strains (e.g. Runtz) are sensitive to high EC, while others (e.g. Pie Hoe) can take very high EC (Transcript P.196). OGs might prefer lower EC (Transcript P.196).**
  + **Nutrient Use Efficiency (NUE) varies [45, 99].**
  + **Substrate Suitability: Performance can vary significantly across different substrates (soil, coco coir, peat mixes, rockwool, hydroponics) and may be genotype-specific [2, 3, 31]. Some strains might prefer the buffering of coco over the rapid changes in rockwool (Transcript P.116, P.180).**
* **Desired Effects/Applications: While influenced by environment and post-harvest, the genetic chemotype provides the basis for different effects and applications [72, 86, 100-103].**
  + **Recreational Effects: Energetic/cerebral (sativa-like) vs. relaxing/sedative (indica-like) [47, 102].**
  + **While traditional Sativa/Indica labels are not fully reliable for genetic structure [59, 104, 105], market categorizations persist based on perceived effects [47, 102].**
  + **Entourage effect plays a role [78, 106-109].**
  + **Medical Applications: Specific cannabinoid/terpene profiles are sought for therapeutic outcomes (e.g., high CBD for certain conditions) [85, 101, 110].**
  + **Tailored chemotypes for medicinal needs [111].**

#### 1.6 Pest/Disease Resistance Parameters

**Parameters defining a strain's inherent ability to resist common pests and diseases.**

* **Resistance Levels: Genotype-dependent inherent resistance or susceptibility to:**
  + **Fungal Diseases (e.g., Powdery Mildew (PM), Bud Rots like Botrytis, Root/Crown Rots like Fusarium/Pythium) [32, 33, 112, 113]. Botrytis is a significant issue, especially with dense buds or under LED lights if humidity is not managed. Calcium deficiency can exacerbate botrytis (Transcript P.7-8, P.15). Fusarium is a concern in hydroponic/recirculating systems, no cure, spreads via water (Transcript P.84). PM resistance is a highly desirable trait (Transcript P.79).**
  + **Mold resistance is a crucial agronomic trait [114]. Strains from humid regions may have higher mold resistance [58].**
  + **Bacterial Diseases [32, 33].**
  + **Viral Pathogens (e.g., Hop Latent Viroid - HLVd) [32, 33]. HLVd resistance varies by genotype [94]. Some strains may be asymptomatic carriers (Transcript P.80-81). Symptoms include stunting, dudding, brittle stems, abnormal branching, reduced trichomes/yield/quality (Transcript P.3, P.16, P.80, P.171). Spreads via mechanical damage (tools, hands) (Transcript P.80). Present in roots (Transcript P.83). Can be in seeds (unconfirmed for cannabis, Tumi studying) (Transcript P.17, P.81).**
  + **Nematode Infestations (e.g., Root-knot nematodes) [115].**
  + **Insect Pests (e.g., Spider Mites, Aphids, Whiteflies, Thrips, Fungus Gnats) [32, 33, 113, 116]. Thrips and mites are common (Transcript P.80, P.179).**
* **Mechanism of Resistance: May involve structural defenses, production of defensive compounds (e.g., secondary metabolites like cannabinoids and terpenes can act as deterrents/protectants) [20, 21, 117], or activation of immune pathways. Plant polycultures may attract beneficial organisms for natural pest/disease control [118].**
* **Stress-Induced Susceptibility: Stress (abiotic or biotic) can weaken a plant's defenses and increase susceptibility to pests and diseases [34, 119]. Older mother plants may be more susceptible [34]. Stress can also cause HLVd to express symptoms in previously asymptomatic plants (Transcript P.17).**
* **Impact on Yield/Quality: Resistance (or lack thereof) directly impacts yield quantity and quality by minimizing (or maximizing) damage and systemic infection [32, 33, 113]. HLVd can devastate crops (Transcript P.3, P.16-17).**

### 2. Cannabis Breeding and Genetics Parameters

**This section outlines the parameters governing the inheritance of traits, breeding methodologies, genetic management, and related analytical and simulation considerations within the Cannabis sativa L. breeding context. This is a core area for the simulation, driving strain development and player progression. Breeding for specific terpene profiles (e.g., "candy," "gas") and unique genetic expressions is a primary goal (Transcript P.152, P.172, P.187). The philosophy of finding "keepers" through pheno hunting is central (Transcript P.150, P.154).**

#### 2.1 Foundational Genetic Parameters

**Parameters defining the basic mechanisms of inheritance and genome structure in cannabis.**

* **2.1.1 Genome Structure**
  + **Ploidy Level: Diploid (2n=20) [1, 2]. Simulation models diploid genetics as default.**
  + **Chromosome Number: 9 pairs of autosomes and XY sex chromosomes [1, 2].**
  + **Genome Size: Approximately 818 Mb (XX) to 843 Mb (XY) [1]. Influences data for genomic analysis. Cannabis genome still being fully mapped (Transcript P.78).**
  + **Chloroplast Genome: Parameter for maternal lineage or plastid traits (e.g., Yunma 7 approx. 153,899 bp) [3].**
  + **Mitochondrial Genome: Parameter for specific research paths, less critical for core breeding [4].**
* **2.1.2 Inheritance Models**
  + **Mendelian Inheritance: For traits controlled by single genes with dominant/recessive or co-dominant alleles [5-8].**
    - **Alleles: Different forms of a gene.**
    - **Genotype: The genetic makeup (e.g., BB, Bb, bb).**
    - **Phenotype: Observable characteristics from genotype and environment (e.g., Silver Bud vs. Golden Bud) [1].**
    - **Homozygous: Two identical alleles (e.g., BB, bb) [2, 3].**
    - **Heterozygous: Two different alleles (e.g., Bb) [4].**
    - **Dominance: One allele masks another's effect [5, 19].**
    - **Recessiveness: The masked allele [5].**
    - **Co-dominance: Both alleles contribute to the phenotype [6].**
  + **Polygenic Inheritance: For traits controlled by multiple genes (e.g., yield, potency, flowering time, disease resistance) [6, 7, 9-11].**
    - **Quantitative Trait Loci (QTLs): Genomic regions influencing quantitative traits [6, 8-10, 12-17]. Simulation models cumulative effect.**
    - **Additive Gene Action/Effects: Multiple genes contribute cumulatively [8, 21].**
    - **Dominance Effects: Interactions between alleles at the same locus [8].**
    - **Epistasis: Interactions between genes at different loci influencing expression [6, 8-10, 18-20]. Crucial for complex traits.**
  + **Pleiotropy: A single gene/QTL affecting multiple traits [6, 9, 10, 18].**
  + **Gene Linkage: Genes close on the same chromosome are often inherited together [6, 8, 10].**
    - **Recombination/Crossing Over: Process shuffling genetic material; frequency depends on gene distance [8-10, 21, 22].**
    - **Genetic Maps: Represent gene order based on recombination frequency [8, 22].**
    - **Recombination Rate: Frequency of crossing over, influenced by genetic map distances (cM) [21, 22].**
  + **Mutation Rate: Spontaneous DNA sequence change introducing new variation [21, 23, 24]. Parameter for novel trait appearance.**
* **2.1.3 Genetic Variation and Population Genetics**
  + **Genetic Variation: Differences in DNA among individuals.**
  + **Allele Frequency: Proportion of a specific allele in a population.**
  + **Genetic Diversity: Total genetic characteristics in a species; maintaining it is a challenge [7, 11].**
  + **Genetic Erosion: Loss of genetic diversity [11].**
  + **Gene Flow: Transfer of genetic variation between populations [7].**
* **2.1.4 Sex Determination**
  + **XY System: Male (XY), Female (XX) as primary mechanism [1, 25, 26].**
  + **Environmental Influence on Sex Expression: Conditions like light leaks, temperature swings can lead to hermaphroditism [26] (Transcript P.158, P.171).**
  + **Genetic Influence on Sex Expression: Genes on sex chromosomes and autosomes [27]. Sex identification markers (PCR-based) used in reality [28-30]. Some strains have higher genetic predisposition to herm (e.g., Dante's Inferno #6, Transcript P.152).**
  + **Chemically Induced Reversal: Using agents like Silver Thiosulfate (STS) or colloidal silver to induce male flowers on female plants for feminized seed production (Transcript P.169). Pollen viability/sterility from induced males can vary (Transcript P.152).**
* **2.1.5 Genotype-by-Environment Interaction (GxE)**
  + **The effect of an environmental factor on phenotypic expression depends on the genotype [6, 7, 10, 12-14]. Critical for realism. (Transcript P.113, P.116, P.160-161, P.187, P.196, P.200-207).**
  + **Norm of Reaction: Range of phenotypes from one genotype across different environments.**
  + **Different strains perform differently under varying conditions (e.g., indoor vs. outdoor, different nutrient regimes, light spectra - HPS vs LED, specific LED brands like ThinkGrow vs Luxx, under canopy lighting) [15, 16] (Transcript P.113, P.116, P.160-161, P.202-207, P.225). Cold temperatures or "Fade" nutrients can induce purple coloration (Transcript P.14-15).**

#### 2.2 Trait Parameters (Specific to Cannabis)

**Parameters defining the heritable characteristics that breeding programs aim to manipulate.**

* **2.2.1 Agronomic Traits**
  + **Yield Components:**
    - **Flower Biomass (g/plant, g/m²) [11, 19, 22, 30, 31, 58-75]. Influenced by genetics and environment [31, 59]. Can range from low (Cookies, LCG - Transcript P.116, P.241) to high (2.5-4 lbs/light - Transcript P.116, P.204). Under canopy lighting can increase yield by 20-50% (Transcript P.225).**
    - **Bud Density (airy, medium, compact, "rock-hard" under LEDs (Transcript P.202)) [32, 72, 321, 324, 327].**
    - **Harvest Index (ratio of harvestable biomass to total biomass) [31].**
    - **Hash Yield (% return from fresh frozen or dry material). Varies significantly by strain. "Fade" nutrients increased hash yield by 1.3% absolute in one test (Transcript P.9). Some strains are bred/selected specifically as "washers."**
  + **Growth Habit/Architecture:**
    - **Plant Height/Stature (e.g., tall, medium, short, dwarfing) [32, 33, 34, 60, 64, 65, 67, 70, 74, 75, 106, 123, 144, 174, 185, 234, 248, 315, 317, 318, 321-328]. Stretch varies significantly (e.g., Sherb Banger 22: 4-week stretch, 12" to 5ft; Rainbow Belts/Zkittlez: short) (Transcript P.114-115).**
    - **Branching Pattern (e.g., apical dominant, lateral spread, balanced) [32, 42, 322, 329]. Some OGs have minimal lateral branching without topping (Transcript P.182-183). Untopped plants often develop a dominant main cola (Transcript P.183).**
    - **Leaf Morphology (leaflet number, shape, size, margin, color - e.g. black leaves with Fade (Transcript P.14)) [32, 321].**
  + **Flowering Time:**
    - **Photoperiod Response (short-day) [34, 35]. Requires specific light/dark cycle (e.g., 12/12, or 11/13 to push finish - Transcript P.115) [34, 36-38].**
    - **Days to Maturity (after flowering initiation) [2, 6, 25, 31, 33, 34, 37, 39, 40, 60, 63, 65, 66, 68-71, 73, 75, 90, 92, 93, 98, 100, 102, 106, 123, 131, 146, 162, 178, 185, 188, 189, 192, 194, 234, 235, 248, 250, 314-320]. Strain-dependent, from 7 weeks (Zkittlez crosses, Transcript P.115) to 10+ weeks (Hazes, OGs, Transcript P.115, P.169, P.308). Far-red light can shorten by a week+ (Transcript P.204).**
    - **Autoflowering (day-neutral) Trait [13, 25, 32, 35, 41, 42, 53-57]. Flowers based on age, not photoperiod [43, 53]. Controlled by ruderalis genes [13, 41]. Cannot be reverted [53].**
    - **Semi-Full-Term (Quicks): Hybrids flowering 2-3 weeks earlier [44].**
  + **Seed Production Traits:**
    - **Seed Yield (seeds per plant/flower) [31]. Can be 5,000 to 20,000+ per light (Transcript P.309).**
    - **Seed Maturity (timing, hardness, visual cues) [45, 106, 370].**
    - **Seed Viability (% germinating) [46, 47]. Influenced by genetics, storage, maturity. Old seeds may have poor germination (Transcript P.168).**
    - **Germination Rate (speed) [23, 34, 36, 41, 46, 48, 370]. Influenced by genetics, environment, media.**
    - **Seed Characteristics: Natural markings, stripes [23, 36, 41, 106, 370].**
  + **Stress Tolerance (Abiotic):**
    - **Drought Tolerance [49].**
    - **Heat Tolerance [49]. Some strains herm easily with temperature swings (Transcript P.158, P.171).**
    - **Salinity Tolerance [49]. Some strains sensitive to high EC (Runtz), others tolerant (Pie Hoe) (Transcript P.196).**
    - **Temperature Extremes Tolerance [49]. Cold can induce purple colors (Transcript P.14-15).**
    - **Nutrient Deficiency/Toxicity Tolerance [50-52]. Some strains are heavy feeders, others are sensitive (Transcript P.196).**
    - **Light Intensity Tolerance: Some strains sensitive to high PPFD (old Indicas, Transcript P.116).**
  + **Stress Tolerance (Biotic):**
    - **Pest Resistance/Tolerance (e.g., mites, thrips, aphids, fungus gnats) [11, 13, 19, 22, 25, 31, 49, 53, 54, 72, 92, 123, 316, 319, 329, 338-344]. Resistance Level (susceptible, moderate, resistant) [31].**
    - **Disease Resistance/Tolerance (e.g., powdery mildew, botrytis, fusarium, pythium, rust, blights, leaf spots, viruses, HLVd) [11, 13, 16, 19, 22, 25, 31, 49, 54-60, 72, 92, 123, 316, 319, 329, 338-344]. Specific resistance (e.g., Powdery Mildew Resist - Transcript P.79) [31, 319, 329, 343]. HLVd resistance varies; some asymptomatic carriers (Transcript P.17, P.80-81).**
  + **Nutrient Requirements/Use Efficiency (NUE): [19, 22, 31, 61, 62, 76, 345-360]. Strain-dependent [31, 358]. Influence on deficiency/toxicity symptoms [319, 348, 361]. OGs may prefer lower EC (Transcript P.196).**
  + **Water Use Efficiency (WUE): [61-63].**
  + **Recalcitrance to Tissue Culture/Regeneration: Genotype-dependent difficulty [64-69]. HLVd eradication via meristem TC varies by genotype (Transcript P.17-18, P.81).**
  + **Responses to Training Techniques (pruning, topping, LST): [70-72]. Influenced by genetics and growth stage [42, 322, 329]. Some growers prefer no topping (Transcript P.182-183, P.200). Defoliation strategy interacts with nutrient plans like "Fade" (Transcript P.12, P.15-16).**
  + **Root Development: Genetic influence on root structure and vigor [41, 44, 47, 321, 367-369]. Cloned plants have weaker, more lateral roots (Transcript P.32).**
  + **Environmental Adaptation: Suitability for specific environments (indoor, outdoor, greenhouse, climates, altitude) [2, 7, 10, 12, 16, 56, 57, 64, 65, 67, 70, 73-75, 106, 123, 144, 189, 234, 250, 315, 317-319, 322, 324, 325, 362-366]. Michigan's humidity and cold fall temps are challenging for out-of-state genetics (Transcript P.5-6).**
* **2.2.2 Chemotype Traits**
  + **Cannabinoid Profile: Concentrations (% Dry Weight or mg/plant) of major/minor cannabinoids and acidic forms [9, 10, 11, 15, 30, 31, 59, 62, 63, 73-89, 76-89].**
    - **THC/THCA Content: [1, 9, 15, 31, 32, 34, 40, 59, 64, 66, 68, 71-75, 77-81, 87-202]. Influenced by genetics (THCAS locus) [82], environment, maturity [83-85]. Ranges from 12% to 35%+ (Transcript P.13, P.170, P.187, P.197). Moisture content at testing is critical (Transcript P.12, P.22). "Fade" nutrients can increase THC (Transcript P.13).**
    - **CBD/CBDA Content: [1, 9, 15, 25, 31, 62, 63, 69, 73-75, 77, 79-86, 87-89, 121, 122, 129, 133, 136, 139, 143, 147, 149, 152, 154-162, 164-177, 189-192, 196-205]. Influenced by genetics (CBDAS locus) [82], environment, maturity [83-85].**
    - **CBG/CBGA Content: [15, 73-75, 77]. Precursor [73]. Influenced by genetics (CBGAS locus) [82], maturity [77]. CBGA-predominant chemotype [87, 88].**
    - **CBC/CBCA Content: [15, 73-75, 77]. Influenced by genetics (CBCAS locus) [82].**
    - **THCV/THCVA Content: [15, 73, 74, 77]. Propyl cannabinoid [89]. Influenced by genetics (e.g., stacking Apr alleles) [89].**
    - **CBDV/CBDVA Content: [15, 73, 74, 77]. Propyl cannabinoid [89].**
    - **CBN/CBNA Content: [73, 74, 77, 90]. Degradation product of THC/THCA [90]. Increases with oxidation, heat, aging [90].**
    - **Minor Cannabinoids (Delta-8/10 THC, HHC, THCP, THCB, etc.): [12, 31, 62, 73, 76-89, 206]. Potential for breeding for high levels [30, 83]. Delta-8 can be synthesized from CBD (Transcript P.279-281).**
    - **Cannabinoid Purity: Proportion of target cannabinoid relative to total [77]. Key for medicinal cultivars [76, 91].**
    - **Total Cannabinoids: Sum of quantified cannabinoids [77].**
  + **Terpene Profile: Concentrations and ratios of individual terpenes [9, 10, 15, 31, 62, 73, 75, 76, 77, 79-82, 85-89, 92, 203, 206-209]. Contributors to aroma, flavor, effects [73, 93, 94]. Influenced by genetics (TPS genes) [61], environment (e.g. "Fade" nutrients, Transcript P.8-9), maturity, drying/curing (Transcript P.179, P.298-299) [75, 94].**
    - **Major/Individual Terpenes: Myrcene, Limonene, Caryophyllene, Pinene, Ocimene, Terpinolene, Humulene, Linalool, Bisabolol, Nerolidol, Geraniol, etc. [73, 76, 81, 207-209].**
    - **Minor Terpenes [73].**
    - **Total Terpenes. "Yield dilution" can reduce total terps if biomass is pushed too hard (Transcript P.62).**
    - **Terpene Ratios [76, 81].**
  + **Aroma and Flavor Descriptors: (e.g., citrus, pine, fuel, earthy, skunky, sweet, spicy, cheese, fruity, "candy" (Transcript P.152, P.172), "gas" (Transcript P.187)) [16, 30, 31, 40, 55, 66, 67, 71, 75, 79-81, 86, 93-103, 105, 107, 111, 113, 115-119, 121, 122, 125, 127-131, 133, 136, 137, 140, 142-151, 153-155, 157-160, 162, 163, 165-179, 181-203, 205-281]. Linked to terpene profiles. Market preference for unique profiles (Transcript P.152, P.170, P.192).**
  + **Flavonoid Content: Contribution to pigmentation (anthocyanins for purples, Transcript P.14-15) and other effects [96, 97].**
  + **Volatile Sulfur Compound (VSC) Content: Contribution to pungent notes ("gas," "skunk") [96].**
  + **Decarboxylation Profile: How readily cannabinoid acids convert to neutral cannabinoids [76-78, 87-89].**
* **2.2.3 Visual/Morphological Quality Traits (Bag Appeal)**
  + **Bud Appearance: Overall shape (e.g., "golf balls" Transcript P.181), trim quality [31, 59, 98-100, 107, 140, 176, 189, 220, 267, 277, 314].**
  + **Bud Density: (airy, medium, compact, "rock-hard" under LEDs Transcript P.202).**
  + **Bud Color: (e.g., green, purple, orange hues) [67, 98, 107, 113, 123, 140, 189, 194, 247, 249, 262, 264, 265, 314, 317, 318, 332]. Often influenced by genetics and temperature (cold for purples, Transcript P.14-15) or "Fade" nutrients (Transcript P.14).**
  + **Trichome Density/Coverage ("frostiness") [34, 49, 55, 59, 66, 71, 75, 93, 101-104, 134, 137, 158, 220, 233, 267, 280, 318, 321, 332-337]. Athena Stack can visually increase (Transcript P.160).**
  + **Trichome Color/Appearance: Clear to milky to amber as maturity indicator [90, 98, 105-109]. Differentiated by fluorescence [107, 110, 111]. Important for hash making timing (Transcript P.197).**
  + **Trichome Characteristics: Type, size [34, 49, 55, 59, 66, 71, 75, 93, 134, 137, 158, 220, 233, 267, 280, 318, 321, 332-337].**
  + **Pistil Color (Mature): Orange-red, pink-purple, brown [90, 98, 105, 220, 321]. Indicator of maturity.**
  + **Leaf-to-Calyx Ratio: Influences trim efficiency [98, 112].**
* **2.2.4 Effect Profile & Other Traits**
  + **Effect Profile: Psychoactive, physical, therapeutic effects [25, 34, 36, 40, 55, 63-66, 68-72, 75, 90, 93-105, 107-110, 112-115, 117, 118, 120-122, 125-137, 139-151, 153-203, 205, 206, 211, 212, 222, 223, 226, 229, 230, 232, 233, 235-246, 248-258, 260-313]. Linked to cannabinoid/terpene profiles (entourage effect) [93, 114]. Categories like "creative focus," "relaxation," "energy" [115, 116, 282, 293]. Market preference shifting from pure THC to overall experience/terps (Transcript P.170, P.192, P.197, P.239).**
  + **Uniformity and Stability: How consistently a trait is expressed [11, 17, 19, 20, 24, 25, 30, 31, 68, 75, 92, 106, 123, 316, 330, 331]. Important for reliable product.**
  + **Sex Expression Tendency: Dioecy, monoecy, hermaphroditism [23, 321]. Genetic predisposition to herm under stress (Dante's Inferno #6, Transcript P.152). Ability to induce for breeding (STS, Transcript P.169) [30, 321].**
  + **Other Morphological Traits: Stem color (e.g., purple stems) [17], foxtailing (genetic in some strains, Transcript P.120) [119, 135, 148, 295, 318, 321].**
  + **Biostimulant/Microbial Response: Genetic variability in response [346].**
  + **Water Activity: For storage and mold prevention [117].**
  + **Shelf Life/Stability: Preservation of cannabinoids/terpenes. Affected by drying/curing (Transcript P.179, P.298-299).**
  + **Nutritional Content (Seeds): Protein, oil, phenolic compounds [119, 120].**

#### 2.3 Breeding Methodologies and Processes Parameters

**Parameters defining the techniques and strategies used to create and manage new cannabis varieties. Breeding philosophy: MHigh Dave emphasizes finding unique terpene profiles and not just chasing hype (Transcript P.150-152); Bean Fiends emphasizes thorough testing before release (Transcript P.187).**

* **2.3.1 Parent Selection**
  + **Based on desired traits (e.g., unique terpenes, vigor, structure, resistance) [5, 7, 10, 17, 45, 132, 135, 142, 176, 202]. (Transcript P.151-152, P.170-171).**
  + **Phenotypic Selection: Based on observable traits [5, 7, 17-20, 127, 145, 173-176]. Critical in pheno hunts.**
  + **Genotypic Selection: Based on genetic information (e.g., from DNA fingerprinting or marker analysis).**
  + **Marker-Assisted Selection (MAS): Using genetic markers linked to traits [7, 8, 11, 13, 16, 21, 22, 131, 198, 203, 225-227]. (e.g., for HLVd resistance, PM resistance genes, Transcript P.79).**
  + **Genomic Selection (GS): Using genome-wide markers to predict breeding value [7, 8, 10, 11, 13, 16, 18, 198, 203, 225, 226, 229]. Higher tier [7, 22].**
  + **Optimal Contribution Selection: Maximize genetic gain, minimize inbreeding [7].**
  + **Male Selection: Crucial. Structure, vigor, stem rubs for aroma, and ultimately, progeny testing (performance of offspring) are key (Symbiotic, Transcript P.170-171).**
* **2.3.2 Mating Designs and Sexual Reproduction**
  + **Generations: Tracking P, F1, F2, F3+ [132, 151-155]. F1s for diversity, later generations for stabilization (Transcript P.168, P.188, P.319).**
  + **Manual Pollination: Player identifies plants, collects/applies pollen [5, 23, 135-137, 145, 146]. Shaking males in a room with females (Symbiotic, Transcript P.170).**
    - **Pollen Collection Rate: Amount of viable pollen [137]. Some reversed females produce little or delayed pollen (Transcript P.169-170).**
    - **Pollination Success Rate: Probability of seed set [47, 147].**
    - **Controlled Environment: Isolated breeding spaces to prevent unwanted pollination [23, 42, 146, 148, 149].**
  + **Natural/Open Pollination: Pollen drift distance parameter [23, 42, 145, 147-150].**
  + **Controlled Crosses: Manually pollinating specific plants [23]. (e.g., Bean Fiends x Symbiotic collabs, Transcript P.318).**
  + **Reciprocal Crosses: A x B and B x A to assess maternal effects [7].**
  + **Diallel Crosses: All possible crosses between a set of parents [7]. For general/specific combining ability.**
* **2.3.3 Asexual Reproduction (Propagation for Preserving Genetics)**
  + **Cloning (Vegetative Cuttings): Genetically identical copies from mother plant [4, 5, 19, 31, 38, 42-48, 121, 133, 156-160]. Preserves phenotype/genotype [19, 31, 38, 49, 138, 163-166]. Standard practice for maintaining "keepers."**
    - **Cutting Success Rate: [133, 159]. Influenced by technique, hormones, environment, mother plant health, genetics [133, 159, 160]. Some strains are hard to clone.**
    - **Rooting Time: [160-162]. Influenced similarly [159, 160].**
    - **Mother Plant Maintenance: Keeping plants in vegetative state [4, 19, 31, 45, 47, 121, 133, 156, 159, 160]. Regular refresh of moms is good practice (e.g., every 6-8 weeks, Transcript P.183). Older moms can decline or accumulate pathogens (Transcript P.34, P.183).**
    - **Cloning from Flowering Plants: Possible, may take longer [157, 162].**
    - **Genetic Stability: Clones are identical; phenotypic differences due to GxE [5, 138, 163-167].**
    - **Clonal Rejuvenation: Tissue culture to restore vigor or clean pathogens [168] (Transcript P.17-18).**
  + **Tissue Culture/Micropropagation: Advanced sterile lab technique [6, 33, 43, 50-52, 56, 59, 64, 66, 138, 165, 169-171].**
    - **Protocol Success Rate: For initiation, multiplication, rooting, acclimatization [56, 69, 138]. Genotype-dependent [33, 56, 67, 69].**
    - **Pathogen Eradication (Meristem Culture): [33, 50, 51, 56, 59, 67, 138]. Especially for HLVd (Transcript P.17-18, P.81). Success varies by genotype and lab skill. Can take multiple attempts (Transcript P.17-18).**
    - **Regeneration Capability: From explants (nodal segments, callus, protoplasts) [64, 67, 68, 138]. Protoplast regeneration is a bottleneck [68].**
    - **Genetic Stability: Assessed with markers (e.g., ISSR) [138, 163, 165]. Generally stable.**
    - **Equipment and Sterile Technique: Required (Laminar flow hood, autoclave, microscope) [169, 170, 172] (Transcript P.18-19). Cost can be $5k-$50k for a lab (Transcript P.18-20).**
    - **Benefits: Cleaning genetics, long-term storage/archiving of genetic libraries, rapid multiplication (Transcript P.17-22).**
* **2.3.4 Population Development and Breeding Strategies/Schemes**
  + **Selective Breeding (Phenotype Selection): [5, 127, 145, 173-176]. Traditional, slower [173]. Still the primary method in pheno hunts (Transcript P.150-155).**
  + **Crossbreeding & Hybridization: Creating hybrids from distinct parents [6, 20, 135, 147, 173, 176, 177]. Creates new combinations, hybrid vigor [6, 20, 173]. (e.g., Symbiotic crossing Purple Punch male with various elite females, Transcript P.167).**
  + **Population Types:**
    - **F1 Hybrid: First generation from distinct parents [5, 11, 19, 25, 30-32, 136, 152, 155, 183, 186, 187]. Often exhibit heterosis. Uniform if parents stable. High diversity for pheno hunting (Transcript P.168, P.188).**
    - **F2 Population: From selfing/intercrossing F1s; segregation occurs [4, 5]. Can reveal recessive traits.**
    - **Recombinant Inbred Lines (RILs): From repeated selfing of F2 individuals [7]. For mapping/gene interaction studies.**
    - **Backcross Populations (BC1, BC2, etc.): [4, 24, 25, 29]. Used to introgress specific traits (Transcript P.319-320, TH Seeds explanation).**
    - **Synthetic Varieties: Intercrossing parental lines, random mating [7].**
    - **Diversity Panels: For association mapping [128].**
  + **Developing True-Breeding Lines (Inbred Lines - IBLs): Mating related individuals for homozygosity/stability [2, 3, 6, 10, 11, 16, 17, 19, 20, 24-27, 30, 31, 34, 136, 151, 153, 178-182]. Breed true [2-4, 29, 151, 180, 182]. Requires many generations [2]. Working lines to F4/F5 for stability (TH Seeds, Transcript P.320).**
    - **Inbreeding: Essential for stable lines [9, 10].**
    - **Inbreeding Depression: Reduced vigor/fertility from deleterious recessives [6, 144, 178, 183, 184].**
    - **Managing Inbreeding: Population size, new genetics, nucleus breeding [144, 178, 185].**
  + **Backcrossing (BX): Crossing hybrid to recurrent parent to transfer specific trait [4, 6, 7, 18, 24-29, 136, 151, 152, 178, 181, 183, 188, 189]. Percentage of recurrent parent genome increases each generation [183, 189]. Used to reinforce traits of a mother plant using new male offspring (TH Seeds, Transcript P.319-320).**
  + **Self-Pollination (Selfing, S1): Crossing plant with itself [6, 18, 190, 191]. Increases homozygosity. Induced chemically [1, 25, 41]. Used to create S1s of elite cuts (e.g., Tear Gas S1, Transcript P.188) for preservation or finding similar phenos.**
  + **Stabilization: Reducing genetic variation for consistent trait expression [2, 11, 19, 20, 24-27, 30, 31, 34]. Goal of many breeding programs.**
  + **Phenotype Hunting (Pheno Hunting): Growing populations (e.g., 100s-1000s of seeds) to identify desirable individuals [6, 11, 35, 202, 204, 205]. (MHigh Dave 400 seeds, Transcript P.154; Highline 5k-10k seeds/year, Transcript P.238). Requires meticulous observation and record keeping. Taking cuts of all plants before flower is a common SOP (Transcript P.154).**
  + **Seed Production Methods:**
    - **Seeds: Generative propagation, introduces variation unless stable lines [23, 31, 36-41].**
    - **Feminized Seeds: Using induced female pollen (from STS/colloidal silver treatment (Transcript P.169)) on females for all-female offspring [25, 31, 41, 192]. Risk of hermaphroditism if unstable genetics [148, 192, 193]. European market demand is high (Transcript P.170). Some reversed females are poor pollen producers or pollen is delayed (Transcript P.169-170).**
    - **Autoflowering Genetics: Breeding with C. ruderalis [53-57].**
    - **Triploid Seeds: Crossing tetraploid (4x) with diploid (2x) for sterile triploid (3x) offspring [11, 150, 194, 195]. Prevents seeding. May have distinct morphology/aromas, not necessarily higher potency [196]. More variation if parents not homozygous [197]. (Post-MVP)**
    - **Developing Semi-Full-Term Varieties (Quicks): Crossing autoflowering and photoperiod parents [44].**
  + **Doubled Haploids (DHs): Homozygous lines in one generation from haploid cells [18, 33, 138, 139]. Accelerates breeding.**
* **2.3.5 Breeding Program Management**
  + **Breeding Goals/Objectives: Defining desired traits (e.g., unique terps, yield, disease resistance, market trends like "candy" or "gas") [198-201] (Transcript P.151-152, P.172, P.187).**
  + **Record Keeping: Pedigree, phenotype, genotype, stock inventory [121, 152, 207]. Crucial for tracking selections.**
  + **Data Collection: Meticulous recording of observations during pheno hunts [45, 121, 134, 202, 206].**
  + **Selection Intensity: Proportion of individuals selected (e.g., finding 9 keepers from 231 seeds - Coffin Candy hunt, Transcript P.305).**
  + **Breeding Cycle/Generation Time: [18, 208, 209]. From seed to tested selection can take a year or more (MHigh Dave, Transcript P.154). Seed production itself is 3-4 months plus testing (Symbiotic, Transcript P.168).**
  + **Resource Constraints: Space (veg space for holding cuts during pheno hunt is critical, Transcript P.186), labor, budget [64, 65, 202, 208, 232, 244]. Pheno hunts are expensive (MHigh Dave $10k-$15k on seeds, Transcript P.150, P.154).**
  + **Testing: Sending selections to multiple testers in varied environments for feedback before release (TH Seeds, Transcript P.320).**

#### 2.4 Genetic Resource Management Parameters

**Parameters related to acquiring, storing, and managing genetic material.**

* **2.4.1 Germplasm Acquisition**
  + **Source: Landraces (diverse, locale-adapted, unique alleles, risk of erosion) [14, 20, 49, 50, 121-127], Feral populations [49, 50], Heirloom varieties [82], Modern cultivars (elite cuts from other breeders/growers, Transcript P.1, P.163, P.165) [14, 122], Breeder collections [128].**
  + **Access Restrictions: Legal/regulatory hurdles [64, 129-131]. DEA rescheduling has eased shipping of seeds and <0.3% THC cuttings (Transcript P.1-2, P.276-277).**
  + **Acquisition Methods: Expeditions, NPC contacts, quests, vendors (e.g., Clone America, Transcript P.1), events [6]. Direct trades/purchases between growers.**
  + **Origin Dossier/Acquisition Report: Source and characteristics info [6]. Verifying authenticity of acquired cuts is a challenge (HLVd risk, mislabeling).**
* **2.4.2 Genetic Material Storage**
  + **Seed Bank: Long-term seed storage [47, 50, 121, 132, 133]. Keeping extensive seed libraries (Highline 5-10k seeds/year hunts, Transcript P.238).**
    - **Storage Conditions: Temperature (-20°C), humidity influence viability [121].**
    - **Inventory Management: Tracking lots, parentage, generation, traits [121, 132-134].**
  + **Pollen Inventory: Storage of collected pollen [132, 135-137]. Fresh pollen preferred by some (Symbiotic, Transcript P.170).**
    - **Storage Conditions: Temperature, humidity influence viability [132]. Freezer storage with desiccant.**
    - **Viability Degradation Rate: Decreases over time [132].**
  + **Tissue Culture Inventory: In vitro storage for preserving "keepers" and mother stock [69, 132, 138] (Transcript P.21-22).**
    - **Storage Methods: Slow growth (short-medium term), Cryopreservation (long-term) [69, 138, 139]. Influence stability/viability [69].**
    - **Passage Number: Subculture count, can influence stability [138].**
    - **Benefit: Massive space saving for large genetic libraries (Jungle Boys 400-500 strains in TC vs. traditional moms, Transcript P.21).**
* **2.4.3 Germplasm Conservation**
  + **Importance: Preserving genetic diversity for future breeding/resilience [20, 49, 50, 124, 127, 134, 140-142]. Preventing loss of valuable cuts (Craft Farmer, Transcript P.21).**
  + **Methods: Genebanks (ex situ via TC or seed banks) [69, 121, 124, 125, 138, 140, 143], On-farm conservation (in situ - maintaining mother plants) [140, 143], Documentation of traditional knowledge [124, 140].**
  + **Effective Population Size (Ne): Maintaining large Ne to slow inbreeding/drift [125, 144].**

#### 2.5 Genetic Analysis and Advanced Breeding Technologies Parameters

**Parameters defining tools for understanding and manipulating genetics at a deeper level.**

* **2.5.1 Genetic Analysis**
  + **DNA Extraction: Obtaining genetic material [210]. (Leaf samples for HLVd/fingerprinting, Transcript P.81, P.332).**
  + **Molecular Markers: Specific DNA sequences (SNPs, SSRs/STRs, ISSRs) for identification/tracking [8, 13, 16, 17, 51, 122, 131, 203, 210, 211].**
    - **STR Analysis: For DNA fingerprinting, relatedness [210-212].**
    - **SNP Analysis: For high-density genotyping, association mapping [13, 16, 17, 121, 122, 203].**
  + **Genotyping: Determining genetic makeup [17, 121, 131, 203, 213].**
  + **Sequencing (DNA/RNA): Determining nucleotide order [14, 16, 17, 121, 122, 130, 214-218]. Cannabis genome still being fully mapped (Transcript P.78).**
    - **Whole Genome Sequencing (WGS) [213, 216].**
    - **Genotyping-by-Sequencing (GBS) [121, 213].**
    - **RNA Sequencing (RNA-seq) for transcriptomics (gene expression) [14, 214, 218-221].**
  + **Bioinformatics Pipelines: Tools for processing and analyzing large genetic/omics datasets [6, 16, 131, 206, 362, 372].**
  + **Genetic Mapping: Determining relative positions of genes/markers [14, 17, 21, 213].**
  + **Association Mapping (GWAS/mGWAS): Identifying genomic regions/genes associated with traits [14, 15, 19, 121, 213, 222, 223]. mGWAS links variation to metabolite profiles [222]. (e.g., finding genes for PM resistance, Transcript P.79).**
  + **QTL Mapping: Identifying QTLs in biparental populations [12, 14-16, 128, 213, 223].**
  + **Parentage Testing: Confirming parentage [210].**
  + **Strain Identification/Authentication: Genetic fingerprinting to verify cultivars (MyFloraDNA CCI, Transcript P.331-334) [82, 134, 224]. Helps combat renaming and ensures consumers get authentic genetics.**
  + **Hemp vs. Drug-Type Differentiation: Genetic/chemical tests [75, 224]. Based on Δ⁹-THC content (Transcript P.2, P.276-277).**
  + **Population Structure and Diversity Analysis: Understanding genetic relationships/diversity [7, 10, 11, 12, 21, 122, 141, 144, 233, 362, 372].**
  + **Fine Mapping and Causal Gene Validation: Identifying specific genes/polymorphisms [21].**
  + **Pathogen Testing: PCR-based tests for HLVd (Tumi Genomics, MyFloraDNA, Transcript P.77, P.81-84, P.327), Fusarium (Transcript P.84), and other viruses/fungi. Importance of regular testing of mother stock (Transcript P.82). Sample pooling for cost efficiency in large scale testing (Transcript P.17).**
  + **Transcriptomics and Proteomics: Studying gene expression and protein production [21, 214, 218-221, 347].**
  + **Metabolomics: Comprehensive analysis of metabolites [12, 21, 79-81, 85, 87-89, 222, 347].**
  + **Epigenetics: Heritable gene expression changes without DNA sequence changes [12, 371].**
* **2.5.2 Advanced Breeding Technologies**
  + **Marker-Assisted Selection (MAS): (Covered in 2.3.1, fundamental to advanced breeding strategies).**
  + **Genomic Selection (GS): (Covered in 2.3.1, fundamental to advanced breeding strategies).**
  + **Genomic Prediction Accuracy: Parameter defining how accurately genetic merit is predicted [7, 9, 10].**
  + **Gene/Genome Editing (CRISPR/Cas9): Precise gene modification [6, 14, 16, 21, 66, 84, 198, 203, 225, 230, 231]. Potential for targeted trait modification (e.g., PM resistance, Transcript P.79) [16, 84, 230]. Requires efficient transformation/regeneration [224]. Subject to regulations [16, 50, 65].**
  + **Genetic Transformation (Introducing foreign DNA): [6, 16, 64, 138].**
  + **Somatic Hybridization (Protoplast Fusion): Fusing cells to create hybrid [68, 138, 139]. Regeneration is a bottleneck [68].**
  + **Doubled Haploid (DH) Production: (Covered in 2.3.4).**
  + **Speed Breeding: Shortening generation time [18, 232].**
  + **Consensus Genetic Maps/Reference Genomes: Integrated data for comprehensive resources [372].**
* **2.5.3 AI Research Lab (In-Game Concept)**
  + **Probabilistic Predictions: For breeding outcomes based on genetic data/AI models [6, 11].**
  + **Genetic Marker Analysis (Simplified): Abstracted MAS/GS for early seedling selection [6, 11, 170, 228].**
  + **AI Model Complexity: Potential for complex models (e.g., small neural networks) [6].**

#### 2.6 Genetic Simulation Parameters (Game Engine Specific)

**Parameters specific to modeling genetic inheritance and population dynamics within the game.**

* **Trait Heritability (h²): Proportion of phenotypic variation due to additive genetic effects [21, 208, 233]. Influences selection effectiveness.**
* **Genetic Correlation: Degree to which two traits are influenced by the same genes [21, 208].**
* **Breeding Value (BV) / Genomic Estimated Breeding Value (GEBV): Estimated genetic merit [208, 229, 233].**
* **Allele Frequencies: Proportion of a specific allele in a population [21, 102, 103, 233, 234].**
* **Linkage Disequilibrium (LD): Non-random association of alleles at different loci [208, 233, 234].**
* **Inbreeding Coefficient (F): Probability of homozygosity by descent [233, 234].**
* **Genetic Diversity Metrics: Quantifying genetic variation (e.g., heterozygosity, alleles per locus, Ne) [122, 141, 144, 233].**
* **Genotype x Environment Interaction (GxE) Modeling: Parameters for how genotypes respond to environmental variations (light, temp, nutrients) [9, 21, 52, 70, 167, 208, 224, 235-238]. (Transcript passim).**
* **Burn-in Phase (Simulated Historical Breeding): Modeling historical selection to create realistic starting LD and diversity [234].**

#### 2.7 Data Management and Visualization Parameters (In-Game)

**Parameters related to handling and displaying genetic and breeding data within the simulation.**

* **Breeding Database: Centralized system for pedigree, phenotype, genotype, environmental, trial metadata [121, 129]. Tracking selections from large pheno hunts (Transcript P.154, P.238).**
* **Trait Library: Player-populated database of known traits and associated markers/genotypes [6, 228].**
* **Pedigree Tracking: Visualizing and managing family trees [6, 134, 152, 239].**
* **Genetic Data Display: Presenting simulated genotype ID, alleles, markers, linked to traits [203, 228, 240]. Displaying CCI from MyFloraDNA (Transcript P.331-332).**
* **Phenotype Observation Data: Recording visual/measured characteristics [5, 202, 241]. Linking observed traits to genetics [5, 241].**
* **Breeding Interface: UI for parent selection, crosses, project management, outcome prediction [118, 132, 203, 228, 239].**
* **Data Visualization: Tables, charts, graphs, visual overlays on plant models [70, 118, 134, 203, 228, 240, 241].**
* **Workflow Management: Tools for outlining/tracking breeding program steps [209, 239]. Managing multiple ongoing hunts and breeding lines.**

#### 2.8 Challenges and Risks Parameters (In-Game)

**Parameters representing potential difficulties and failures in breeding and genetic work.**

* **2.8.1 Biological Challenges**
  + **Tissue Culture Recalcitrance: Genotype-dependent regeneration difficulty [65, 67, 69]. Some strains are very difficult to clean via TC (Transcript P.17-18).**
  + **Genetic Instability: Somaclonal variation, inbreeding depression [138, 144, 163, 178, 183, 184]. Hermaphroditism in feminized lines or due to stress (Transcript P.152, P.169-171).**
  + **Disease/Pest Transmission: Through cloning (HLVd is notorious, Transcript P.17, P.80) or seed (HLVd in seeds being studied, Transcript P.17, P.81) [56, 59, 157, 242].**
  + **Poor Germination: Old seeds or bad genetics (Transcript P.168).**
  + **Low Pollen Production/Viability: In some males or reversed females (Transcript P.152, P.169-170).**
* **2.8.2 Technical Challenges**
  + **Phenotyping Bottlenecks: Difficulty in accurate, high-throughput data collection for large hunts [118, 243]. Subjectivity in selection.**
  + **Data Integration and Management Complexity [19, 129].**
  + **Modeling Complexity: Simulating epistasis, dominance accurately [19].**
  + **HLVd Testing Inconsistencies: Different labs, sample times, or locations within plant can give varied results (Transcript P.17, P.81-82).**
* **2.8.3 Legal and Regulatory Obstacles (Abstracted)**
  + **Licensing, permit requirements for research/access to genetics [16, 21, 50, 64, 66, 129, 130, 227, 243]. Evolving DEA rules on shipping genetics (Transcript P.1-2).**
  + **Banking challenges for cannabis businesses, including seed sales (Transcript P.2).**
* **2.8.4 Resource Constraints**
  + **Limited budget (pheno hunts are expensive - seeds, space, labor, testing, Transcript P.150, P.154), space, equipment, skilled personnel [64, 65, 202, 208, 232, 244].**
* **2.8.5 Ethical Considerations (Abstracted)**
  + **Impacts on genetic diversity, IP (importance of DNA fingerprinting, Transcript P.331-334), access to genetics/technology [140, 142, 245-248]. Misappropriation of genetics/renaming (Transcript P.154, P.313).**
* **2.8.6 Unforeseen Outcomes**
  + **Unexpected trait combinations from recombination/complex interactions [6, 46, 103, 180]. Not all traits fully predictable. Finding no keepers in a large hunt (MHigh Dave, Transcript P.154).**

### 3. Facility and Grow Operation Science Parameters

**This section details the parameters related to the physical infrastructure, environmental controls, operational processes, and resource management within cannabis cultivation facilities, drawing upon principles from agricultural physics, engineering, and horticulture. Facility design and operational SOPs are critical for success and preventing issues like HLVd or pest outbreaks (Transcript P.17, P.80, P.341).**

#### 3.1 Facility Infrastructure Parameters

**Parameters defining the physical structure, layout, and materials of cultivation spaces.**

* **Facility Types:**
  + **Residential House Interior [1-3]: Initial small-scale environment. Pre-defined layout [3]. Initial wear and tear can be simulated [3]. Often limited power (Transcript P.108). "Trap grows" or caregiver setups are often in residential settings (Transcript P.3, P.6, P.30-33).**
  + **Warehouse [1-3]: Larger scale, unlocked after Residential [1, 4]. Giant open shell to build within [3]. Common for commercial grows (Transcript P.44, P.56, P.166).**
  + **Greenhouse [2, 5, 6]: Moderate control, leverages natural light [7, 8]. Glass or polycarbonate covering [2]. Requires ventilation and temperature control [6]. Can be hoop house or more advanced [9, 10]. Mix-light (HPS/LED + natural light) is common (Transcript P.42, P.223, P.296). Susceptible to outdoor environmental pressures (pests, temp/humidity swings).**
  + **Vertical Farm [11]: High density, max space use [12]. Multi-tiered racking/towers [13, 14]. Requires vertical transportation logistics [15].**
  + **Research Lab [2, 5]: Specialized, sterile environment [2, 16]. Required for advanced techniques like Tissue Culture [16] (Transcript P.18-20).**
  + **Outdoor Field [2, 5]: Low control, relies on natural environment [8, 9]. Subject to weather/pest risks [7]. Can include secure plots [9]. Challenging in climates like Michigan due to humidity/cold (Transcript P.5-6).**
  + **Subterranean Lab [3, 17]: Potential future map [3, 17].**
  + **Abandoned Research Outpost [3, 17]: Potential future map [3, 17].**
  + **Geothermal Greenhouse Complex [3, 17]: Potential future map [3, 17].**
* **Structural Elements: Parameters defining buildable components within facilities.**
  + **Walls [3, 18, 19]: Sections/panels [19]. Material properties: cost, appearance, insulation (R-value), light/air barrier, cleanliness [3, 19]. Non-porous, smooth, durable, non-absorbent, chemical-resistant materials preferred for sanitation (e.g., FRP, insulated metal panels) [20, 21]. Materials influence cleaning ease [20]. Coving at wall-floor junctions recommended [20]. False walls used in "trap grows" (Transcript P.209).**
  + **Floors [3, 22]: Sections (Concrete, Wood, Grate - load ratings) [22]. Drains (Standard, Trench - capacity) [22]. Non-porous materials preferred (epoxy coated concrete) [20]. Coving at wall-floor junctions recommended [20]. Sloped floors for drainage.**
  + **Roofs/Ceilings [3, 22]: Sections (Drywall, Suspended Grid, Concrete) [22]. Suspended Tiles (acoustic, cleanroom) [22]. Open Rafters/Trusses (Wood, Metal) [22]. Influence large-scale microclimate patterns [13]. High ceilings can cause thermal stratification [13]. Ceiling height impacts light placement and stretch management (Transcript P.114). Typical grow room ceiling height 8-10ft, some newer facilities higher.**
  + **Doors [3, 18, 22]: Various types (Standard, Industrial Roller, Air Lock) [22]. Air locks minimize contaminant entry [23]. Weather stripping and seals important.**
  + **Windows [22]: Various types (Standard, Greenhouse, Industrial) [22]. Greenhouse-specific windows [22]. Can be blocked out in grow rooms [24]. Light leaks are a major concern for photoperiod control (Transcript P.171).**
  + **Stairs/Ladders/Catwalks [25]: Vertical access [25]. Relevant for multi-story/vertical facilities [25].**
  + **Support Pillars/Beams [25]: (Concrete, Steel) [25]. For structural support in large spaces [25].**
  + **Containment Structures (Tents): Pre-fab grow tents [26]. Provide dedicated grow spaces [26]. Sealable for environmental control [8].**
* **Facility Layout and Zoning: Parameters defining the spatial arrangement and compartmentalization of facilities.**
  + **Grid System: Grid-based construction [3, 18]. Base unit 1 foot [27]. Snapping to grid lines, intersections, object points [27].**
  + **Zoning: Designating distinct areas by cultivation stage/activity [3, 28]. Mother Rooms, Propagation (Clone Rooms), Vegetative, Flowering, Drying, Curing, Trimming, Packaging, Waste Handling, Ancillary Areas (Offices, Labs, Storage, Decontamination) [29, 30] (Transcript P.58-59, P.98-99). Physical barriers prevent contaminant movement [23, 28]. Allows tailored environmental/hygiene protocols [28]. Veg rooms often 30% of flower footprint (Transcript P.98).**
  + **"Clean Flow" Principles: Layout/workflows minimize contaminant movement [23, 31]. Unidirectional process flow (cleaner to dirtier areas) [23, 32]. Strategic management of people, plant materials, supplies, waste flow [23]. Controlled access points with hygiene stations (booty/gown change, hand wash) [33, 34] (Transcript P.341). Dedicated staff/protocols for high-risk zones [33, 34].**
  + **Workflow Optimization: Designing layouts for efficient movement of plants, materials, personnel [32, 35]. Reducing travel distances [32]. Incorporating workflow principles for post-harvest processing [36]. Cellular layouts for grouping processes [37]. (Kings Garden example, Transcript P.58-59).**
  + **Vertical Layout Challenges: Managing horizontal and vertical movement of plants/supplies in multi-level farms [15]. Integrating automated systems or designing ergonomic manual solutions [15].**
  + **Clutter Management: Providing adequate space, encouraging vertical space use, incorporating storage solutions [38, 39]. Designing assets with clear footprints [39].**
  + **Facility Aesthetics: Maintaining a clean, pristine, professional visual aesthetic [38, 40]. Materials influence appearance [19].**
* **Utility Networks: Parameters defining the infrastructure for power, water, and potentially gas/other systems.**
  + **Plumbing Network: Detailed, interconnected networks [3]. 3D routing, snapping/free placement, collisions [3]. Sizing (diameters) impacts performance (flow, pressure drop) [3]. Material impacts cost, durability, efficiency, appearance [3]. Logical source-endpoint connections [3]. Recirculating DWC systems require careful plumbing to avoid pathogen spread (e.g. Fusarium, Transcript P.84).**
  + **Electrical Network: Detailed, interconnected networks [3]. 3D routing, snapping/free placement, collisions [3]. Sizing (gauges) impacts performance (capacity, voltage drop) [3]. Material impacts cost, durability, efficiency, appearance [3]. Logical source-endpoint connections [3]. Basic abstracted utility connections (power draw) in MVP [18, 41]. Power limitations are a major constraint in many grows (Transcript P.5, P.108). Transformer upgrades can lower electricity costs (Transcript P.5).**
  + **HVAC Ducting: Part of HVAC system, routed through facility [3]. Size and design impact airflow, pressure loss, noise [42]. Material impacts cost, durability, efficiency, appearance [3]. Designed for accessibility for cleaning [28].**
  + **Source Connection Points: Main Power Grid Connection Point (Abstracted) [41]. Water Supply Connection Point (Abstracted - Tap, RO, Treated) [41]. Gas line connection (for generators/heaters). Some facilities require substations built for power needs (Transcript P.5).**
  + **Utility View/ "X-Ray" Mode: Visual overlay to see hidden networks [3, 39, 43]. Shows pipes, ducts, wires, flow/pressure indicators [39, 43]. Unlocked with progression [44]. Simple, non-simulated flow animations for feedback [3, 39].**

#### 3.2 Environmental Control Science Parameters

**Parameters defining the systems and principles for regulating the atmospheric conditions within cultivation spaces. Environmental control is key to quality and preventing issues like bud rot (Transcript P.7-8, P.15).**

* **Temperature Management:**
  + **Optimal Ranges: Vary by growth stage (Seedling, Vegetative, Flowering) [45-48]. Vegetative: 21-29°C (70-85°F) day, ~10°F lower night [47, 48]. Flowering: 18-27°C (65-80°F) day, ~10°F lower night [47, 48]. Some run flowering temps 73-76°F with "Fade" (Transcript P.15), or even 76-80°F with LEDs (Transcript P.161, P.61-62). Root zone: 18-24°C (65-75°F) [48, 49]. Optimal range can be cultivar-specific [50]. Cold temps (e.g., mid-60s F) can induce purple colors (Transcript P.14-15).**
  + **Measurement: Air temperature sensors (Thermistors, RTDs, Thermocouples, Infrared) [51]. Root zone temperature probes [46]. Leaf surface temperature sensors (for VPD) [52]. Sensor placement critical for accuracy (Transcript P.11).**
  + **Control Systems: Thermostats [53, 54]. HVAC systems (Heating and Cooling components) [55, 56]. Supplemental heaters/coolers [57]. Diurnal temperature variations can be programmed [58]. Growlink Blueprint for scheduling (Transcript P.139).**
  + **Heat Sources: Grow lights (HID produce more heat than LED, Transcript P.61-62, P.113, P.160-161, P.202, P.223-224) [59-62]. Electrical equipment [59, 62]. Plant transpiration (latent heat load) [62, 63]. Outside air infiltration/ventilation [62]. Conduction/convection through building envelope [62].**
  + **Heat Management: Ventilation (mechanical/natural) for removing excess heat [56, 64]. Insulation (R-value) minimizes heat transfer [65]. Facility design (sealed rooms) [66]. HVAC systems sized to manage sensible heat loads (e.g., 0.6 tons/light, Transcript P.62) [60]. Airflow patterns influence temperature uniformity [60, 67].**
  + **Dew Point Control: Managing temperature fall and humidity to prevent condensation/fungal proliferation [68].**
* **Humidity Management:**
  + **Optimal Ranges: Vary by growth stage [45-48]. Seedlings/Clones: 65-80% RH [48, 69]. Vegetative: 50-70% RH [48, 69]. Flowering: 40-50% RH [46, 48, 69, 70], though some run higher with LEDs (60-65% RH, Transcript P.161) if airflow is excellent. Persistently high humidity (esp. root ball) -> fungal issues [66] (Transcript P.7-8, P.15). Optimal range can be cultivar-specific [50].**
  + **Measurement: Humidity sensors (Hygrometers) [54]. Canopy microclimate RH sensors [52]. Sensor placement critical (Transcript P.11).**
  + **Control Systems: Humidistats [53, 54]. Dehumidifiers [55, 56]. Humidifiers [71]. Integrated HVACD systems [55, 72]. Diurnal RH variations can be programmed [58]. Growlink Blueprint for scheduling (Transcript P.139).**
  + **Moisture Sources: Plant transpiration/evapotranspiration (major latent heat load driver) [62, 63, 73, 74]. Evaporation from growing medium/reservoirs [74]. Outside air infiltration/ventilation [75].**
  + **Moisture Management: Ventilation for removing excess moisture [56, 64]. Dehumidifiers sized based on lighting wattage and transpiration rate [76]. Airflow patterns influence humidity uniformity [60, 67]. Environmental controls integrated with sanitation for disease prevention [77, 78]. Michigan's high humidity is a challenge (Transcript P.5-6).**
* **Vapor Pressure Deficit (VPD):**
  + **Concept: Air moisture vs. saturation capacity; integrates temp/RH [79]. Optimizing VPD enhances transpiration/nutrient uptake [79, 80]. (Transcript P.121-122, P.235).**
  + **Calculation: Based on air temp, leaf surface temp, and RH [79].**
  + **Measurement: Requires sensors for air temp, RH, and ideally leaf surface temp [52].**
  + **Control: Managed by adjusting temperature and humidity [79]. VPD setpoints can be strain-specific [81]. Optimal target range (e.g., 1.0-1.5 kPa) [46].**
  + **Impact: Influences water transpiration rate [79], nutrient uptake [79], pest/disease susceptibility [48]. Critical for healthy growth (Transcript P.235).**
* **Lighting Management:**
  + **Types: HID (MH/HPS - with Ballasts/Hoods, Transcript P.103, P.108, P.202), LED Panels (e.g., Luxx, ThinkGrow, Fluence, Transcript P.113, P.160, P.202, P.235), Fluorescent (T5/CFL), LEC [54, 82-84]. Spectral output varies [54, 60, 83]. HPS vs LED debates on quality/yield/heat (Transcript P.61-62, P.113, P.160-161, P.181-182, P.202-207, P.223-224). Mixed HPS/LED or checkerboard setups (Transcript P.202-203, P.223). Under canopy LED lighting (Transcript P.196, P.205, P.224-225).**
  + **Parameters:**
    - **Photosynthetically Active Radiation (PAR): Light wavelengths (400-700nm) for photosynthesis [79].**
    - **Photosynthetic Photon Flux Density (PPFD): Light quantity (µmol/m²/s) [46, 79, 85]. Optimal levels vary by stage [45, 46]. Vegetative: 200-600 µmol·m⁻²·s⁻¹ (Transcript P.161). Flowering: 800-1200+ µmol·m⁻²·s⁻¹ (esp. with CO2) [46, 86] (Transcript P.114, P.161). Some genetics sensitive to high PPFD (Transcript P.116).**
    - **Daily Light Integral (DLI): Total amount of light over a 24-hour period. Low PPFD can be fine if DLI met (Transcript P.161).**
    - **Spectrum: Influence growth, stage transition, cannabinoid/terpene synthesis [83, 87-89]. Blue-dominant for vegetative [60, 66, 83]. Red-dominant for flowering [60, 83]. Full-spectrum LEDs [66]. Customizable spectrum with LEDs [83, 87]. Far-red (Emerson effect) for end-of-day signal, can shorten flower time, improve quality (Transcript P.203-204).**
    - **Photoperiod: Light hours per day [47, 66, 85, 90]. Vegetative: 18-24 hrs light/day [47, 66, 85, 89, 90]. Flowering: strict 12 hrs light / 12 hrs uninterrupted dark [85, 89-91]. Some use 11/13 to finish (Transcript P.115). Deviations/light leaks -> hermaphroditism/reversion [89, 91]. Autoflowers are not photoperiod dependent [16, 92].**
  + **Equipment: Grow lights (fixtures) [54, 82, 84]. Ballasts (generate heat, often kept outside grow space) [54, 93, 94]. Reflective hoods/materials (focus/direct light) [54, 91, 93]. Light timers/controllers [54, 82, 95]. Light meters (measure PAR/PPFD) [54, 96].**
  + **Control: Adjust intensity (dimming), fixture height/layout for target PPFD [52]. Set light cycles [97]. Manage light leaks [89, 91, 97]. Automated systems for sunrise/sunset simulation [98]. Growlink Blueprint for scheduling (Transcript P.139).**
  + **Impact: Primary driver of growth (photosynthesis) [89]. Influences morphology, stage transition, cannabinoid/terpene production [47, 89, 99]. Light stress (photoinhibition, bleaching, burning tips if plants grow into lights, Transcript P.114) [79, 100].**
* **CO2 Management:**
  + **Concept: CO2 enhances photosynthesis, boosts yield (esp. vegetative/flowering) [87, 97, 101, 102].**
  + **Optimal Concentrations: 800-1500 ppm (flowering stage, Transcript P.161) [101]. Optimal varies with stage, light, temp, cultivar [103]. Ambient CO2 ~400 ppm [104]. CO2 uptake rate depends on canopy photosynthetic activity [102].**
  + **Measurement: CO2 sensors/monitors [71].**
  + **Control Systems: CO2 controllers [71]. CO2 enrichment systems [84, 102]. Automated systems for measured release [105]. Growlink Blueprint for scheduling (Transcript P.139).**
  + **Methods: Compressed CO2 tanks, generators (produce heat/moisture) [87, 101]. CO2-releasing pads [101].**
  + **Management: Requires careful monitoring, integration with ventilation/airflow [97, 101]. Use in sealed rooms for effectiveness [80]. Discontinue late in flowering cycle [106].**
* **Airflow and Ventilation:**
  + **Purpose: Air circulation, renewal, temperature/humidity regulation, CO2 distribution, prevents stagnant microclimates, reduces pest/disease risk (powdery mildew) [66, 79, 84, 97].**
  + **Methods: Intake/exhaust fans (basic), oscillating fans (internal) [97, 107]. Mechanical ventilation [56]. Natural ventilation (thermal buoyancy, wind manipulation in greenhouses) [64].**
  + **Equipment: Fans (various types) [1, 54, 84]. Filters (carbon filters for odor, air filtration systems with MERV ratings, HEPA filters for intake/recirculation, Transcript P.347) [82, 108]. Ductwork [42].**
  + **Air Exchange Rate (ACH): Number of times air is completely replaced per hour [109]. Typical indoor cannabis: 12-60 ACH [110]. Affects HVAC energy use and CO2 levels [109].**
  + **Calculation: Room volume (L x W x H) divided by desired turnover time [111].**
  + **Impact: Influences temperature uniformity [60, 67], humidity uniformity [60, 67], CO2 distribution [97], disease/pest spread [77]. Strong airflow can cause physical leaf damage [112]. Poor airflow exacerbates humidity problems [112].**
* **Microclimate Dynamics:**
  + **Concept: Spatial/temporal variations in temp, humidity, airflow, CO2, light within a grow space [67]. Creates heterogeneity [67]. Sensor placement is critical to understanding and managing (Transcript P.11).**
  + **Causes: Equipment placement/influence (fans, lights, HVAC project radius/cone of effect) [113, 114]. Airflow patterns [60, 67]. Plant canopy architecture/density (affects local humidity/CO2) [67, 114]. Facility geometry (room dimensions, internal structures) [13, 67]. Obstructions (walls, equipment) [113, 114].**
  + **Modeling: Abstracted microclimate modeling based on zone-based influence [113-115]. Periodically recalculate based on active equipment and structure [113, 114]. Not full CFD [113, 115].**
  + **Impact: Influences plant growth, development, uniformity [67]. Can lead to issues like tipburn [116]. Resource use efficiency [67].**
  + **Mitigation: Strategic equipment placement [116]. Airflow management [116]. Uniform environmental control aims to reduce heterogeneity [66]. Environmental heat maps can visualize microclimate variations [39, 117]. Validating sensor data by physically checking plants/pots in different locations (Transcript P.11).**

#### 3.3 Resource Management Parameters

**Parameters related to the inputs and outputs of cultivation: water, nutrients, energy, waste.**

* **Water Management:**
  + **Source Water: Tap, RO (Reverse Osmosis), Well water, Treated water, Recycled water (condensate, treated wastewater) [41, 118, 119]. Water quality analysis needed [120, 121]. Impurities (dissolved minerals, hardness - Ca/Mg), agrochemicals, microorganisms [120, 122, 123]. RO water is common, but may require CalMag supplementation (Transcript P.8, P.115).**
  + **Water Quality Parameters: pH (Acidity/alkalinity) [47, 82, 120, 124, 125]. Ideal range for nutrient uptake: soil 6.0-6.8, soilless/hydro 5.2-6.5 (Coco often 6.0-6.2, Transcript P.158) [47, 106, 124, 126, 127]. EC (Electrical Conductivity) / PPM (Parts Per Million) / TDS (Total Dissolved Solids) [124, 125, 128]. Measure total dissolved solids/nutrient concentration [124, 125, 128]. EC increases with added salt-based nutrients [128].**
  + **Water Treatment: Filtration (Pre-filtration for particles - Sed/Carb) [121, 123]. Purification (RO for removing dissolved solids) [118, 120, 121]. Disinfection (UV, Ozone, Chlorine injection for iron/disinfection, Transcript P.65) [121, 122, 129, 130]. Monitoring efficacy of treatment systems essential [131].**
  + **Irrigation Methods: Drip (common with coco/rockwool, Transcript P.49, P.113-114, P.124, P.174, P.180), Hydroponics (DWC, NFT, Ebb & Flow, Aeroponics), Subirrigation (Flood and Drain), Manual (watering cans), Fertigation (nutrients via irrigation) [14, 55, 89, 124, 125, 132, 133]. Method influences water use efficiency [61]. Precision irrigation with multiple small shots (P1, P2, P3 phases, Transcript P.121-125).**
  + **Irrigation Control: Timed, Manual, Sensor-driven (real-time soil moisture/EC, e.g., Growlink, Aroya, Transcript P.11, P.121-142). Automated systems (e.g., Netafim, Dosatron, Edatrons with Dilution Solutions controller, Transcript P.74, P.95, P.115, P.148) [55, 119].**
  + **Watering Frequency/Volume: Depends on medium, plant size/stage, environmental conditions [89, 136]. Overwatering leads to root/nutrient issues, disease risk (Transcript P.11, P.126) [137, 138]. Underwatering leads to dehydration [48]. Crop steering involves manipulating watering volume and drybacks (Transcript P.62, P.121-125). Hand watering once a day for some (MHigh Dave, Transcript P.157).**
  + **Water Temperature: Optimal root zone temp: 18-24°C (65-75°F) [49, 124, 139]. Affects DO, nutrient uptake, microbial growth [49, 139-141]. Colder water at end of flower can induce color (Transcript P.14). Target 2-3°C below room temp (TH Seeds, Transcript P.324).**
  + **Water Conservation: Drip irrigation, recycling/reclamation (condensate, treated wastewater, e.g., Hydrologic skids, Transcript P.64-65), media selection (water retention) [61, 142]. Condensate can provide 40-50% of water needs in desert climates (Transcript P.65).**
  + **Drainage: Proper drainage from pots/media is critical [126, 127]. Avoid standing water [127]. Influenced by substrate properties [126, 143]. Runoff management (collection, testing, disposal/recirculation, Transcript P.64-65, P.157-158). Target 15-30% runoff (Transcript P.64, P.158, P.307).**
* **Nutrient Management:**
  + **Essential Nutrients: Macronutrients (N, P, K, Ca, Mg, S), Micronutrients (Fe, Mn, Zn, Cu, B, Mo, Si) [126, 144-146]. Calcium critical for cell wall, preventing bud rot (Transcript P.7-8).**
  + **Nutrient Ratios (NPK): Vary by growth stage [82, 146, 147]. High N / low P in vegetative. Low-to-medium N and medium-to-high P/K in flowering [146, 147]. Optimal ratios can be cultivar-specific [148, 149]. "Fade" products reduce N late flower (Transcript P.7-9).**
  + **Fertilizer Types: Organic, Inorganic/Synthetic (salts, e.g., Athena ProLine/Blended, Transcript P.7-13, P.25, P.59-63, P.116, P.157, P.175, P.184, P.221), Slow-release [150-152]. Organic inputs often have higher upfront cost [152]. Simplicity of 2-part salt lines valued (Athena, Transcript P.25, P.62).**
  + **Nutrient Solution Management (Hydroponics/Soilless): Precise control of EC/PPM, pH, temperature, DO [49, 106, 124, 128, 139]. Nutrient uptake efficiency [49, 55]. Nutrient partitioning [148]. Nutrient lockout (pH imbalances, ion competition, salt buildup from high EC/inadequate runoff, Transcript P.11, P.123, P.158) [100, 149]. Precise nutrient plans needed [153]. Athena ProLine often run at 3.0 EC (Transcript P.12, P.15, P.126, P.157, P.175, P.221).**
  + **Nutrient Application: Fertigation (via irrigation) [55, 151]. Top dressing [151]. Foliar spraying (e.g. Athena Stack, IPM, Transcript P.160, P.178) [52]. Rate depends on plant maturity, stage, other factors [69, 124]. Increase concentration with maturity, peak flowering, reduce pre-harvest [124].**
  + **Nutrient Uptake: Influenced by nutrient availability, concentration, form, pH (coco 6.0-6.2, Transcript P.158), substrate type, root health, water temperature, DO [49, 125, 126, 139, 140]. Nutrient uptake efficiency [148].**
  + **Nutrient Deficiency/Toxicity: Visual symptoms (chlorosis, necrosis, stunting, leaf deformation, tip burn) [79, 100, 154]. Can interact with pH imbalances [100]. Diagnosis requires visual cues, data (EC/PPM, pH of feed and runoff, Transcript P.11, P.157-158), tissue analysis [100, 148]. Flushing with straight RO or pulling Core nutrients too early can cause Ca deficiency/bud rot (Transcript P.7-8, P.12).**
  + **Nutrient Recycling/Recirculation: Feasibility/cost-effectiveness for large-scale operations [155]. Requires water treatment skids (Hydrologic, Transcript P.64-65). Risk of pathogen spread (Fusarium, Transcript P.84).**
  + **Biostimulants/Microbial Inoculants: Potential impact on nutrient uptake efficiency, secondary metabolism, plant performance [156]. (e.g., Mycorrhizae, Trichoderma, Bacillus, Transcript P.59-60, P.62). Can cause biofilm/clogging issues with salt nutrients (Transcript P.13, P.62, P.65).**
* **Energy Consumption:**
  + **Major Consumers: Artificial lighting (primary energy use), Climate control (HVAC - heating, cooling, ventilation, dehumidification), Water pumps, Fans [155, 157-159].**
  + **Measurement: Electricity (kWh), Natural Gas (for heating) [110]. Energy Use Intensity (kWh/kg flower; kWh/m²/yr) [61]. Power Demand (Peak kW, load factor) [61]. Lighting Efficacy (μmol/J) [61]. Electricity costs can be significant (e.g., 6-17 cents/kWh, up to 42 cents in CA, Transcript P.5).**
  + **Energy Efficiency: Energy-efficient HVAC technologies [108, 160]. LED lights (more efficient, less heat than HPS, Transcript P.61-62, P.113, P.160-161, P.202, P.223-224) [60, 61, 87, 161]. Optimized environmental control strategies [50]. Building envelope optimization (insulation, air seal) [162]. Smart control strategies (VSDs, MPC, AI/ML) [42, 160]. Water/nutrient use efficiency also contributes to energy savings [135]. Transformer ownership can reduce costs (Transcript P.5).**
  + **Energy Sources: Grid power, Generators (Diesel/Gas - backup), Battery Banks/UPS (short-term buffer), On-site renewable energy (solar) [41, 163, 164]. Co-generation plants (Transcript P.5).**
  + **Energy Costs: Major OPEX (esp. indoor/controlled GH) [61, 159]. Fluctuating energy prices [153].**
  + **Environmental Impact: GHG emissions from energy consumption [61, 157, 159].**
  + **Optimization: Strategic energy management (audits, benchmarking), optimized facility design [165].**
* **Waste Management:**
  + **Waste Streams: Plant material (leaves, stems, roots, trimmed material), Used substrates, Packaging, Consumables [163]. Failed/unsellable product (Transcript P.3, P.6-7).**
  + **Characterization/Quantification: Waste generation rate (m³/kg waste categories/kg yield) [166].**
  + **Management Practices: Composting (plant material, some substrates), Recycling, Residual value extraction, Compliant disposal (metric system tracking) [163] (Transcript P.6-7). Diversion Rates (% waste diverted from landfill) [166].**
  + **Costs: Waste management costs ($/kg yield) [166].**
  + **Integration: Waste management flow prevents contamination [34]. Designated routes/areas for waste [34].**
  + **Future Vision: Explore processing/re-using waste for beneficial byproducts [27].**

#### 3.4 Cultivation Practices and Operational Parameters

**Parameters related to the day-to-day activities, workflows, and management strategies in cultivation. SOPs are critical for consistency and scalability (Transcript P.58-59, P.67, P.199, P.215).**

* **Propagation:**
  + **Methods: Seeds (Feminized, Regular, Transcript P.153, P.168-170, P.187-189, P.309, P.318-320), Clones (Cuttings from mother plants, Transcript P.1, P.17-18, P.80-82, P.154, P.183, P.228, P.308), Tissue Culture (Micropropagation, Transcript P.17-22, P.81, P.153, P.330).**
  + **Seed Germination: Requires moisture, warmth (medium temp), darkness (usually) [90, 169]. Optimal medium temperature is critical [169, 170]. Dormancy may require protocols (scarification, stratification, GA3) [126]. Influenced by genetics, medium composition, light, pH, temperature [171]. Old seeds can have poor germination (Transcript P.168).**
  + **Cloning: Cuttings from "mother plants" or plants about to flower [35, 172, 173]. Requires rooting (rooting hormones/compounds) [174, 175]. Success rate depends on heat, humidity, light, hormone, medium [176]. Clones are genetically identical [172]. Risk of inheriting pests/diseases (HLVd spread is a major concern, Transcript P.17, P.80, P.83-84) [177, 178]. Weaker roots than seed plants [177, 179]. Requires dedicated space/infrastructure [178]. Clone shipping is evolving legally (Transcript P.1-2). VP Domes or similar high-humidity environments for rooting (Transcript P.177-178). Clone dunking in IPM solutions (e.g., Athena IPM + Stack) as preventative (Transcript P.178, P.228).**
  + **Tissue Culture: Sterile lab process [16, 168]. Excising explant (shoot tips, nodal segments, meristems), surface sterilizing [168]. Establishment in vitro on nutrient medium with PGRs [180]. Multiplication/Proliferation via subculturing [180]. Potential for pathogen eradication (HLVd, Transcript P.17-18, P.81, P.330) [181, 182]. Renews old mother stock vigor [182]. High setup cost ($5k-50k, Transcript P.18-20), technical expertise required [183]. Risks: contamination, somaclonal variation, acclimatization failure, genotype specificity, vitrification [184-186]. Multi-stage process [168, 180]. Meristem culture is key for cleaning genetics (Transcript P.17-18).**
  + **Seed vs. Clone Comparison: Seeds offer genetic diversity, stronger roots; variable growth [177, 179]. Clones offer speed, predictability, uniformity; weaker roots (Transcript P.32) [177, 179]. Cost/logistics differ [187]. Most commercial grows rely on clones for uniformity (Transcript P.17).**
* **Vegetative Growth:**
  + **Initiation: Rapid leaf/root production in seedlings/clones [188].**
  + **Duration: Depends on desired plant size, cultivar growth rate, symbiotic rotation schedule [188-190]. Prolonging veg increases plant/root size but requires more space/light/time [189]. SOG requires short veg period [191, 192]. Commercial veg times vary: 10-18 days (Transcript P.58, P.176, P.217), 14-18 days (Transcript P.300), up to 5-6 weeks (Transcript P.200). "Veg in place" in flower rooms becoming more common to save labor/time (Transcript P.175-176, P.198-200, P.300).**
  + **Requirements: Long light periods (18-24 hrs, Transcript P.181) [47, 66, 90]. High nitrogen nutrients [146, 147, 193]. Moderate humidity (60-70% RH, Transcript P.161) [48, 69]. Optimal temperature (70-85F, Transcript P.161) [47, 48, 170]. Airflow/ventilation [66, 79]. Adequate space [189]. Low PPFD (200-600, Transcript P.161) can be sufficient if DLI is met.**
  + **Daily Care: Watering/irrigation, monitoring health/environment [194, 195]. Fairly tough stage [194].**
* **Flowering Growth:**
  + **Initiation: Triggered by light cycle change (12/12 for photoperiod strains, Transcript P.115) [89, 90]. Some chemicals can induce flowering [196].**
  + **Duration: Varies by cultivar (e.g., 7-10+ weeks, Transcript P.115, P.169, P.308) [197]. Affected by genetics, environment, nutrients [47, 99]. Far-red light can shorten by a week+ (Transcript P.204). 11/13 light cycle to push finish (Transcript P.115).**
  + **Requirements: Strict 12 hrs light / 12 hrs uninterrupted dark for photoperiod strains [89-91]. Lower humidity (40-65% RH, Transcript P.15, P.161) [46, 48]. Intense light (high PPFD, 800-1500+ with CO2, Transcript P.114, P.161) [46, 86]. Higher phosphorus/potassium nutrients, lower N (e.g. Athena Fade, Transcript P.7-9) [146, 147]. Optimal temperature (65-80F, Transcript P.161) [47, 48].**
  + **Processes: Female plants produce buds/flowers [90]. Trichome development and cannabinoid/terpene synthesis occur [47, 63, 197]. Stretch period in first 1-4 weeks (Transcript P.114).**
  + **Challenges: Bud density/structure can affect airflow/mold risk (Botrytis, Transcript P.7-8, P.15) [198]. Requires robust structure/roots to support bud weight [195].**
* **Plant Training & Care:**
  + **Techniques: Topping (removes apical meristem, encourages lateral branching), Low-Stress Training (LST), Screen of Green (ScrOG - trains plants through a screen for horizontal canopy), Sea of Green (SOG - dense packing of small plants/clones for many colas), Lollipopping (removing lower branches) [53, 80, 133, 173, 190]. Techniques alter growth patterns, influence yield, morphology [53, 133]. Some growers are moving away from topping to reduce labor and stress, focusing on plant density and natural structure (Transcript P.182-183, P.200-201, P.225).**
  + **Other Tasks: Pruning/Defoliation (removes fan leaves/branches, improves airflow/light penetration, redirects energy, Transcript P.12, P.15-16, P.205) [133, 199]. Watering/substrate moisture checks (visual, meters, pot lift method, Transcript P.11) [133]. Providing plant support (stakes, trellis netting, Transcript P.200-201) [190, 200]. Transplanting (moving plants to larger containers/different zones) [90, 190, 201].**
* **Harvest and Post-Harvest Processing:**
  + **Harvest Timing: Critical for chemical profile, quality, effects [202]. Indicators: Trichome maturation (color: clear -> milky -> brown/amber, Transcript P.12, P.197), pistil color, yield/plant [197, 202-204]. Optimal timing is strain/grow-specific [205]. Monitoring trichome appearance via loupe [204]. Hash production often requires earlier harvest (Transcript P.197).**
  + **Harvesting Methodologies: Manual (whole plants vs. branches), Automated (machines) [206-208]. Sharp, sanitized tools essential [199]. Pre-harvest defoliation (large fan leaves) [199]. Organized workspace [199]. Harvest can take 2.5 days for a 7200 sq ft room (Transcript P.199-200).**
  + **Trimming: Hand trim (meticulous, preferred for quality, Transcript P.5), Automated machines (speed vs. quality trade-off) [206, 207, 209]. Wet trim (immediately post-harvest) vs. Dry trim (after drying) [207]. Dedicated trimming space [206]. Cost of hand trimming $100-150/lb (Transcript P.5).**
  + **Drying: Manual hanging/rack in dedicated space [1, 210]. Environment (temp 60F, humidity 60%RH, airflow) impacts time (7-14 days, Transcript P.22, P.298-299) /quality [199, 202, 210, 211]. Too fast -> harshness, terpene loss, uneven drying [210]. Too slow -> mold/mildew, hay smell [198, 210]. Optimal environment needed for quality preservation [202, 211]. Weight loss during drying [211]. Refrigerated trailers used by some outdoor grows (Transcript P.6).**
  + **Curing: Manual container curing (jars, "Grove Bags" / terp block bags, Transcript P.22) [1, 212]. Manual "burping" (releases moisture, exchanges air) [1, 212]. Duration (weeks to months) [212]. Environmental stability (cool, dark) crucial [212]. Target RH (container interior): 58-62% [212]. Influences aroma, flavor, smoothness [211, 212]. Automated curing (smart containers, climate-controlled rooms) [213]. Strain-specific curing may exist [213].**
  + **Bulk Storage: Preserve quality, stability, potency over time [202, 214]. Requires controlled environment (temp, light, O2, humidity) [214]. Evidence-based practices for large-scale storage [214].**
  + **Processing (Extraction/Manufacturing): Converting harvested product to other forms (oils, concentrates like rosin/hydrocarbon, edibles, topicals) [1, 215] (Transcript P.3, P.9-10). Requires specialized equipment and facilities [215].**
  + **Packaging: Preparing final product for sale/storage [215]. Weighing, containerization (bags, jars), sealing, labeling [215]. Cost of testing per batch is a factor (Transcript P.6).**
  + **Minimizing Degradation: Efficient facility layout, batch management/tracking, dedicated environmental controls, inventory management (FIFO) [216].**
* **Cleaning and Sanitation:**
  + **Importance: Prevents pest/pathogen buildup, contamination, ensures product safety/quality [133, 217-219]. Cornerstone of IPM [220]. Critical for preventing HLVd spread (Transcript P.17, P.80, P.82-83, P.341).**
  + **Practices: Routine daily cleaning (debris removal) [217]. Wet/dry cleaning [221]. Deep cleaning (between cycles, post-contamination) [29, 133]. System flushing (irrigation, tanks, HVAC) [20, 133]. Equipment-specific sanitation [20]. Personnel hygiene (handwashing, PPE, foot baths, changing clothes/gloves between rooms/plants, Transcript P.80, P.341-342) [33]. Controlled access/workflow [33]. Quarantine new materials/genetics (Transcript P.17, P.83, P.136, P.137). Sterilizing tools (bleach 10-20% for 30-60s for HLVd, Virkon S; alcohol/flame NOT effective for HLVd, Transcript P.82-83) [20, 222, 223]. Disinfectant use (concentration, contact time, rotation, e.g., Athena Reset foamer, Transcript P.117, P.199) [222, 224, 225].**
  + **Monitoring Effectiveness: Environmental monitoring (air, surface, water sampling for microbes/pathogens, e.g. EnvyCan swabs, Transcript P.341-344) [225, 226]. Rapid assessment tools (ATP bioluminescence testing, visual inspections) [227]. Data analysis for continuous improvement [228].**
  + **Integration: Sanitation protocols integrated into facility design, workflows, staff training [218]. Coordinated efforts with environmental controls [77]. Indispensable for sustainable IPM [220].**
  + **Scale Differences: Strategies, intensity, resources, regulatory pressure differ by scale (hobbyist to large commercial) [225, 229]. Cardboard is a contamination risk (Transcript P.340-341).**
* **Staff Management & Training (Abstracted for MVP):**
  + **Hiring: Finding skilled and reliable labor can be a challenge (Transcript P.2-3, P.58-59).**
  + **Training: SOPs, hygiene, cultivation tasks (Transcript P.19, P.58-59).**
  + **Team Size: Varies by facility size and automation (e.g., 4 people for 300 lights, Transcript P.4; 5 full-time for 1000 lights + floating crew, Transcript P.58; 14 trimmers + 5 cultivators for 500 lights, Transcript P.216).**
  + **Cost of Labor: Significa​​nt operational expense (Transcript P.2, P.5).**
  + **Motivation & Culture: Creating a positive work environment (Transcript P.185, P.210).**

## Comprehensive Simulation Parameters for Project Chimera

**This document outlines potential parameters for the simulation mechanics of Project Chimera, drawing upon extensive research into Cannabis sativa L. biology, cultivation, genetics, and industry practices, significantly enhanced with details from cultivator discussions as recorded in "transcriptss.pdf" (hereafter cited as "Transcript P.[PageNumber]").**

### 1. Cannabis Biology and Characteristics Parameters (Part 1: Botanical & Chemical)

**This section details fundamental biological parameters of the Cannabis sativa L. plant, its morphology, chemistry, and inherent characteristics related to its interaction with the environment and biological threats.**

#### 1.1 Botanical Features Parameters

**Parameters defining the physical structure, classification, and life cycle stages of the cannabis plant.**

* **Taxonomy and Classification:**
  + **Species: *Cannabis sativa L.* [1]**
  + **Subspecies/Varieties: *sativa*, *indica*, *ruderalis*.**
    - **Note: Traditional classifications may not correlate perfectly with genetic structure [2, 3]. Cultivator experience suggests that even within these, traits like stretch and nutrient preference can vary significantly (Transcript P.114, P.196). For example, some OG cuts have minimal lateral branching (Transcript P.182-183).**
  + **Hemp vs. Drug-type distinction: Based on THC content (e.g., <0.3% Δ⁹-THC for hemp) [1]. This is a critical botanical and regulatory parameter [1] (Transcript P.2, P.276-277).**
    - **Range: % Δ⁹-THC can range from negligible (<0.1%) in some hemp varieties to over 30% in high-potency drug-type cultivars [4-6]. Some cultivars test around 15-19% THC, while others can reach 28-35% THC (Transcript P.187, P.197). THCA flower is also a market factor under hemp regulations (Transcript P.276-279).**
  + **Chemovars: Classification based on cannabinoid profile [7, 8] (e.g., Type I: THC-dominant, Type II: THC/CBD mixed, Type III: CBD-dominant, Type IV: CBG-dominant, Type V: negligible cannabinoids) [2].**
    - **Game should support differentiation based on chemical profile rather than just traditional labels [2]. Consumer markets show preferences for different profiles; e.g., some European markets value specific terpene expressions over pure THC content (Transcript P.192).**
* **Morphology: Parameters defining the physical structure and form of the plant.**
  + **Plant Height: Potential range (e.g., 0.2m to >12m cultivated) [1]. Influenced by genetics and environment [1].**
    - **Hemp types tend to be taller and less branched, drug-types bushier [1, 9].**
    - **Range: Dwarf varieties can be 0.2m [1]. Fiber hemp can exceed 12m [1].**
    - **Drug types typically range from 0.5m to over 3m. Some strains can stretch significantly, e.g., a 12-inch plant stretching to 5 feet (Transcript P.114). Sherb Banger 22 known for a 4-week stretch period (Transcript P.114-115).**
  + **Stem Structure: Erect, furrows, branching patterns, woody interior, hollow internodes [1].**
    - **Stem diameter can range from 1-3cm in mature plants, influenced by genetics and vigor [13].**
    - **Base can become very big and thick [14].**
    - **Branching Pattern: Influenced by genetics and environment (e.g., apical dominant, lateral spread, balanced) [15]. Sativa-like strains tend to have more lateral branching. Some OG cuts show minimal lateral branching without topping (Transcript P.182-183). HLVd infection can cause abnormal, horizontal branching (Transcript P.80).**
    - **Sativas tend to have more lanky branches, Indicas more compact [16-18].**
  + **Leaf Morphology: Compound leaves with leaflets radiating from the petiole end [1].**
    - **Leaflet Number: Number of leaflets (e.g., 3-13) [1].**
    - **Developmental sequence: 1 (seedlings/stressed), 3, 5, 7, 9, then potentially more (up to 13+) on robust mature plants, decreasing later [19].**
    - **Leaflet Shape: Lanceolate, ovoid, oblanceolate [1]. Influenced by genetics (e.g., broad in Indica types, narrow in Sativa types) [19].**
    - **Serrated margins [1].**
    - **Leaf Size: Broad (Indica) vs. long/slender (Sativa) [19].**
    - **Changes throughout lifecycle, peaking around the 12th node [19].**
    - **Leaf Angle/Droop: Angle relative to stem, turgidity.**
      * **Heavily influenced by hydration (underwatered-drooping) [13, 20]. Genetics may influence baseline angle [13]. Hybrids show a spectrum [13]. HLVd may cause leaves to curl or appear malformed (Transcript P.80).**
    - **Diagnostic Leaf Venation [1].**
  + **Leaf Arrangement: Opposite (lower nodes) to alternate (main stem) [1, 19].**
    - **Phyllotaxy shift typically occurs around the 12th node [19].**
  + **Bud/Flower Structure: Shape (e.g., conical, spear, round, "golf balls" (Transcript P.181), foxtail), density (airy, medium, compact, "rock-hard" under LEDs (Transcript P.202)), leaf-to-calyx ratio [15].**
    - **Indica types tend to have dense, compact buds, Sativa types longer, airy buds [11, 16].**
    - **Foxtailing can occur, sometimes accelerating towards harvest [21]. Some strains exhibit foxtailing as a genetic trait, not necessarily negative (Transcript P.120).**
    - **HLVd can cause "dudding" or significantly reduced bud development and trichome production (Transcript P.80, P.171).**
  + **Pistil Color (Mature): Colors such as orange-red, pink-purple, brown [15].**
  + **Trichome Density: Potential levels (low, medium, high) [15].**
    - **A key visual quality indicator (frostiness, resin) [15, 22, 23]. Influenced by genetics and environment [15, 24, 25]. Some strains are known for high resin production suitable for hash (Transcript P.9, P.21).**
    - **Can vary dramatically between strains [24]. Use of products like Athena Stack can visually increase trichome production (Transcript P.160).**
  + **Trichome Appearance: Transition in color (clear to milky to brown/amber) indicates maturity [15, 22, 26].**
    - **Visual cues for resin and ripeness [15, 22, 26]. Trichomes contain cannabinoids [24]. For hash production, plants might be harvested earlier when trichomes are optimal for separation (e.g., day 40 for a 70-day flower strain) (Transcript P.197).**
  + **Trichome Degradation: Can be induced by experiments [27]. Poor storage can lead to reduced trichome vibrancy [28, 29]. Improper drying/curing can lead to terpene loss (Transcript P.179).**
  + **Root System: Adaptable taproot with lateral branching [1].**
    - **Can reach up to 2.5m deep in soil depending on soil/water [1, 30].**
    - **Root health and development influenced by growing media [30, 31]. HLVd can be present in roots (Transcript P.83). Fusarium also infects through roots (Transcript P.84).**
    - **Plants from seed have a strong, deep taproot; cloned plants typically have weaker, more lateral, not as deep roots [32].**
    - **Rootbound plants stress plant if left untreated [33].**
    - **Root restriction (small containers) stunts growth, limits nutrient/water uptake, alters structure [30, 34, 35]. Smaller pots (e.g., 1-2 gallons) preferred by some for more control with frequent irrigations (Transcript P.127).**
  + **Visual Representation: Potential for root system visualization showing medium, water, nutrient response [36].**
  + **Fruit (Achene)/Seed: <3.8mm length, often in persistent perianth (mottled/marbled) [1]. Seed production can yield 5,000 to over 20,000 seeds per light depending on cultivation methods and nutrient lines (Transcript P.309). Shipping seeds is generally legal (DEA rescheduled, Transcript P.2), but banking for seed sales can be problematic (Transcript P.2). Cuttings/clones shipping legality is evolving, based on <0.3% THC in the cutting itself (Transcript P.1-2, P.276-277).**
* **Sex Determination:**
  + **Predominantly dioecious (separate male (XY)/female (XX) plants) [1, 37]. Females are valued for cannabinoids in inflorescences [37].**
  + **Monoecious/Hermaphroditic forms: Can occur naturally (stress-induced, e.g., light leaks, temperature swings (Transcript P.158, P.171)) or be chemically induced (e.g., silver thiosulfate, STS (Transcript P.169)) for breeding [37].**
    - **Hermaphroditism involves producing both male and female flowers on the same plant, leading to "seeded" crops [38, 39]. Some strains have a higher genetic predisposition to herm under stress (e.g., Dante's Inferno #6) (Transcript P.152). Sterility of pollen from hermaphroditic plants can vary (Transcript P.152).**
* **Growth Stages:**
  + **Germination: First physiological stage [40].**
    - **Requires proper medium temperature (8-10°C average daily minimum for outdoor sowing, or specific ranges for in vitro/controlled) [41, 42].**
    - **Light not required [42]. Influenced by genetics, physical factors (medium composition, env conditions) [40].**
    - **Optimal conditions and quality seeds yield 80-100% germination [43]. Poor germination rates can be associated with bad genetics [44] or old seeds (Transcript P.168).**
    - **Range/Likely Level: Germination rate can be affected by genotype, medium composition, and environmental conditions [40, 43]. Reputable breeders aim for near 100% [43].**
  + **Seedling: Early growth [45, 46].**
    - **Typically single leaflet leaves initially, progressing to 3, then 5 [19]. Sensitive stage [47].**
  + **Vegetative: Rapid growth stage, building root system and stems, then foliage [46, 48].**
    - **Needs high nitrogen [46, 49]. Fairly tough during this stage [50]. Environmental conditions like temp/humidity deviations impact growth speed [51]. Optimal VPD is crucial (Transcript P.235). Low light (e.g. 200s PPFD) can be sufficient if DLI is met (Transcript P.161). Veg duration varies (e.g., 10-18 days for some commercial setups (Transcript P.176, P.217), up to 5-6 weeks for others (Transcript P.200)).**
    - **Problems often begin to show here [52]. Duration modeled as 50 days in one facility example [53].**
  + **Flowering: Stage where inflorescences develop [45, 46].**
    - **Requires lower humidity (especially late flower, e.g. 40-50% RH, though some run higher at 60-65% with LEDs (Transcript P.161)) and specific light spectrum/intensity [47]. Needs higher phosphorus/potassium [45, 49]. Light cycle typically 12/12, but some manipulate to 11/13 to finish plants or influence expression (Transcript P.115).**
    - **Longest stage in one model (57 days) [53]. Can range from 7 weeks (e.g., Rainbow Belts, Zkittlez crosses (Transcript P.115)) to 10+ weeks (e.g., Haze varieties, some OGs (Transcript P.115, P.169, P.308)) depending on genetics. Stretch period (first 1-4 weeks of flower) can last 3-4 weeks for some strains (e.g., Sherb Banger 22 (Transcript P.114-115)).**
  + **Maturation: Buds thicken, trichomes mature [21, 27].**
    - **Harvest timing determined by trichome appearance (clear to milky to amber) and yield/chemistry correlation [54]. Cannabinoid and terpene profiles change during maturation (Transcript P.8, P.172). Some harvest earlier for specific products like hash (Transcript P.197).**
  + **Harvest: Physical removal of plants/flowers [55]. Timing crucial for potency/quality [54, 56].**
* **Phenotypic Plasticity: The ability of a plant with a specific genotype to exhibit different phenotypes in different environments [38, 57-60].**
  + **This is a fundamental concept for GxE modeling [38, 57-60]. Environment (light, temp, nutrients, stress) heavily influences expression of genetic potential (Transcript P.187, P.200-207).**
  + **Clones with identical genotype can show different phenotypes with varied conditions [3, 58].**

#### 1.2 Chemical Profile Parameters

**Parameters defining the chemical composition of the cannabis plant, particularly secondary metabolites produced primarily in glandular trichomes [4, 24, 61].**

* **Cannabinoids: (>140 identified) [62].**
  + **Major Cannabinoids:**
    - **Δ⁹-tetrahydrocannabinol (THC): Psychoactive compound [63].**
      * **Potency often measured as % DW [64]. Levels up to 25-30% of floral dry weight achieved [4]. Some cultivars testing at 28-35% THC reported (Transcript P.187). Others may test lower (e.g. 12-19%) but still be desirable (Transcript P.170, P.197). Moisture content at testing significantly impacts reported THC % (Transcript P.12, P.22).**
      * **Can reach 30% in some plants [5].**
      * **Likely Levels: High THC strains can exceed 20%, some even reaching 30% [4-6]. Cultivator discussions mention THC levels from 12% to 35%+ (Transcript P.13, P.170, P.187, P.197).**
      * **Traditional hemp is <0.3% [1]. THCA flower market exists under hemp definition (Transcript P.276-279).**
    - **Cannabidiol (CBD): Non-psychoactive, therapeutic potential [63, 65].**
      * **Potency often measured as % DW [64].**
      * **Likely Levels: High CBD strains can exceed 15-20%. Many hybrids have mixed ratios.**
    - **Cannabigerol (CBG): Precursor to other cannabinoids [63]. Increasing interest in breeding [66].**
    - **Cannabinol (CBN): Sedative effects [63]. Accumulates with degradation/aging [63].**
  + **Minor Cannabinoids: Growing interest (distinct therapeutic benefits) [66].**
    - **Δ⁹-tetrahydrocannabivarin (THCV): Investigating production genetics crucial [66].**
    - **Cannabidivarin (CBDV): Investigating production genetics crucial [66].**
    - **Cannabichromene (CBC): Investigating production genetics crucial [66].**
    - **Cannabichromenevarin (CBCV) [63].**
    - **Cannabigerovarin (CBGV) [63].**
    - **Delta-8 THC [63], Delta-10 THC [63], HHC [63]: Novel cannabinoids often in legal grey areas, facing evolving scrutiny [67]. Delta-8 can be synthesized from CBD (Transcript P.279-281).**
    - **THCP, THCB [63].**
  + **Cannabinoid Acids: Biosynthetic precursors, convert to neutral form via decarboxylation (heat, aging) [63, 68, 69].**
    - **THCA (tetrahydrocannabinolic acid) [63]. THCA flower being sold under hemp regulations is a major market factor (Transcript P.276-279).**
    - **CBDA (cannabidiolic acid) [63].**
    - **CBGA (cannabigerolic acid) [63].**
  + **Total Cannabinoids (e.g., Total THC: THCA \* 0.877 + THC, Total CBD: CBDA \* 0.877 + CBD) [63].**
    - **Critical quality parameters [68]. Content variability in plant material is an issue for consistency [68].**
    - **Can reach 25-30% of floral dry weight [4]. Potency is a key driver in many markets, though this is being questioned by connoisseurs (Transcript P.170, P.197, P.239). Moisture content at testing significantly impacts reported THC % (Transcript P.12, P.22). Using products like "Fade" can increase THC by 2-6% absolute (Transcript P.13).**
* **Terpenes: (>120 identified) [62].**
  + **Aromatic compounds contributing to aroma, flavor, and potential effects (entourage effect) [63, 65, 70]. Produced in glandular trichomes [61]. Critical for consumer preference, especially in connoisseur markets (Transcript P.8, P.152, P.179, P.192).**
  + **Concentration influenced by genetics, environment, post-harvest handling [71]. Late-stage nutrient protocols (like "Fade") can enhance terpene expression (Transcript P.8-9). Drying and curing are critical for terpene preservation (Transcript P.179, P.298-299).**
  + **Dominant Terpenes: Myrcene, Limonene, Caryophyllene, Pinene, Ocimene, Terpinolene [63].**
  + **Other Terpenes: Humulene, Linalool, Bisabolol, Nerolidol, Geraniol, Borneol, Fenchol, Cineole, Camphor, Phellandrene, Terpineol, Carene, Farnesene, Phytol, Carvacrol, Aromadendrene, Eudesmol [63].**
  + **Terpene Profiles: Concentrations and ratios of individual terpenes [64, 65, 71]. Contributes to market demand [71]. Breeding for unique terpene profiles is a major goal for some (Transcript P.152, P.172).**
  + **System for classification (e.g., Cream/Cake/Cookies/Candy, Fruity, Herbal, Pine, Skunk, Spicy, Sweet, Tropical, Woody/Earth) [72]. The "candy" profile (e.g., from Dante's Inferno #6) is currently popular (Transcript P.152, P.172). "Gas" is another popular profile (Transcript P.187).**
  + **Total Terpenes [63]. High terpene content is desirable but can be diluted by excessive yield focus ("yield dilution") (Transcript P.62).**
  + **Volatilization: Terpenes can volatilize, especially during drying/curing at warmer temperatures [73].**
    - **Proper drying/curing crucial for retention [25, 54, 73]. Target 7-10 days dry time, 60F/60%RH environment (Transcript P.298-299).**
* **Flavonoids: Contribute to pigmentation and aroma/flavor [8, 63].**
  + **Cannflavins [63]. Anthocyanins responsible for purple colors, influenced by genetics and cold temperatures (Transcript P.14-15).**
* **Volatile Sulfur Compounds (VSCs): Contribute to pungent/characteristic notes like "gas" or "skunk" [63]. Unstable over time [63].**
* **Esters: Contribute sweet/fruity notes [63].**
* **Other Constituents: Hydrocarbons, phenolics, sugars [63].**
* **Entourage Effect: Synergistic interaction between cannabinoids, terpenes, and other compounds influencing effects and therapeutic potential [8, 63].**

#### 1.3 Physiological Processes Parameters (Continuation)

**Parameters governing the internal functions and responses of the cannabis plant, building on the initial photosynthesis, transpiration, nutrient uptake, and biosynthesis parameters.**

* **Water Relations: Beyond basic transpiration.**
  + **Water Uptake Rate: Influenced by root system size/health, substrate moisture content, substrate type (e.g., coir's high water retention vs. rockwool's quick dry down) [1-3]. VPD heavily influences uptake (Transcript P.125, P.235).**
  + **Aquaporin activity (e.g., PIP aquaporins) may play a role at a molecular level [2].**
  + **Leaf Water Potential: Measure of plant water stress. Influenced by substrate moisture, humidity, airflow, transpiration rate.**
  + **Stomatal Response: Opening and closing of stomata to regulate gas exchange and water loss.**
    - **Influenced by light intensity, CO2 levels, humidity, wind. Can be reduced in later maturation stages [4]. Far-red light at end of day can influence stomatal closure and plant sleep cycles (Transcript P.203).**
* **Carbon Metabolism:**
  + **Carbon Fixation Rate: Directly related to photosynthetic rate.**
  + **Photoassimilate Production: Synthesis of sugars.**
  + **Photoassimilate Partitioning: Allocation of sugars to different plant parts (roots, shoots, leaves, flowers).**
    - **Influenced by growth stage, nutrient availability (e.g., Nitrogen for vegetative growth vs. Phosphorus for flowering/bud development) [5]. Late flower N restriction (e.g., using "Fade") encourages resource allocation to flowers (Transcript P.7-9, P.15).**
* **Hormonal Regulation: Internal plant hormones (phytohormones) play crucial roles in growth, development, and responses to environment and stress.**
  + **Auxins: Involved in root development, apical dominance, vegetative growth. Auxin activity typically decreases during flowering transition [6].**
  + **Cytokinins: Promote cell division, shoot development. Certain cytokinins increase during flowering transition [6].**
    - **Meta-topolin (mT), a natural cytokinin, is effective for shoot proliferation in tissue culture [7].**
  + **Gibberellins: Involved in stem elongation (e.g., "stretch" at flowering onset) [6].**
  + **Abscisic Acid (ABA): Stress hormone, involved in stomatal closure and dormancy. Increases under drought stress. Drought stress (generative steering) is a key crop steering technique (Transcript P.122-123).**
  + **Ethylene: Involved in senescence, ripening, stress responses.**
  + **Brassinosteroids: Promote growth and stress tolerance.**
  + **Phytohormone Balance: The relative levels and interactions of these hormones regulate developmental transitions (e.g., vegetative to flowering, re-vegetation) [6, 8].**
    - **Mother plants in long-term vegetative state may experience subtle changes in hormonal balance [4].**
* **Nutrient Mobility and Translocation: Movement of absorbed nutrients within the plant (e.g., from older leaves to new growth/flowers).**
  + **Efficiency may diminish with physiological age [4]. Nitrogen is highly mobile and translocated from fan leaves during late flower if root zone N is restricted (e.g. when using "Fade") (Transcript P.8, P.15). Calcium is immobile; deficiencies (e.g., from flushing with straight RO water or pulling Core too early) can lead to issues like bud rot (Transcript P.7-8, P.12).**
* **Resource Remobilization: Breakdown of macromolecules (proteins, lipids, nucleic acids) in senescing tissues and transport of resulting nutrients to other parts of the plant [9].**
  + **Occurs in older leaves even in vegetative mothers [4]. Crucial for reproductive success in nature [9]. This is a key mechanism during "Fade" or flushing (Transcript P.8, P.15).**
* **Developmental Plasticity: Ability to alter growth patterns in response to environmental cues (e.g., branching patterns influenced by light distribution, nutrient availability) [10].**
* **Circadian Rhythms: Internal biological clock regulating daily physiological processes (e.g., photosynthesis, transpiration, flowering time). Interacts with photoperiod. Use of far-red light to signal end-of-day can influence these rhythms (Transcript P.203).**

#### 1.4 Stress Responses Parameters

**Parameters defining how the cannabis plant reacts to and is affected by various abiotic and biotic stressors, and its ability to tolerate them. Stress can impact yield, quality, and even chemotype. Strategic stress (e.g., controlled drought, specific nutrient withdrawal like "Fade") can enhance desired traits like terpene and cannabinoid production (Transcript P.8, P.122-124).**

* **Abiotic Stress Responses: Responses to non-living environmental factors.**
  + **Drought Stress: (Intentional for generative steering)**
    - **Physiological Effects: Reduced stomatal conductance, decreased photosynthesis, wilting, reduced transpiration.**
    - **Can induce changes in leaf water potential [11]. Induces hormonal responses for survival and reproduction (Transcript P.122).**
    - **Growth/Yield Effects: Stunted growth, reduced biomass, lower flower yield.**
    - **Controlled drought stress in flowering stage can increase inflorescence dry weight and cannabinoid content [12]. Key part of "generative steering" by manipulating drybacks (Transcript P.11, P.122-123).**
    - **Chemotype Effects: May increase cannabinoid/terpene concentration (due to reduced biomass/water content or stress-induced synthesis) or decrease total production (due to reduced metabolic activity) [11, 13]. (Transcript P.8, P.124).**
    - **Stress-induced synthesis vs. dilution [13].**
  + **Heat Stress:**
    - **Physiological Effects: Denaturation of enzymes, impaired photosynthesis, increased respiration, heat shock protein production.**
    - **Can cause managing temperature to be critical for quality [14]. Excessive heat can stress plants, leading to reduced quality or hermaphroditism (Transcript P.158, P.171).**
    - **Growth/Yield Effects: Stunted growth, reduced flower development, wilting, leaf damage.**
    - **Chemotype Effects: Can degrade cannabinoids (e.g., THC) and volatilize terpenes, reducing overall potency and aroma profile [14].**
  + **Cold Stress:**
    - **Physiological Effects: Reduced enzymatic activity, membrane damage, impaired nutrient uptake.**
    - **Growth/Yield Effects: Stunted growth, leaf damage, reduced yield.**
    - **Chemotype Effects: Can impact cannabinoid/terpene synthesis.**
    - **Some varieties may show color changes (e.g., purple hues) in response to cold [15]. This is a common technique to enhance "bag appeal" (Transcript P.14-15). Colder water at end of flower can also induce color (Transcript P.14).**
  + **Light Stress (Too High/Low Intensity):**
    - **Physiological Effects: Photoinhibition (damage to photosynthetic apparatus) from excessive light [16].**
    - **Reduced photosynthesis from insufficient light. Plants growing into lights will burn (Transcript P.114).**
    - **Growth/Yield Effects: Leaf burn, stunted growth, reduced yield from excessive light.**
    - **Leggy growth, low yield from insufficient light.**
    - **Chemotype Effects: Optimal light intensity and spectrum are crucial for cannabinoid and terpene production [17-19]. Some genetics are more sensitive to high PPFD than others (e.g., old Indicas) (Transcript P.116).**
    - **UV light can stimulate cannabinoid production (protective mechanism) [20, 21], but excessive UV can be damaging.**
    - **Different light spectra affect morphological, physiological, and chemical parameters [17, 22]. Far-red can influence flowering time and stretch (Transcript P.203). Mixed HPS/LED can give unique expressions (Transcript P.202-207).**
  + **Nutrient Deficiency/Toxicity:**
    - **Physiological Effects: Impaired metabolic processes, reduced photosynthesis, visible symptoms (e.g., leaf yellowing from N deficiency, brown spots from P deficiency/toxicity, leaf burn from nutrient excess/toxicity) [23, 24]. Calcium deficiency in late flower can lead to bud rot (Transcript P.7-8).**
    - **Can trigger/accelerate senescence [25]. Removing core nutrients (e.g., Athena ProLine Core) too early or using straight RO water can cause deficiencies (Transcript P.8, P.12).**
    - **Growth/Yield Effects: Stunted growth, reduced biomass, lower yield [5, 23, 24].**
    - **Nutrient imbalance can restrict development [26]. Overwatering can lead to nutrient lockout or root issues mistaken for deficiencies (Transcript P.11).**
    - **Chemotype Effects: Nutrient availability significantly impacts cannabinoid and terpene biosynthesis and concentration [18, 27, 28].**
    - **High Nitrogen can decrease cannabinoid/terpene concentration while increasing biomass (dilution effect) [5, 29]. This is a reason for products like "Fade" (Transcript P.7-9).**
    - **Phosphorus is conventionally supplied at high amounts for optimal function and yield, but deficiency at vegetative stage impacts functional phenotyping and ionome [30].**
  + **Waterlogged Soil/Root Zone Hypoxia:**
    - **Physiological Effects: Root damage, impaired nutrient/water uptake, reduced oxygen availability to roots. Increased risk with overwatering, especially in dense media like coco if not managed (Transcript P.11, P.126).**
    - **Growth/Yield Effects: Wilting, stunted growth, root rot susceptibility [31], reduced yield.**
    - **Chemotype Effects: Reduced plant health negatively impacts secondary metabolite production.**
  + **Salinity Stress: Accumulation of soluble salts in the root zone, particularly in hydroponics/soilless media [26]. High EC in media due to insufficient runoff or excessive drybacks (Transcript P.123, P.158).**
    - **Physiological Effects: Impaired water uptake, ion toxicity.**
    - **Growth/Yield Effects: Stunted growth, reduced yield. Lockout of other nutrients.**
    - **Chemotype Effects: Can impact metabolite profiles. Extreme EC can burn plants.**
* **Biotic Stress Responses: Responses to living organisms.**
  + **Pest Infestation: (See also 1.6 Pest/Disease Resistance Parameters)**
    - **Damage Types: Feeding damage (leaf loss, tissue damage), disease transmission, growth hindrance [32, 33]. Thrips, mites mentioned as common problems (Transcript P.80, P.179).**
    - **Physiological Effects: Allocation of resources to defense mechanisms (e.g., production of defensive compounds).**
    - **Growth/Yield Effects: Reduced vigor, stunted growth, significant yield loss [32, 33].**
    - **Trichome damage/loss can directly reduce cannabinoid/terpene yield [34].**
  + **Pathogen Infection: (See also 1.6 Pest/Disease Resistance Parameters)**
    - **Damage Types: Tissue damage, impaired physiological function (e.g., nutrient/water transport, photosynthesis), systemic infection [32, 35]. Bud rot (Botrytis) is a major concern, linked to calcium deficiency and high humidity (Transcript P.7-8, P.15). Fusarium is a root pathogen, no cure, spreads via water (Transcript P.84). HLVd causes stunting, dudding, reduced quality (Transcript P.3, P.16, P.80, P.171).**
    - **Physiological Effects: Activation of plant immune response, production of defense compounds.**
    - **Older mothers may have potentially weakened immune response or chronic stress leading to higher susceptibility [34].**
    - **Growth/Yield Effects: Reduced vigor, stunted growth, wilting, necrosis, significant yield loss [32, 35]. HLVd can devastate crops (Transcript P.3, P.16-17).**
    - **Can be mistaken for age-related decline [34]. Systemic pathogens like HLVd cause stunting and reduced trichome production/yields [34].**
  + **Competition (Light, Nutrients, Water, Space): Competition from other cannabis plants or companion plants [36].**
    - **Physiological Effects: Altered growth patterns (e.g., reaching for light), reduced resource uptake efficiency.**
    - **Growth/Yield Effects: Reduced individual plant yield. Plant spacing is important for maximizing yield per area [37, 38]. Density of 1.6 plants/sq ft mentioned (Transcript P.183).**
  + **Stress-Induced Senescence: Premature aging and death of plant tissues or the whole plant due to severe or prolonged stress [9]. Can be desirable at end of flower (e.g., with "Fade") but problematic if premature (Transcript P.8).**

#### 1.5 Strain-Specific Optimal Conditions and Characteristics Parameters

**Parameters defining the variations in optimal growth conditions, growth habits, and other characteristics between different cannabis genotypes (strains/cultivars). Cultivars show wide variation in response to environment and inputs (Transcript P.114, P.163, P.187, P.200).**

* **Optimal Environmental Ranges: Genotype-dependent ideal ranges for:**
  + **Temperature: Specific optimal temperature ranges for vegetative and flowering stages [39]. Some strains are more sensitive to temperature swings (Transcript P.15, P.158). Some growers run 73-76F even in late flower with "Fade" (Transcript P.15).**
  + **Humidity: Specific optimal humidity ranges for vegetative and flowering stages [39]. Some strains are more prone to mold in high humidity (Transcript P.15). Some run 60-65% RH with LEDs in flower (Transcript P.161).**
  + **Light Intensity (PPFD): Different strains may utilize light more or less efficiently and have different saturation points. Some strains are sensitive to high PPFD (e.g. old indicas) (Transcript P.116).**
  + **Light Spectrum: Different strains may respond differently to specific light wavelengths [17, 22, 39]. Some strains show better color or terpene expression under specific spectra (e.g. mixed HPS/LED, or specific LED spectra like ThinkGrow vs. Luxx) (Transcript P.202-207, P.113, P.160). Far-red for end-of-day signal (Transcript P.203).**
  + **CO2 Concentration: Optimal CO2 levels for different strains, especially in CEA [39-41]. Typically 1500ppm in flower (Transcript P.161).**
  + **Airflow/Ventilation: Specific needs for different growth structures and densities to prevent mold/pests [42]. Dense bud structures require more airflow (Transcript P.15).**
  + **Substrate Moisture Content: Optimal levels and tolerance for drying out or waterlogging vary [1-3]. Some strains prefer larger drybacks than others (Transcript P.11, P.124). Rockwool vs. Coco drydown characteristics (Transcript P.113, P.180).**
  + **Nutrient Solution pH: Optimal pH range for nutrient uptake can vary slightly by strain and substrate [16, 43, 44]. Some growers maintain a consistent pH (e.g. 6.0-6.2) for all strains in coco (Transcript P.158). Monosilicic acid can affect pH in rockwool (Transcript P.11).**
  + **Nutrient Concentrations (EC/PPM): Optimal nutrient strength varies by strain and growth stage [27, 43, 45]. Some strains are heavy feeders, others sensitive (e.g., OGs might prefer lower EC than Runtz; Runtz sensitive to high EC, Pie Hoe can take very high EC) (Transcript P.196). Some run 3.0 EC all the way through with Athena ProLine (Transcript P.12, P.15).**
  + **Specific Nutrient Ratios (NPK, Ca:Mg, etc.): Optimal ratios can be strain-specific and outcome-specific (e.g., maximizing yield vs. maximizing cannabinoid concentration) [13, 27, 45].**
* **Growth Habits and Morphology: Genotype-dependent traits:**
  + **Plant Height and Structure: Tall/thin (sativa-like) vs. short/bushy (indica-like) [10, 47, 48]. Some strains have significant stretch (e.g. Sherb Banger 22, 4-week stretch from 12" to 5ft (Transcript P.114-115)) while others are short (e.g. Rainbow Belts, Zkittlez finishing in 7 weeks (Transcript P.115)).**
  + **Branching patterns (apical dominant vs. lateral spread, OG minimal lateral without topping) [10] (Transcript P.182-183). Untopped plants develop a main cola with lateral branches reaching near the top (Transcript P.183).**
  + **Internodal spacing [49].**
  + **Leaf Morphology: Leaflet number and width (narrow-leaf vs. broad-leaf) [49, 50].**
  + **Flower Structure: Shape, density, leaf-to-calyx ratio [10, 51]. Some genetics known for specific structures (e.g. "golf balls" (Transcript P.181)). Some LED-grown flower can be rock-hard (Transcript P.202).**
  + **Root System Development: Efficiency and structure of the root system can be strain-specific [3]. Cloned plants have weaker, more lateral roots than seed plants (Transcript P.32).**
* **Life Cycle and Flowering Time: Genotype-dependent duration of growth stages:**
  + **Seedling Stage Duration [10, 54].**
  + **Vegetative Stage Duration: Ability to remain vegetative under specific photoperiods [10, 55, 56]. Commercial grows may have veg times from 10-18 days (Transcript P.176, P.217) to several weeks (Transcript P.200).**
  + **Flowering Time/Duration: Crucial parameter for breeding and cultivation planning [10, 39, 57, 58]. Ranges from 7 weeks (e.g. some Zkittlez crosses (Transcript P.115)) to 10+ weeks (e.g. Haze varieties, some OGs (Transcript P.115, P.169, P.308)).**
  + **Sativa varieties typically have longer flowering times (10-16 weeks) than indica (6-10 weeks) [10, 57]. Photoperiod-dependent flowering vs. autoflowering [59-61]. Use of far-red light can shorten flowering time by a week or more (Transcript P.204).**
  + **Semi-full-term/fast-flowering strains [62, 63].**
  + **Maturation Indicators: Visual cues (pistil color, trichome appearance) indicating peak ripeness can vary slightly by strain [10, 64-66].**
  + **Trichome gland head phenotypes change over the flowering period [67]. Optimal harvest timing varies by strain [68]. For hash production, plants might be harvested earlier (e.g. day 40 for a 70-day flower strain) (Transcript P.197).**
  + **Re-vegetation Potential: Ability to revert to vegetative growth after flowering can be strain-dependent [6, 69].**
  + **Older plants may struggle more [69].**
* **Yield Potential: Genotype-dependent inherent capacity for biomass and flower production under optimal conditions.**
  + **Measured in grams per plant or grams per square foot [65]. Can be influenced by substrate choice [1, 3]. Yields of 2.5-4 lbs per light reported by cultivators (Transcript P.116, P.204). Some strains are known low yielders (e.g. cookies, lcg) but high value (Transcript P.116, P.241). Under canopy lighting can increase yield by 20-50% (Transcript P.225). Hash yields also vary (e.g., 3% vs 4-5.5% with Fade) (Transcript P.9).**
* **Chemical Profile (Chemovar): Genotype-dependent production of specific cannabinoids, terpenes, and other compounds, defining the chemovar [70-73]. Huge driver of market value (Transcript P.152, P.170).**
  + **Major Cannabinoid Ratios (THC:CBD, THC:CBG, CBD:CBG, etc.) [28, 74].**
  + **Controlled by alleles at cannabinoid synthase loci [74, 75]. Breeding can target specific ratios [76, 77].**
  + **Minor Cannabinoid Production (THCV, CBDV, CBG, CBC, CBN, etc.) [72, 78, 79]. Genetics control production [76, 77].**
  + **Terpene Profile: Specific terpenes produced and their relative concentrations [72, 73, 78, 80, 81]. Unique terpene profiles are highly sought after (e.g. Dante's Inferno #6 cherry candy (Transcript P.152, P.172)).**
  + **Genetics are foundational, but expression influenced by environment and post-harvest [82]. Terpene synthase (TPS) genes are involved [45, 79].**
  + **Unique flavor/aroma profiles are strain-defining [58, 80, 83]. "Gas" and "candy" profiles are popular (Transcript P.172, P.187).**
  + **Flavonoid Production (Cannflavins, Anthocyanins for color) [78, 84] (Transcript P.14-15).**
  + **Total Cannabinoid Potency (% DW) [71, 74, 78]. THC levels are often a primary market driver, but this is shifting (Transcript P.170, P.197, P.239).**
  + **Total Terpene Content [78].**
  + **Stability of Chemical Profile: Consistency across different grows/environments (less plastic chemotypes) [85, 86].**
  + **Desirable for medicinal/commercial purposes [18, 71, 85, 87]. Influenced by genetic stability and environmental control [71, 88].**
* **Propagation Characteristics:**
  + **Seed Germination Rate and Speed [10, 89, 90]. Old seeds may have poor germination (Transcript P.168).**
  + **Cloning Success Rate: Ease of rooting cuttings, influenced by genetics and mother plant health [25, 91]. Some strains are notoriously difficult to clone.**
  + **Tissue Culture Recalcitrance: Difficulty of in vitro regeneration and transformation for certain genotypes [48, 92, 93].**
  + **Genotype-dependent HLVd eradication success in meristem culture [94]. (Transcript P.17-18, P.81).**
  + **Doubled Haploid (DH) Production Recalcitrance: Difficulty in generating homozygous lines rapidly [41, 93].**
* **Responses to Cultivation Techniques: Different strains may respond better or worse to specific methods.**
  + **Pruning and Training (e.g., Topping, LST, ScrOG, SOG): Effectiveness for yield and structure optimization can be strain-dependent [91, 95-98]. Some growers prefer no topping to encourage a dominant main cola and specific canopy structures (Transcript P.182-183). Stretch characteristics heavily influence training needs (Transcript P.114). Defoliation timing and extent interact with nutrient strategies like "Fade" (Transcript P.12, P.15-16).**
  + **Fertigation/Nutrient Management: Optimal nutrient timing, strength, and ratios may differ [13, 26, 27, 43, 45]. Some strains (e.g. Runtz) are sensitive to high EC, while others (e.g. Pie Hoe) can take very high EC (Transcript P.196). OGs might prefer lower EC (Transcript P.196).**
  + **Nutrient Use Efficiency (NUE) varies [45, 99].**
  + **Substrate Suitability: Performance can vary significantly across different substrates (soil, coco coir, peat mixes, rockwool, hydroponics) and may be genotype-specific [2, 3, 31]. Some strains might prefer the buffering of coco over the rapid changes in rockwool (Transcript P.116, P.180).**
* **Desired Effects/Applications: While influenced by environment and post-harvest, the genetic chemotype provides the basis for different effects and applications [72, 86, 100-103].**
  + **Recreational Effects: Energetic/cerebral (sativa-like) vs. relaxing/sedative (indica-like) [47, 102].**
  + **While traditional Sativa/Indica labels are not fully reliable for genetic structure [59, 104, 105], market categorizations persist based on perceived effects [47, 102].**
  + **Entourage effect plays a role [78, 106-109].**
  + **Medical Applications: Specific cannabinoid/terpene profiles are sought for therapeutic outcomes (e.g., high CBD for certain conditions) [85, 101, 110].**
  + **Tailored chemotypes for medicinal needs [111].**

#### 1.6 Pest/Disease Resistance Parameters

**Parameters defining a strain's inherent ability to resist common pests and diseases.**

* **Resistance Levels: Genotype-dependent inherent resistance or susceptibility to:**
  + **Fungal Diseases (e.g., Powdery Mildew (PM), Bud Rots like Botrytis, Root/Crown Rots like Fusarium/Pythium) [32, 33, 112, 113]. Botrytis is a significant issue, especially with dense buds or under LED lights if humidity is not managed. Calcium deficiency can exacerbate botrytis (Transcript P.7-8, P.15). Fusarium is a concern in hydroponic/recirculating systems, no cure, spreads via water (Transcript P.84). PM resistance is a highly desirable trait (Transcript P.79).**
  + **Mold resistance is a crucial agronomic trait [114]. Strains from humid regions may have higher mold resistance [58].**
  + **Bacterial Diseases [32, 33].**
  + **Viral Pathogens (e.g., Hop Latent Viroid - HLVd) [32, 33]. HLVd resistance varies by genotype [94]. Some strains may be asymptomatic carriers (Transcript P.80-81). Symptoms include stunting, dudding, brittle stems, abnormal branching, reduced trichomes/yield/quality (Transcript P.3, P.16, P.80, P.171). Spreads via mechanical damage (tools, hands) (Transcript P.80). Present in roots (Transcript P.83). Can be in seeds (unconfirmed for cannabis, Tumi studying) (Transcript P.17, P.81).**
  + **Nematode Infestations (e.g., Root-knot nematodes) [115].**
  + **Insect Pests (e.g., Spider Mites, Aphids, Whiteflies, Thrips, Fungus Gnats) [32, 33, 113, 116]. Thrips and mites are common (Transcript P.80, P.179).**
* **Mechanism of Resistance: May involve structural defenses, production of defensive compounds (e.g., secondary metabolites like cannabinoids and terpenes can act as deterrents/protectants) [20, 21, 117], or activation of immune pathways. Plant polycultures may attract beneficial organisms for natural pest/disease control [118].**
* **Stress-Induced Susceptibility: Stress (abiotic or biotic) can weaken a plant's defenses and increase susceptibility to pests and diseases [34, 119]. Older mother plants may be more susceptible [34]. Stress can also cause HLVd to express symptoms in previously asymptomatic plants (Transcript P.17).**
* **Impact on Yield/Quality: Resistance (or lack thereof) directly impacts yield quantity and quality by minimizing (or maximizing) damage and systemic infection [32, 33, 113]. HLVd can devastate crops (Transcript P.3, P.16-17).**

### 2. Cannabis Breeding and Genetics Parameters

**This section outlines the parameters governing the inheritance of traits, breeding methodologies, genetic management, and related analytical and simulation considerations within the Cannabis sativa L. breeding context. This is a core area for the simulation, driving strain development and player progression. Breeding for specific terpene profiles (e.g., "candy," "gas") and unique genetic expressions is a primary goal (Transcript P.152, P.172, P.187). The philosophy of finding "keepers" through pheno hunting is central (Transcript P.150, P.154).**

#### 2.1 Foundational Genetic Parameters

**Parameters defining the basic mechanisms of inheritance and genome structure in cannabis.**

* **2.1.1 Genome Structure**
  + **Ploidy Level: Diploid (2n=20) [1, 2]. Simulation models diploid genetics as default.**
  + **Chromosome Number: 9 pairs of autosomes and XY sex chromosomes [1, 2].**
  + **Genome Size: Approximately 818 Mb (XX) to 843 Mb (XY) [1]. Influences data for genomic analysis. Cannabis genome still being fully mapped (Transcript P.78).**
  + **Chloroplast Genome: Parameter for maternal lineage or plastid traits (e.g., Yunma 7 approx. 153,899 bp) [3].**
  + **Mitochondrial Genome: Parameter for specific research paths, less critical for core breeding [4].**
* **2.1.2 Inheritance Models**
  + **Mendelian Inheritance: For traits controlled by single genes with dominant/recessive or co-dominant alleles [5-8].**
    - **Alleles: Different forms of a gene.**
    - **Genotype: The genetic makeup (e.g., BB, Bb, bb).**
    - **Phenotype: Observable characteristics from genotype and environment (e.g., Silver Bud vs. Golden Bud) [1].**
    - **Homozygous: Two identical alleles (e.g., BB, bb) [2, 3].**
    - **Heterozygous: Two different alleles (e.g., Bb) [4].**
    - **Dominance: One allele masks another's effect [5, 19].**
    - **Recessiveness: The masked allele [5].**
    - **Co-dominance: Both alleles contribute to the phenotype [6].**
  + **Polygenic Inheritance: For traits controlled by multiple genes (e.g., yield, potency, flowering time, disease resistance) [6, 7, 9-11].**
    - **Quantitative Trait Loci (QTLs): Genomic regions influencing quantitative traits [6, 8-10, 12-17]. Simulation models cumulative effect.**
    - **Additive Gene Action/Effects: Multiple genes contribute cumulatively [8, 21].**
    - **Dominance Effects: Interactions between alleles at the same locus [8].**
    - **Epistasis: Interactions between genes at different loci influencing expression [6, 8-10, 18-20]. Crucial for complex traits.**
  + **Pleiotropy: A single gene/QTL affecting multiple traits [6, 9, 10, 18].**
  + **Gene Linkage: Genes close on the same chromosome are often inherited together [6, 8, 10].**
    - **Recombination/Crossing Over: Process shuffling genetic material; frequency depends on gene distance [8-10, 21, 22].**
    - **Genetic Maps: Represent gene order based on recombination frequency [8, 22].**
    - **Recombination Rate: Frequency of crossing over, influenced by genetic map distances (cM) [21, 22].**
  + **Mutation Rate: Spontaneous DNA sequence change introducing new variation [21, 23, 24]. Parameter for novel trait appearance.**
* **2.1.3 Genetic Variation and Population Genetics**
  + **Genetic Variation: Differences in DNA among individuals.**
  + **Allele Frequency: Proportion of a specific allele in a population.**
  + **Genetic Diversity: Total genetic characteristics in a species; maintaining it is a challenge [7, 11].**
  + **Genetic Erosion: Loss of genetic diversity [11].**
  + **Gene Flow: Transfer of genetic variation between populations [7].**
* **2.1.4 Sex Determination**
  + **XY System: Male (XY), Female (XX) as primary mechanism [1, 25, 26].**
  + **Environmental Influence on Sex Expression: Conditions like light leaks, temperature swings can lead to hermaphroditism [26] (Transcript P.158, P.171).**
  + **Genetic Influence on Sex Expression: Genes on sex chromosomes and autosomes [27]. Sex identification markers (PCR-based) used in reality [28-30]. Some strains have higher genetic predisposition to herm (e.g., Dante's Inferno #6, Transcript P.152).**
  + **Chemically Induced Reversal: Using agents like Silver Thiosulfate (STS) or colloidal silver to induce male flowers on female plants for feminized seed production (Transcript P.169). Pollen viability/sterility from induced males can vary (Transcript P.152).**
* **2.1.5 Genotype-by-Environment Interaction (GxE)**
  + **The effect of an environmental factor on phenotypic expression depends on the genotype [6, 7, 10, 12-14]. Critical for realism. (Transcript P.113, P.116, P.160-161, P.187, P.196, P.200-207).**
  + **Norm of Reaction: Range of phenotypes from one genotype across different environments.**
  + **Different strains perform differently under varying conditions (e.g., indoor vs. outdoor, different nutrient regimes, light spectra - HPS vs LED, specific LED brands like ThinkGrow vs Luxx, under canopy lighting) [15, 16] (Transcript P.113, P.116, P.160-161, P.202-207, P.225). Cold temperatures or "Fade" nutrients can induce purple coloration (Transcript P.14-15).**

#### 2.2 Trait Parameters (Specific to Cannabis)

**Parameters defining the heritable characteristics that breeding programs aim to manipulate.**

* **2.2.1 Agronomic Traits**
  + **Yield Components:**
    - **Flower Biomass (g/plant, g/m²) [11, 19, 22, 30, 31, 58-75]. Influenced by genetics and environment [31, 59]. Can range from low (Cookies, LCG - Transcript P.116, P.241) to high (2.5-4 lbs/light - Transcript P.116, P.204). Under canopy lighting can increase yield by 20-50% (Transcript P.225).**
    - **Bud Density (airy, medium, compact, "rock-hard" under LEDs (Transcript P.202)) [32, 72, 321, 324, 327].**
    - **Harvest Index (ratio of harvestable biomass to total biomass) [31].**
    - **Hash Yield (% return from fresh frozen or dry material). Varies significantly by strain. "Fade" nutrients increased hash yield by 1.3% absolute in one test (Transcript P.9). Some strains are bred/selected specifically as "washers."**
  + **Growth Habit/Architecture:**
    - **Plant Height/Stature (e.g., tall, medium, short, dwarfing) [32, 33, 34, 60, 64, 65, 67, 70, 74, 75, 106, 123, 144, 174, 185, 234, 248, 315, 317, 318, 321-328]. Stretch varies significantly (e.g., Sherb Banger 22: 4-week stretch, 12" to 5ft; Rainbow Belts/Zkittlez: short) (Transcript P.114-115).**
    - **Branching Pattern (e.g., apical dominant, lateral spread, balanced) [32, 42, 322, 329]. Some OGs have minimal lateral branching without topping (Transcript P.182-183). Untopped plants often develop a dominant main cola (Transcript P.183).**
    - **Leaf Morphology (leaflet number, shape, size, margin, color - e.g. black leaves with Fade (Transcript P.14)) [32, 321].**
  + **Flowering Time:**
    - **Photoperiod Response (short-day) [34, 35]. Requires specific light/dark cycle (e.g., 12/12, or 11/13 to push finish - Transcript P.115) [34, 36-38].**
    - **Days to Maturity (after flowering initiation) [2, 6, 25, 31, 33, 34, 37, 39, 40, 60, 63, 65, 66, 68-71, 73, 75, 90, 92, 93, 98, 100, 102, 106, 123, 131, 146, 162, 178, 185, 188, 189, 192, 194, 234, 235, 248, 250, 314-320]. Strain-dependent, from 7 weeks (Zkittlez crosses, Transcript P.115) to 10+ weeks (Hazes, OGs, Transcript P.115, P.169, P.308). Far-red light can shorten by a week+ (Transcript P.204).**
    - **Autoflowering (day-neutral) Trait [13, 25, 32, 35, 41, 42, 53-57]. Flowers based on age, not photoperiod [43, 53]. Controlled by ruderalis genes [13, 41]. Cannot be reverted [53].**
    - **Semi-Full-Term (Quicks): Hybrids flowering 2-3 weeks earlier [44].**
  + **Seed Production Traits:**
    - **Seed Yield (seeds per plant/flower) [31]. Can be 5,000 to 20,000+ per light (Transcript P.309).**
    - **Seed Maturity (timing, hardness, visual cues) [45, 106, 370].**
    - **Seed Viability (% germinating) [46, 47]. Influenced by genetics, storage, maturity. Old seeds may have poor germination (Transcript P.168).**
    - **Germination Rate (speed) [23, 34, 36, 41, 46, 48, 370]. Influenced by genetics, environment, media.**
    - **Seed Characteristics: Natural markings, stripes [23, 36, 41, 106, 370].**
  + **Stress Tolerance (Abiotic):**
    - **Drought Tolerance [49].**
    - **Heat Tolerance [49]. Some strains herm easily with temperature swings (Transcript P.158, P.171).**
    - **Salinity Tolerance [49]. Some strains sensitive to high EC (Runtz), others tolerant (Pie Hoe) (Transcript P.196).**
    - **Temperature Extremes Tolerance [49]. Cold can induce purple colors (Transcript P.14-15).**
    - **Nutrient Deficiency/Toxicity Tolerance [50-52]. Some strains are heavy feeders, others are sensitive (Transcript P.196).**
    - **Light Intensity Tolerance: Some strains sensitive to high PPFD (old Indicas, Transcript P.116).**
  + **Stress Tolerance (Biotic):**
    - **Pest Resistance/Tolerance (e.g., mites, thrips, aphids, fungus gnats) [11, 13, 19, 22, 25, 31, 49, 53, 54, 72, 92, 123, 316, 319, 329, 338-344]. Resistance Level (susceptible, moderate, resistant) [31].**
    - **Disease Resistance/Tolerance (e.g., powdery mildew, botrytis, fusarium, pythium, rust, blights, leaf spots, viruses, HLVd) [11, 13, 16, 19, 22, 25, 31, 49, 54-60, 72, 92, 123, 316, 319, 329, 338-344]. Specific resistance (e.g., Powdery Mildew Resist - Transcript P.79) [31, 319, 329, 343]. HLVd resistance varies; some asymptomatic carriers (Transcript P.17, P.80-81).**
  + **Nutrient Requirements/Use Efficiency (NUE): [19, 22, 31, 61, 62, 76, 345-360]. Strain-dependent [31, 358]. Influence on deficiency/toxicity symptoms [319, 348, 361]. OGs may prefer lower EC (Transcript P.196).**
  + **Water Use Efficiency (WUE): [61-63].**
  + **Recalcitrance to Tissue Culture/Regeneration: Genotype-dependent difficulty [64-69]. HLVd eradication via meristem TC varies by genotype (Transcript P.17-18, P.81).**
  + **Responses to Training Techniques (pruning, topping, LST): [70-72]. Influenced by genetics and growth stage [42, 322, 329]. Some growers prefer no topping (Transcript P.182-183, P.200). Defoliation strategy interacts with nutrient plans like "Fade" (Transcript P.12, P.15-16).**
  + **Root Development: Genetic influence on root structure and vigor [41, 44, 47, 321, 367-369]. Cloned plants have weaker, more lateral roots (Transcript P.32).**
  + **Environmental Adaptation: Suitability for specific environments (indoor, outdoor, greenhouse, climates, altitude) [2, 7, 10, 12, 16, 56, 57, 64, 65, 67, 70, 73-75, 106, 123, 144, 189, 234, 250, 315, 317-319, 322, 324, 325, 362-366]. Michigan's humidity and cold fall temps are challenging for out-of-state genetics (Transcript P.5-6).**
* **2.2.2 Chemotype Traits**
  + **Cannabinoid Profile: Concentrations (% Dry Weight or mg/plant) of major/minor cannabinoids and acidic forms [9, 10, 11, 15, 30, 31, 59, 62, 63, 73-89, 76-89].**
    - **THC/THCA Content: [1, 9, 15, 31, 32, 34, 40, 59, 64, 66, 68, 71-75, 77-81, 87-202]. Influenced by genetics (THCAS locus) [82], environment, maturity [83-85]. Ranges from 12% to 35%+ (Transcript P.13, P.170, P.187, P.197). Moisture content at testing is critical (Transcript P.12, P.22). "Fade" nutrients can increase THC (Transcript P.13).**
    - **CBD/CBDA Content: [1, 9, 15, 25, 31, 62, 63, 69, 73-75, 77, 79-86, 87-89, 121, 122, 129, 133, 136, 139, 143, 147, 149, 152, 154-162, 164-177, 189-192, 196-205]. Influenced by genetics (CBDAS locus) [82], environment, maturity [83-85].**
    - **CBG/CBGA Content: [15, 73-75, 77]. Precursor [73]. Influenced by genetics (CBGAS locus) [82], maturity [77]. CBGA-predominant chemotype [87, 88].**
    - **CBC/CBCA Content: [15, 73-75, 77]. Influenced by genetics (CBCAS locus) [82].**
    - **THCV/THCVA Content: [15, 73, 74, 77]. Propyl cannabinoid [89]. Influenced by genetics (e.g., stacking Apr alleles) [89].**
    - **CBDV/CBDVA Content: [15, 73, 74, 77]. Propyl cannabinoid [89].**
    - **CBN/CBNA Content: [73, 74, 77, 90]. Degradation product of THC/THCA [90]. Increases with oxidation, heat, aging [90].**
    - **Minor Cannabinoids (Delta-8/10 THC, HHC, THCP, THCB, etc.): [12, 31, 62, 73, 76-89, 206]. Potential for breeding for high levels [30, 83]. Delta-8 can be synthesized from CBD (Transcript P.279-281).**
    - **Cannabinoid Purity: Proportion of target cannabinoid relative to total [77]. Key for medicinal cultivars [76, 91].**
    - **Total Cannabinoids: Sum of quantified cannabinoids [77].**
  + **Terpene Profile: Concentrations and ratios of individual terpenes [9, 10, 15, 31, 62, 73, 75, 76, 77, 79-82, 85-89, 92, 203, 206-209]. Contributors to aroma, flavor, effects [73, 93, 94]. Influenced by genetics (TPS genes) [61], environment (e.g. "Fade" nutrients, Transcript P.8-9), maturity, drying/curing (Transcript P.179, P.298-299) [75, 94].**
    - **Major/Individual Terpenes: Myrcene, Limonene, Caryophyllene, Pinene, Ocimene, Terpinolene, Humulene, Linalool, Bisabolol, Nerolidol, Geraniol, etc. [73, 76, 81, 207-209].**
    - **Minor Terpenes [73].**
    - **Total Terpenes. "Yield dilution" can reduce total terps if biomass is pushed too hard (Transcript P.62).**
    - **Terpene Ratios [76, 81].**
  + **Aroma and Flavor Descriptors: (e.g., citrus, pine, fuel, earthy, skunky, sweet, spicy, cheese, fruity, "candy" (Transcript P.152, P.172), "gas" (Transcript P.187)) [16, 30, 31, 40, 55, 66, 67, 71, 75, 79-81, 86, 93-103, 105, 107, 111, 113, 115-119, 121, 122, 125, 127-131, 133, 136, 137, 140, 142-151, 153-155, 157-160, 162, 163, 165-179, 181-203, 205-281]. Linked to terpene profiles. Market preference for unique profiles (Transcript P.152, P.170, P.192).**
  + **Flavonoid Content: Contribution to pigmentation (anthocyanins for purples, Transcript P.14-15) and other effects [96, 97].**
  + **Volatile Sulfur Compound (VSC) Content: Contribution to pungent notes ("gas," "skunk") [96].**
  + **Decarboxylation Profile: How readily cannabinoid acids convert to neutral cannabinoids [76-78, 87-89].**
* **2.2.3 Visual/Morphological Quality Traits (Bag Appeal)**
  + **Bud Appearance: Overall shape (e.g., "golf balls" Transcript P.181), trim quality [31, 59, 98-100, 107, 140, 176, 189, 220, 267, 277, 314].**
  + **Bud Density: (airy, medium, compact, "rock-hard" under LEDs Transcript P.202).**
  + **Bud Color: (e.g., green, purple, orange hues) [67, 98, 107, 113, 123, 140, 189, 194, 247, 249, 262, 264, 265, 314, 317, 318, 332]. Often influenced by genetics and temperature (cold for purples, Transcript P.14-15) or "Fade" nutrients (Transcript P.14).**
  + **Trichome Density/Coverage ("frostiness") [34, 49, 55, 59, 66, 71, 75, 93, 101-104, 134, 137, 158, 220, 233, 267, 280, 318, 321, 332-337]. Athena Stack can visually increase (Transcript P.160).**
  + **Trichome Color/Appearance: Clear to milky to amber as maturity indicator [90, 98, 105-109]. Differentiated by fluorescence [107, 110, 111]. Important for hash making timing (Transcript P.197).**
  + **Trichome Characteristics: Type, size [34, 49, 55, 59, 66, 71, 75, 93, 134, 137, 158, 220, 233, 267, 280, 318, 321, 332-337].**
  + **Pistil Color (Mature): Orange-red, pink-purple, brown [90, 98, 105, 220, 321]. Indicator of maturity.**
  + **Leaf-to-Calyx Ratio: Influences trim efficiency [98, 112].**
* **2.2.4 Effect Profile & Other Traits**
  + **Effect Profile: Psychoactive, physical, therapeutic effects [25, 34, 36, 40, 55, 63-66, 68-72, 75, 90, 93-105, 107-110, 112-115, 117, 118, 120-122, 125-137, 139-151, 153-203, 205, 206, 211, 212, 222, 223, 226, 229, 230, 232, 233, 235-246, 248-258, 260-313]. Linked to cannabinoid/terpene profiles (entourage effect) [93, 114]. Categories like "creative focus," "relaxation," "energy" [115, 116, 282, 293]. Market preference shifting from pure THC to overall experience/terps (Transcript P.170, P.192, P.197, P.239).**
  + **Uniformity and Stability: How consistently a trait is expressed [11, 17, 19, 20, 24, 25, 30, 31, 68, 75, 92, 106, 123, 316, 330, 331]. Important for reliable product.**
  + **Sex Expression Tendency: Dioecy, monoecy, hermaphroditism [23, 321]. Genetic predisposition to herm under stress (Dante's Inferno #6, Transcript P.152). Ability to induce for breeding (STS, Transcript P.169) [30, 321].**
  + **Other Morphological Traits: Stem color (e.g., purple stems) [17], foxtailing (genetic in some strains, Transcript P.120) [119, 135, 148, 295, 318, 321].**
  + **Biostimulant/Microbial Response: Genetic variability in response [346].**
  + **Water Activity: For storage and mold prevention [117].**
  + **Shelf Life/Stability: Preservation of cannabinoids/terpenes. Affected by drying/curing (Transcript P.179, P.298-299).**
  + **Nutritional Content (Seeds): Protein, oil, phenolic compounds [119, 120].**

#### 2.3 Breeding Methodologies and Processes Parameters

**Parameters defining the techniques and strategies used to create and manage new cannabis varieties. Breeding philosophy: MHigh Dave emphasizes finding unique terpene profiles and not just chasing hype (Transcript P.150-152); Bean Fiends emphasizes thorough testing before release (Transcript P.187).**

* **2.3.1 Parent Selection**
  + **Based on desired traits (e.g., unique terpenes, vigor, structure, resistance) [5, 7, 10, 17, 45, 132, 135, 142, 176, 202]. (Transcript P.151-152, P.170-171).**
  + **Phenotypic Selection: Based on observable traits [5, 7, 17-20, 127, 145, 173-176]. Critical in pheno hunts.**
  + **Genotypic Selection: Based on genetic information (e.g., from DNA fingerprinting or marker analysis).**
  + **Marker-Assisted Selection (MAS): Using genetic markers linked to traits [7, 8, 11, 13, 16, 21, 22, 131, 198, 203, 225-227]. (e.g., for HLVd resistance, PM resistance genes, Transcript P.79).**
  + **Genomic Selection (GS): Using genome-wide markers to predict breeding value [7, 8, 10, 11, 13, 16, 18, 198, 203, 225, 226, 229]. Higher tier [7, 22].**
  + **Optimal Contribution Selection: Maximize genetic gain, minimize inbreeding [7].**
  + **Male Selection: Crucial. Structure, vigor, stem rubs for aroma, and ultimately, progeny testing (performance of offspring) are key (Symbiotic, Transcript P.170-171).**
* **2.3.2 Mating Designs and Sexual Reproduction**
  + **Generations: Tracking P, F1, F2, F3+ [132, 151-155]. F1s for diversity, later generations for stabilization (Transcript P.168, P.188, P.319).**
  + **Manual Pollination: Player identifies plants, collects/applies pollen [5, 23, 135-137, 145, 146]. Shaking males in a room with females (Symbiotic, Transcript P.170).**
    - **Pollen Collection Rate: Amount of viable pollen [137]. Some reversed females produce little or delayed pollen (Transcript P.169-170).**
    - **Pollination Success Rate: Probability of seed set [47, 147].**
    - **Controlled Environment: Isolated breeding spaces to prevent unwanted pollination [23, 42, 146, 148, 149].**
  + **Natural/Open Pollination: Pollen drift distance parameter [23, 42, 145, 147-150].**
  + **Controlled Crosses: Manually pollinating specific plants [23]. (e.g., Bean Fiends x Symbiotic collabs, Transcript P.318).**
  + **Reciprocal Crosses: A x B and B x A to assess maternal effects [7].**
  + **Diallel Crosses: All possible crosses between a set of parents [7]. For general/specific combining ability.**
* **2.3.3 Asexual Reproduction (Propagation for Preserving Genetics)**
  + **Cloning (Vegetative Cuttings): Genetically identical copies from mother plant [4, 5, 19, 31, 38, 42-48, 121, 133, 156-160]. Preserves phenotype/genotype [19, 31, 38, 49, 138, 163-166]. Standard practice for maintaining "keepers."**
    - **Cutting Success Rate: [133, 159]. Influenced by technique, hormones, environment, mother plant health, genetics [133, 159, 160]. Some strains are hard to clone.**
    - **Rooting Time: [160-162]. Influenced similarly [159, 160].**
    - **Mother Plant Maintenance: Keeping plants in vegetative state [4, 19, 31, 45, 47, 121, 133, 156, 159, 160]. Regular refresh of moms is good practice (e.g., every 6-8 weeks, Transcript P.183). Older moms can decline or accumulate pathogens (Transcript P.34, P.183).**
    - **Cloning from Flowering Plants: Possible, may take longer [157, 162].**
    - **Genetic Stability: Clones are identical; phenotypic differences due to GxE [5, 138, 163-167].**
    - **Clonal Rejuvenation: Tissue culture to restore vigor or clean pathogens [168] (Transcript P.17-18).**
  + **Tissue Culture/Micropropagation: Advanced sterile lab technique [6, 33, 43, 50-52, 56, 59, 64, 66, 138, 165, 169-171].**
    - **Protocol Success Rate: For initiation, multiplication, rooting, acclimatization [56, 69, 138]. Genotype-dependent [33, 56, 67, 69].**
    - **Pathogen Eradication (Meristem Culture): [33, 50, 51, 56, 59, 67, 138]. Especially for HLVd (Transcript P.17-18, P.81). Success varies by genotype and lab skill. Can take multiple attempts (Transcript P.17-18).**
    - **Regeneration Capability: From explants (nodal segments, callus, protoplasts) [64, 67, 68, 138]. Protoplast regeneration is a bottleneck [68].**
    - **Genetic Stability: Assessed with markers (e.g., ISSR) [138, 163, 165]. Generally stable.**
    - **Equipment and Sterile Technique: Required (Laminar flow hood, autoclave, microscope) [169, 170, 172] (Transcript P.18-19). Cost can be $5k-$50k for a lab (Transcript P.18-20).**
    - **Benefits: Cleaning genetics, long-term storage/archiving of genetic libraries, rapid multiplication (Transcript P.17-22).**
* **2.3.4 Population Development and Breeding Strategies/Schemes**
  + **Selective Breeding (Phenotype Selection): [5, 127, 145, 173-176]. Traditional, slower [173]. Still the primary method in pheno hunts (Transcript P.150-155).**
  + **Crossbreeding & Hybridization: Creating hybrids from distinct parents [6, 20, 135, 147, 173, 176, 177]. Creates new combinations, hybrid vigor [6, 20, 173]. (e.g., Symbiotic crossing Purple Punch male with various elite females, Transcript P.167).**
  + **Population Types:**
    - **F1 Hybrid: First generation from distinct parents [5, 11, 19, 25, 30-32, 136, 152, 155, 183, 186, 187]. Often exhibit heterosis. Uniform if parents stable. High diversity for pheno hunting (Transcript P.168, P.188).**
    - **F2 Population: From selfing/intercrossing F1s; segregation occurs [4, 5]. Can reveal recessive traits.**
    - **Recombinant Inbred Lines (RILs): From repeated selfing of F2 individuals [7]. For mapping/gene interaction studies.**
    - **Backcross Populations (BC1, BC2, etc.): [4, 24, 25, 29]. Used to introgress specific traits (Transcript P.319-320, TH Seeds explanation).**
    - **Synthetic Varieties: Intercrossing parental lines, random mating [7].**
    - **Diversity Panels: For association mapping [128].**
  + **Developing True-Breeding Lines (Inbred Lines - IBLs): Mating related individuals for homozygosity/stability [2, 3, 6, 10, 11, 16, 17, 19, 20, 24-27, 30, 31, 34, 136, 151, 153, 178-182]. Breed true [2-4, 29, 151, 180, 182]. Requires many generations [2]. Working lines to F4/F5 for stability (TH Seeds, Transcript P.320).**
    - **Inbreeding: Essential for stable lines [9, 10].**
    - **Inbreeding Depression: Reduced vigor/fertility from deleterious recessives [6, 144, 178, 183, 184].**
    - **Managing Inbreeding: Population size, new genetics, nucleus breeding [144, 178, 185].**
  + **Backcrossing (BX): Crossing hybrid to recurrent parent to transfer specific trait [4, 6, 7, 18, 24-29, 136, 151, 152, 178, 181, 183, 188, 189]. Percentage of recurrent parent genome increases each generation [183, 189]. Used to reinforce traits of a mother plant using new male offspring (TH Seeds, Transcript P.319-320).**
  + **Self-Pollination (Selfing, S1): Crossing plant with itself [6, 18, 190, 191]. Increases homozygosity. Induced chemically [1, 25, 41]. Used to create S1s of elite cuts (e.g., Tear Gas S1, Transcript P.188) for preservation or finding similar phenos.**
  + **Stabilization: Reducing genetic variation for consistent trait expression [2, 11, 19, 20, 24-27, 30, 31, 34]. Goal of many breeding programs.**
  + **Phenotype Hunting (Pheno Hunting): Growing populations (e.g., 100s-1000s of seeds) to identify desirable individuals [6, 11, 35, 202, 204, 205]. (MHigh Dave 400 seeds, Transcript P.154; Highline 5k-10k seeds/year, Transcript P.238). Requires meticulous observation and record keeping. Taking cuts of all plants before flower is a common SOP (Transcript P.154).**
  + **Seed Production Methods:**
    - **Seeds: Generative propagation, introduces variation unless stable lines [23, 31, 36-41].**
    - **Feminized Seeds: Using induced female pollen (from STS/colloidal silver treatment (Transcript P.169)) on females for all-female offspring [25, 31, 41, 192]. Risk of hermaphroditism if unstable genetics [148, 192, 193]. European market demand is high (Transcript P.170). Some reversed females are poor pollen producers or pollen is delayed (Transcript P.169-170).**
    - **Autoflowering Genetics: Breeding with C. ruderalis [53-57].**
    - **Triploid Seeds: Crossing tetraploid (4x) with diploid (2x) for sterile triploid (3x) offspring [11, 150, 194, 195]. Prevents seeding. May have distinct morphology/aromas, not necessarily higher potency [196]. More variation if parents not homozygous [197]. (Post-MVP)**
    - **Developing Semi-Full-Term Varieties (Quicks): Crossing autoflowering and photoperiod parents [44].**
  + **Doubled Haploids (DHs): Homozygous lines in one generation from haploid cells [18, 33, 138, 139]. Accelerates breeding.**
* **2.3.5 Breeding Program Management**
  + **Breeding Goals/Objectives: Defining desired traits (e.g., unique terps, yield, disease resistance, market trends like "candy" or "gas") [198-201] (Transcript P.151-152, P.172, P.187).**
  + **Record Keeping: Pedigree, phenotype, genotype, stock inventory [121, 152, 207]. Crucial for tracking selections.**
  + **Data Collection: Meticulous recording of observations during pheno hunts [45, 121, 134, 202, 206].**
  + **Selection Intensity: Proportion of individuals selected (e.g., finding 9 keepers from 231 seeds - Coffin Candy hunt, Transcript P.305).**
  + **Breeding Cycle/Generation Time: [18, 208, 209]. From seed to tested selection can take a year or more (MHigh Dave, Transcript P.154). Seed production itself is 3-4 months plus testing (Symbiotic, Transcript P.168).**
  + **Resource Constraints: Space (veg space for holding cuts during pheno hunt is critical, Transcript P.186), labor, budget [64, 65, 202, 208, 232, 244]. Pheno hunts are expensive (MHigh Dave $10k-$15k on seeds, Transcript P.150, P.154).**
  + **Testing: Sending selections to multiple testers in varied environments for feedback before release (TH Seeds, Transcript P.320).**

#### 2.4 Genetic Resource Management Parameters

**Parameters related to acquiring, storing, and managing genetic material.**

* **2.4.1 Germplasm Acquisition**
  + **Source: Landraces (diverse, locale-adapted, unique alleles, risk of erosion) [14, 20, 49, 50, 121-127], Feral populations [49, 50], Heirloom varieties [82], Modern cultivars (elite cuts from other breeders/growers, Transcript P.1, P.163, P.165) [14, 122], Breeder collections [128].**
  + **Access Restrictions: Legal/regulatory hurdles [64, 129-131]. DEA rescheduling has eased shipping of seeds and <0.3% THC cuttings (Transcript P.1-2, P.276-277).**
  + **Acquisition Methods: Expeditions, NPC contacts, quests, vendors (e.g., Clone America, Transcript P.1), events [6]. Direct trades/purchases between growers.**
  + **Origin Dossier/Acquisition Report: Source and characteristics info [6]. Verifying authenticity of acquired cuts is a challenge (HLVd risk, mislabeling).**
* **2.4.2 Genetic Material Storage**
  + **Seed Bank: Long-term seed storage [47, 50, 121, 132, 133]. Keeping extensive seed libraries (Highline 5-10k seeds/year hunts, Transcript P.238).**
    - **Storage Conditions: Temperature (-20°C), humidity influence viability [121].**
    - **Inventory Management: Tracking lots, parentage, generation, traits [121, 132-134].**
  + **Pollen Inventory: Storage of collected pollen [132, 135-137]. Fresh pollen preferred by some (Symbiotic, Transcript P.170).**
    - **Storage Conditions: Temperature, humidity influence viability [132]. Freezer storage with desiccant.**
    - **Viability Degradation Rate: Decreases over time [132].**
  + **Tissue Culture Inventory: In vitro storage for preserving "keepers" and mother stock [69, 132, 138] (Transcript P.21-22).**
    - **Storage Methods: Slow growth (short-medium term), Cryopreservation (long-term) [69, 138, 139]. Influence stability/viability [69].**
    - **Passage Number: Subculture count, can influence stability [138].**
    - **Benefit: Massive space saving for large genetic libraries (Jungle Boys 400-500 strains in TC vs. traditional moms, Transcript P.21).**
* **2.4.3 Germplasm Conservation**
  + **Importance: Preserving genetic diversity for future breeding/resilience [20, 49, 50, 124, 127, 134, 140-142]. Preventing loss of valuable cuts (Craft Farmer, Transcript P.21).**
  + **Methods: Genebanks (ex situ via TC or seed banks) [69, 121, 124, 125, 138, 140, 143], On-farm conservation (in situ - maintaining mother plants) [140, 143], Documentation of traditional knowledge [124, 140].**
  + **Effective Population Size (Ne): Maintaining large Ne to slow inbreeding/drift [125, 144].**

#### 2.5 Genetic Analysis and Advanced Breeding Technologies Parameters

**Parameters defining tools for understanding and manipulating genetics at a deeper level.**

* **2.5.1 Genetic Analysis**
  + **DNA Extraction: Obtaining genetic material [210]. (Leaf samples for HLVd/fingerprinting, Transcript P.81, P.332).**
  + **Molecular Markers: Specific DNA sequences (SNPs, SSRs/STRs, ISSRs) for identification/tracking [8, 13, 16, 17, 51, 122, 131, 203, 210, 211].**
    - **STR Analysis: For DNA fingerprinting, relatedness [210-212].**
    - **SNP Analysis: For high-density genotyping, association mapping [13, 16, 17, 121, 122, 203].**
  + **Genotyping: Determining genetic makeup [17, 121, 131, 203, 213].**
  + **Sequencing (DNA/RNA): Determining nucleotide order [14, 16, 17, 121, 122, 130, 214-218]. Cannabis genome still being fully mapped (Transcript P.78).**
    - **Whole Genome Sequencing (WGS) [213, 216].**
    - **Genotyping-by-Sequencing (GBS) [121, 213].**
    - **RNA Sequencing (RNA-seq) for transcriptomics (gene expression) [14, 214, 218-221].**
  + **Bioinformatics Pipelines: Tools for processing and analyzing large genetic/omics datasets [6, 16, 131, 206, 362, 372].**
  + **Genetic Mapping: Determining relative positions of genes/markers [14, 17, 21, 213].**
  + **Association Mapping (GWAS/mGWAS): Identifying genomic regions/genes associated with traits [14, 15, 19, 121, 213, 222, 223]. mGWAS links variation to metabolite profiles [222]. (e.g., finding genes for PM resistance, Transcript P.79).**
  + **QTL Mapping: Identifying QTLs in biparental populations [12, 14-16, 128, 213, 223].**
  + **Parentage Testing: Confirming parentage [210].**
  + **Strain Identification/Authentication: Genetic fingerprinting to verify cultivars (MyFloraDNA CCI, Transcript P.331-334) [82, 134, 224]. Helps combat renaming and ensures consumers get authentic genetics.**
  + **Hemp vs. Drug-Type Differentiation: Genetic/chemical tests [75, 224]. Based on Δ⁹-THC content (Transcript P.2, P.276-277).**
  + **Population Structure and Diversity Analysis: Understanding genetic relationships/diversity [7, 10, 11, 12, 21, 122, 141, 144, 233, 362, 372].**
  + **Fine Mapping and Causal Gene Validation: Identifying specific genes/polymorphisms [21].**
  + **Pathogen Testing: PCR-based tests for HLVd (Tumi Genomics, MyFloraDNA, Transcript P.77, P.81-84, P.327), Fusarium (Transcript P.84), and other viruses/fungi. Importance of regular testing of mother stock (Transcript P.82). Sample pooling for cost efficiency in large scale testing (Transcript P.17).**
  + **Transcriptomics and Proteomics: Studying gene expression and protein production [21, 214, 218-221, 347].**
  + **Metabolomics: Comprehensive analysis of metabolites [12, 21, 79-81, 85, 87-89, 222, 347].**
  + **Epigenetics: Heritable gene expression changes without DNA sequence changes [12, 371].**
* **2.5.2 Advanced Breeding Technologies**
  + **Marker-Assisted Selection (MAS): (Covered in 2.3.1, fundamental to advanced breeding strategies).**
  + **Genomic Selection (GS): (Covered in 2.3.1, fundamental to advanced breeding strategies).**
  + **Genomic Prediction Accuracy: Parameter defining how accurately genetic merit is predicted [7, 9, 10].**
  + **Gene/Genome Editing (CRISPR/Cas9): Precise gene modification [6, 14, 16, 21, 66, 84, 198, 203, 225, 230, 231]. Potential for targeted trait modification (e.g., PM resistance, Transcript P.79) [16, 84, 230]. Requires efficient transformation/regeneration [224]. Subject to regulations [16, 50, 65].**
  + **Genetic Transformation (Introducing foreign DNA): [6, 16, 64, 138].**
  + **Somatic Hybridization (Protoplast Fusion): Fusing cells to create hybrid [68, 138, 139]. Regeneration is a bottleneck [68].**
  + **Doubled Haploid (DH) Production: (Covered in 2.3.4).**
  + **Speed Breeding: Shortening generation time [18, 232].**
  + **Consensus Genetic Maps/Reference Genomes: Integrated data for comprehensive resources [372].**
* **2.5.3 AI Research Lab (In-Game Concept)**
  + **Probabilistic Predictions: For breeding outcomes based on genetic data/AI models [6, 11].**
  + **Genetic Marker Analysis (Simplified): Abstracted MAS/GS for early seedling selection [6, 11, 170, 228].**
  + **AI Model Complexity: Potential for complex models (e.g., small neural networks) [6].**

#### 2.6 Genetic Simulation Parameters (Game Engine Specific)

**Parameters specific to modeling genetic inheritance and population dynamics within the game.**

* **Trait Heritability (h²): Proportion of phenotypic variation due to additive genetic effects [21, 208, 233]. Influences selection effectiveness.**
* **Genetic Correlation: Degree to which two traits are influenced by the same genes [21, 208].**
* **Breeding Value (BV) / Genomic Estimated Breeding Value (GEBV): Estimated genetic merit [208, 229, 233].**
* **Allele Frequencies: Proportion of a specific allele in a population [21, 102, 103, 233, 234].**
* **Linkage Disequilibrium (LD): Non-random association of alleles at different loci [208, 233, 234].**
* **Inbreeding Coefficient (F): Probability of homozygosity by descent [233, 234].**
* **Genetic Diversity Metrics: Quantifying genetic variation (e.g., heterozygosity, alleles per locus, Ne) [122, 141, 144, 233].**
* **Genotype x Environment Interaction (GxE) Modeling: Parameters for how genotypes respond to environmental variations (light, temp, nutrients) [9, 21, 52, 70, 167, 208, 224, 235-238]. (Transcript passim).**
* **Burn-in Phase (Simulated Historical Breeding): Modeling historical selection to create realistic starting LD and diversity [234].**

#### 2.7 Data Management and Visualization Parameters (In-Game)

**Parameters related to handling and displaying genetic and breeding data within the simulation.**

* **Breeding Database: Centralized system for pedigree, phenotype, genotype, environmental, trial metadata [121, 129]. Tracking selections from large pheno hunts (Transcript P.154, P.238).**
* **Trait Library: Player-populated database of known traits and associated markers/genotypes [6, 228].**
* **Pedigree Tracking: Visualizing and managing family trees [6, 134, 152, 239].**
* **Genetic Data Display: Presenting simulated genotype ID, alleles, markers, linked to traits [203, 228, 240]. Displaying CCI from MyFloraDNA (Transcript P.331-332).**
* **Phenotype Observation Data: Recording visual/measured characteristics [5, 202, 241]. Linking observed traits to genetics [5, 241].**
* **Breeding Interface: UI for parent selection, crosses, project management, outcome prediction [118, 132, 203, 228, 239].**
* **Data Visualization: Tables, charts, graphs, visual overlays on plant models [70, 118, 134, 203, 228, 240, 241].**
* **Workflow Management: Tools for outlining/tracking breeding program steps [209, 239]. Managing multiple ongoing hunts and breeding lines.**

#### 2.8 Challenges and Risks Parameters (In-Game)

**Parameters representing potential difficulties and failures in breeding and genetic work.**

* **2.8.1 Biological Challenges**
  + **Tissue Culture Recalcitrance: Genotype-dependent regeneration difficulty [65, 67, 69]. Some strains are very difficult to clean via TC (Transcript P.17-18).**
  + **Genetic Instability: Somaclonal variation, inbreeding depression [138, 144, 163, 178, 183, 184]. Hermaphroditism in feminized lines or due to stress (Transcript P.152, P.169-171).**
  + **Disease/Pest Transmission: Through cloning (HLVd is notorious, Transcript P.17, P.80) or seed (HLVd in seeds being studied, Transcript P.17, P.81) [56, 59, 157, 242].**
  + **Poor Germination: Old seeds or bad genetics (Transcript P.168).**
  + **Low Pollen Production/Viability: In some males or reversed females (Transcript P.152, P.169-170).**
* **2.8.2 Technical Challenges**
  + **Phenotyping Bottlenecks: Difficulty in accurate, high-throughput data collection for large hunts [118, 243]. Subjectivity in selection.**
  + **Data Integration and Management Complexity [19, 129].**
  + **Modeling Complexity: Simulating epistasis, dominance accurately [19].**
  + **HLVd Testing Inconsistencies: Different labs, sample times, or locations within plant can give varied results (Transcript P.17, P.81-82).**
* **2.8.3 Legal and Regulatory Obstacles (Abstracted)**
  + **Licensing, permit requirements for research/access to genetics [16, 21, 50, 64, 66, 129, 130, 227, 243]. Evolving DEA rules on shipping genetics (Transcript P.1-2).**
  + **Banking challenges for cannabis businesses, including seed sales (Transcript P.2).**
* **2.8.4 Resource Constraints**
  + **Limited budget (pheno hunts are expensive - seeds, space, labor, testing, Transcript P.150, P.154), space, equipment, skilled personnel [64, 65, 202, 208, 232, 244].**
* **2.8.5 Ethical Considerations (Abstracted)**
  + **Impacts on genetic diversity, IP (importance of DNA fingerprinting, Transcript P.331-334), access to genetics/technology [140, 142, 245-248]. Misappropriation of genetics/renaming (Transcript P.154, P.313).**
* **2.8.6 Unforeseen Outcomes**
  + **Unexpected trait combinations from recombination/complex interactions [6, 46, 103, 180]. Not all traits fully predictable. Finding no keepers in a large hunt (MHigh Dave, Transcript P.154).**

### 3. Facility and Grow Operation Science Parameters

**This section details the parameters related to the physical infrastructure, environmental controls, operational processes, and resource management within cannabis cultivation facilities, drawing upon principles from agricultural physics, engineering, and horticulture. Facility design and operational SOPs are critical for success and preventing issues like HLVd or pest outbreaks (Transcript P.17, P.80, P.341).**

#### 3.1 Facility Infrastructure Parameters

**Parameters defining the physical structure, layout, and materials of cultivation spaces.**

* **Facility Types:**
  + **Residential House Interior [1-3]: Initial small-scale environment. Pre-defined layout [3]. Initial wear and tear can be simulated [3]. Often limited power (Transcript P.108). "Trap grows" or caregiver setups are often in residential settings (Transcript P.3, P.6, P.30-33).**
  + **Warehouse [1-3]: Larger scale, unlocked after Residential [1, 4]. Giant open shell to build within [3]. Common for commercial grows (Transcript P.44, P.56, P.166).**
  + **Greenhouse [2, 5, 6]: Moderate control, leverages natural light [7, 8]. Glass or polycarbonate covering [2]. Requires ventilation and temperature control [6]. Can be hoop house or more advanced [9, 10]. Mix-light (HPS/LED + natural light) is common (Transcript P.42, P.223, P.296). Susceptible to outdoor environmental pressures (pests, temp/humidity swings).**
  + **Vertical Farm [11]: High density, max space use [12]. Multi-tiered racking/towers [13, 14]. Requires vertical transportation logistics [15].**
  + **Research Lab [2, 5]: Specialized, sterile environment [2, 16]. Required for advanced techniques like Tissue Culture [16] (Transcript P.18-20).**
  + **Outdoor Field [2, 5]: Low control, relies on natural environment [8, 9]. Subject to weather/pest risks [7]. Can include secure plots [9]. Challenging in climates like Michigan due to humidity/cold (Transcript P.5-6).**
  + **Subterranean Lab [3, 17]: Potential future map [3, 17].**
  + **Abandoned Research Outpost [3, 17]: Potential future map [3, 17].**
  + **Geothermal Greenhouse Complex [3, 17]: Potential future map [3, 17].**
* **Structural Elements: Parameters defining buildable components within facilities.**
  + **Walls [3, 18, 19]: Sections/panels [19]. Material properties: cost, appearance, insulation (R-value), light/air barrier, cleanliness [3, 19]. Non-porous, smooth, durable, non-absorbent, chemical-resistant materials preferred for sanitation (e.g., FRP, insulated metal panels) [20, 21]. Materials influence cleaning ease [20]. Coving at wall-floor junctions recommended [20]. False walls used in "trap grows" (Transcript P.209).**
  + **Floors [3, 22]: Sections (Concrete, Wood, Grate - load ratings) [22]. Drains (Standard, Trench - capacity) [22]. Non-porous materials preferred (epoxy coated concrete) [20]. Coving at wall-floor junctions recommended [20]. Sloped floors for drainage.**
  + **Roofs/Ceilings [3, 22]: Sections (Drywall, Suspended Grid, Concrete) [22]. Suspended Tiles (acoustic, cleanroom) [22]. Open Rafters/Trusses (Wood, Metal) [22]. Influence large-scale microclimate patterns [13]. High ceilings can cause thermal stratification [13]. Ceiling height impacts light placement and stretch management (Transcript P.114). Typical grow room ceiling height 7'11" to 9'2" in some facilities (Transcript P.114).**
  + **Doors [3, 18, 22]: Various types (Standard, Industrial Roller, Air Lock) [22]. Air locks minimize contaminant entry [23]. Weather stripping and seals important.**
  + **Windows [22]: Various types (Standard, Greenhouse, Industrial) [22]. Greenhouse-specific windows [22]. Can be blocked out in grow rooms [24]. Light leaks are a major concern for photoperiod control (Transcript P.171).**
  + **Stairs/Ladders/Catwalks [25]: Vertical access [25]. Relevant for multi-story/vertical facilities [25].**
  + **Support Pillars/Beams [25]: (Concrete, Steel) [25]. For structural support in large spaces [25].**
  + **Containment Structures (Tents): Pre-fab grow tents [26]. Provide dedicated grow spaces [26]. Sealable for environmental control [8].**
* **Facility Layout and Zoning: Parameters defining the spatial arrangement and compartmentalization of facilities.**
  + **Grid System: Grid-based construction [3, 18]. Base unit 1 foot [27]. Snapping to grid lines, intersections, object points [27].**
  + **Zoning: Designating distinct areas by cultivation stage/activity [3, 28]. Mother Rooms, Propagation (Clone Rooms), Vegetative, Flowering, Drying, Curing, Trimming, Packaging, Waste Handling, Ancillary Areas (Offices, Labs, Storage, Decontamination) [29, 30] (Transcript P.58-59, P.98-99). Physical barriers prevent contaminant movement [23, 28]. Allows tailored environmental/hygiene protocols [28]. Veg rooms often 30% of flower footprint (Transcript P.98). Kings Garden has 1 nursery/mom building for 9 cultivation facilities (Transcript P.58). Flower room sizes vary (e.g., 64-120 lights, Transcript P.99; 220-1000 lights, Transcript P.58).**
  + **"Clean Flow" Principles: Layout/workflows minimize contaminant movement [23, 31]. Unidirectional process flow (cleaner to dirtier areas) [23, 32]. Strategic management of people, plant materials, supplies, waste flow [23]. Controlled access points with hygiene stations (booty/gown change, hand wash) [33, 34] (Transcript P.341). Dedicated staff/protocols for high-risk zones [33, 34].**
  + **Workflow Optimization: Designing layouts for efficient movement of plants, materials, personnel [32, 35]. Reducing travel distances [32]. Incorporating workflow principles for post-harvest processing [36]. Cellular layouts for grouping processes [37]. (Kings Garden example, Transcript P.58-59). Lean farming practices to reduce touches and movement (Transcript P.199-202).**
  + **Vertical Layout Challenges: Managing horizontal and vertical movement of plants/supplies in multi-level farms [15]. Integrating automated systems or designing ergonomic manual solutions [15].**
  + **Clutter Management: Providing adequate space, encouraging vertical space use, incorporating storage solutions [38, 39]. Designing assets with clear footprints [39].**
  + **Facility Aesthetics: Maintaining a clean, pristine, professional visual aesthetic [38, 40]. Materials influence appearance [19].**
* **Utility Networks: Parameters defining the infrastructure for power, water, and potentially gas/other systems.**
  + **Plumbing Network: Detailed, interconnected networks [3]. 3D routing, snapping/free placement, collisions [3]. Sizing (diameters) impacts performance (flow, pressure drop) [3]. Material impacts cost, durability, efficiency, appearance [3]. Logical source-endpoint connections [3]. Recirculating DWC systems require careful plumbing to avoid pathogen spread (e.g. Fusarium, Transcript P.84).**
  + **Electrical Network: Detailed, interconnected networks [3]. 3D routing, snapping/free placement, collisions [3]. Sizing (gauges) impacts performance (capacity, voltage drop) [3]. Material impacts cost, durability, efficiency, appearance [3]. Logical source-endpoint connections [3]. Basic abstracted utility connections (power draw) in MVP [18, 41]. Power limitations are a major constraint in many grows (Transcript P.5, P.108). Transformer upgrades can lower electricity costs (Transcript P.5).**
  + **HVAC Ducting: Part of HVAC system, routed through facility [3]. Size and design impact airflow, pressure loss, noise [42]. Material impacts cost, durability, efficiency, appearance [3]. Designed for accessibility for cleaning [28].**
  + **Source Connection Points: Main Power Grid Connection Point (Abstracted) [41]. Water Supply Connection Point (Abstracted - Tap, RO, Treated) [41]. Gas line connection (for generators/heaters). Some facilities require substations built for power needs (Transcript P.5).**
  + **Utility View/ "X-Ray" Mode: Visual overlay to see hidden networks [3, 39, 43]. Shows pipes, ducts, wires, flow/pressure indicators [39, 43]. Unlocked with progression [44]. Simple, non-simulated flow animations for feedback [3, 39].**

#### 3.2 Environmental Control Science Parameters

**Parameters defining the systems and principles for regulating the atmospheric conditions within cultivation spaces. Environmental control is key to quality and preventing issues like bud rot (Transcript P.7-8, P.15).**

* **Temperature Management:**
  + **Optimal Ranges: Vary by growth stage (Seedling, Vegetative, Flowering) [45-48]. Vegetative: 21-29°C (70-85°F) day, ~10°F lower night [47, 48]. Flowering: 18-27°C (65-80°F) day, ~10°F lower night [47, 48]. Some run flowering temps 73-76°F with "Fade" (Transcript P.15), or even 76-80°F with LEDs (Transcript P.161, P.61-62). Root zone: 18-24°C (65-75°F) [48, 49]. Optimal range can be cultivar-specific [50]. Cold temps (e.g., mid-60s F) can induce purple colors (Transcript P.14-15).**
  + **Measurement: Air temperature sensors (Thermistors, RTDs, Thermocouples, Infrared) [51]. Root zone temperature probes [46]. Leaf surface temperature sensors (for VPD) [52]. Sensor placement critical for accuracy (Transcript P.11).**
  + **Control Systems: Thermostats [53, 54]. HVAC systems (Heating and Cooling components) [55, 56]. Supplemental heaters/coolers [57]. Diurnal temperature variations can be programmed [58]. Growlink Blueprint for scheduling (Transcript P.139).**
  + **Heat Sources: Grow lights (HID produce more heat than LED, Transcript P.61-62, P.113, P.160-161, P.202, P.223-224) [59-62]. Electrical equipment [59, 62]. Plant transpiration (latent heat load) [62, 63]. Outside air infiltration/ventilation [62]. Conduction/convection through building envelope [62].**
  + **Heat Management: Ventilation (mechanical/natural) for removing excess heat [56, 64]. Insulation (R-value) minimizes heat transfer [65]. Facility design (sealed rooms) [66]. HVAC systems sized to manage sensible heat loads (e.g., 0.6 tons/light, Transcript P.62) [60]. Airflow patterns influence temperature uniformity [60, 67].**
  + **Dew Point Control: Managing temperature fall and humidity to prevent condensation/fungal proliferation [68].**
* **Humidity Management:**
  + **Optimal Ranges: Vary by growth stage [45-48]. Seedlings/Clones: 65-80% RH [48, 69]. Vegetative: 50-70% RH [48, 69]. Flowering: 40-50% RH [46, 48, 69, 70], though some run higher with LEDs (60-65% RH, Transcript P.161) if airflow is excellent. Persistently high humidity (esp. root ball) -> fungal issues [66] (Transcript P.7-8, P.15). Optimal range can be cultivar-specific [50].**
  + **Measurement: Humidity sensors (Hygrometers) [54]. Canopy microclimate RH sensors [52]. Sensor placement critical (Transcript P.11).**
  + **Control Systems: Humidistats [53, 54]. Dehumidifiers [55, 56]. Humidifiers [71]. Integrated HVACD systems [55, 72]. Diurnal RH variations can be programmed [58]. Growlink Blueprint for scheduling (Transcript P.139).**
  + **Moisture Sources: Plant transpiration/evapotranspiration (major latent heat load driver) [62, 63, 73, 74]. Evaporation from growing medium/reservoirs [74]. Outside air infiltration/ventilation [75].**
  + **Moisture Management: Ventilation for removing excess moisture [56, 64]. Dehumidifiers sized based on lighting wattage and transpiration rate [76]. Airflow patterns influence humidity uniformity [60, 67]. Environmental controls integrated with sanitation for disease prevention [77, 78]. Michigan's high humidity is a challenge (Transcript P.5-6). Greenhouse dehumidification at night is critical (Transcript P.304).**
* **Vapor Pressure Deficit (VPD):**
  + **Concept: Air moisture vs. saturation capacity; integrates temp/RH [79]. Optimizing VPD enhances transpiration/nutrient uptake [79, 80]. (Transcript P.121-122, P.235).**
  + **Calculation: Based on air temp, leaf surface temp, and RH [79].**
  + **Measurement: Requires sensors for air temp, RH, and ideally leaf surface temp [52].**
  + **Control: Managed by adjusting temperature and humidity [79]. VPD setpoints can be strain-specific [81]. Optimal target range (e.g., 1.0-1.5 kPa) [46].**
  + **Impact: Influences water transpiration rate [79], nutrient uptake [79], pest/disease susceptibility [48]. Critical for healthy growth (Transcript P.235).**
* **Lighting Management:**
  + **Types: HID (MH/HPS - with Ballasts/Hoods, Transcript P.103, P.108, P.202), LED Panels (e.g., Luxx, ThinkGrow, Fluence, Transcript P.113, P.160, P.202, P.235), Fluorescent (T5/CFL), LEC [54, 82-84]. Spectral output varies [54, 60, 83]. HPS vs LED debates on quality/yield/heat (Transcript P.61-62, P.113, P.160-161, P.181-182, P.202-207, P.223-224). Mixed HPS/LED or checkerboard setups (Transcript P.202-203, P.223). Under canopy LED lighting (Transcript P.196, P.205, P.224-225).**
  + **Parameters:**
    - **Photosynthetically Active Radiation (PAR): Light wavelengths (400-700nm) for photosynthesis [79].**
    - **Photosynthetic Photon Flux Density (PPFD): Light quantity (µmol/m²/s) [46, 79, 85]. Optimal levels vary by stage [45, 46]. Vegetative: 200-600 µmol·m⁻²·s⁻¹ (Transcript P.161). Flowering: 800-1200+ µmol·m⁻²·s⁻¹ (esp. with CO2) [46, 86] (Transcript P.114, P.161). Some genetics sensitive to high PPFD (Transcript P.116).**
    - **Daily Light Integral (DLI): Total amount of light over a 24-hour period. Low PPFD can be fine if DLI met (Transcript P.161).**
    - **Spectrum: Influence growth, stage transition, cannabinoid/terpene synthesis [83, 87-89]. Blue-dominant for vegetative [60, 66, 83]. Red-dominant for flowering [60, 83]. Full-spectrum LEDs [66]. Customizable spectrum with LEDs [83, 87]. Far-red (Emerson effect) for end-of-day signal (4-8 minutes, Transcript P.203-204), can shorten flower time, improve quality (Transcript P.203-204).**
    - **Photoperiod: Light hours per day [47, 66, 85, 90]. Vegetative: 18-24 hrs light/day [47, 66, 85, 89, 90]. Flowering: strict 12 hrs light / 12 hrs uninterrupted dark [85, 89-91]. Some use 11/13 to push finish (Transcript P.115) or even full run (Transcript P.115-116). Lantern technique (12 on, 5.5 off, 1 on, 5.5 off) for veg with 13 total light hours (Transcript P.181). Deviations/light leaks -> hermaphroditism/reversion [89, 91]. Autoflowers are not photoperiod dependent [16, 92].**
  + **Equipment: Grow lights (fixtures) [54, 82, 84]. Ballasts (generate heat, often kept outside grow space) [54, 93, 94]. Reflective hoods/materials (focus/direct light) [54, 91, 93]. Light timers/controllers [54, 82, 95]. Light meters (measure PAR/PPFD) [54, 96].**
  + **Control: Adjust intensity (dimming), fixture height/layout for target PPFD [52]. Set light cycles [97]. Manage light leaks [89, 91, 97]. Automated systems for sunrise/sunset simulation [98]. Growlink Blueprint for scheduling (Transcript P.139).**
  + **Impact: Primary driver of growth (photosynthesis) [89]. Influences morphology, stage transition, cannabinoid/terpene production [47, 89, 99]. Light stress (photoinhibition, bleaching, burning tips if plants grow into lights, Transcript P.114) [79, 100].**
* **CO2 Management:**
  + **Concept: CO2 enhances photosynthesis, boosts yield (esp. vegetative/flowering) [87, 97, 101, 102].**
  + **Optimal Concentrations: 800-1500 ppm (flowering stage, Transcript P.161) [101]. Optimal varies with stage, light, temp, cultivar [103]. Ambient CO2 ~400 ppm [104]. CO2 uptake rate depends on canopy photosynthetic activity [102].**
  + **Measurement: CO2 sensors/monitors [71].**
  + **Control Systems: CO2 controllers [71]. CO2 enrichment systems [84, 102]. Automated systems for measured release [105]. Growlink Blueprint for scheduling (Transcript P.139).**
  + **Methods: Compressed CO2 tanks, generators (produce heat/moisture) [87, 101]. CO2-releasing pads [101].**
  + **Management: Requires careful monitoring, integration with ventilation/airflow [97, 101]. Use in sealed rooms for effectiveness [80]. Discontinue late in flowering cycle [106].**
* **Airflow and Ventilation:**
  + **Purpose: Air circulation, renewal, temperature/humidity regulation, CO2 distribution, prevents stagnant microclimates, reduces pest/disease risk (powdery mildew) [66, 79, 84, 97].**
  + **Methods: Intake/exhaust fans (basic), oscillating fans (internal) [97, 107]. Mechanical ventilation [56]. Natural ventilation (thermal buoyancy, wind manipulation in greenhouses) [64].**
  + **Equipment: Fans (various types) [1, 54, 84]. Filters (carbon filters for odor, air filtration systems with MERV ratings, HEPA filters for intake/recirculation, Transcript P.347) [82, 108]. Ductwork [42].**
  + **Air Exchange Rate (ACH): Number of times air is completely replaced per hour [109]. Typical indoor cannabis: 12-60 ACH [110]. Affects HVAC energy use and CO2 levels [109].**
  + **Calculation: Room volume (L x W x H) divided by desired turnover time [111].**
  + **Impact: Influences temperature uniformity [60, 67], humidity uniformity [60, 67], CO2 distribution [97], disease/pest spread [77]. Strong airflow can cause physical leaf damage [112]. Poor airflow exacerbates humidity problems [112].**
* **Microclimate Dynamics:**
  + **Concept: Spatial/temporal variations in temp, humidity, airflow, CO2, light within a grow space [67]. Creates heterogeneity [67]. Sensor placement is critical to understanding and managing (Transcript P.11).**
  + **Causes: Equipment placement/influence (fans, lights, HVAC project radius/cone of effect) [113, 114]. Airflow patterns [60, 67]. Plant canopy architecture/density (affects local humidity/CO2) [67, 114]. Facility geometry (room dimensions, internal structures) [13, 67]. Obstructions (walls, equipment) [113, 114].**
  + **Modeling: Abstracted microclimate modeling based on zone-based influence [113-115]. Periodically recalculate based on active equipment and structure [113, 114]. Not full CFD [113, 115].**
  + **Impact: Influences plant growth, development, uniformity [67]. Can lead to issues like tipburn [116]. Resource use efficiency [67].**
  + **Mitigation: Strategic equipment placement [116]. Airflow management [116]. Uniform environmental control aims to reduce heterogeneity [66]. Environmental heat maps can visualize microclimate variations [39, 117]. Validating sensor data by physically checking plants/pots in different locations (Transcript P.11).**

#### 3.3 Resource Management Parameters

**Parameters related to the inputs and outputs of cultivation: water, nutrients, energy, waste.**

* **Water Management:**
  + **Source Water: Tap, RO (Reverse Osmosis), Well water, Treated water, Recycled water (condensate, treated wastewater) [41, 118, 119]. Water quality analysis needed [120, 121]. Impurities (dissolved minerals, hardness - Ca/Mg), agrochemicals, microorganisms [120, 122, 123]. RO water is common, but may require CalMag supplementation (Transcript P.8, P.115).**
  + **Water Quality Parameters: pH (Acidity/alkalinity) [47, 82, 120, 124, 125]. Ideal range for nutrient uptake: soil 6.0-6.8, soilless/hydro 5.2-6.5 (Coco often 6.0-6.2, Transcript P.158) [47, 106, 124, 126, 127]. EC (Electrical Conductivity) / PPM (Parts Per Million) / TDS (Total Dissolved Solids) [124, 125, 128]. Measure total dissolved solids/nutrient concentration [124, 125, 128]. EC increases with added salt-based nutrients [128].**
  + **Water Treatment: Filtration (Pre-filtration for particles - Sed/Carb) [121, 123]. Purification (RO for removing dissolved solids) [118, 120, 121]. Disinfection (UV, Ozone, Chlorine injection for iron/disinfection, Transcript P.65) [121, 122, 129, 130]. Monitoring efficacy of treatment systems essential [131].**
  + **Irrigation Methods: Drip (common with coco/rockwool, Transcript P.49, P.113-114, P.124, P.174, P.180), Hydroponics (DWC, NFT, Ebb & Flow, Aeroponics), Subirrigation (Flood and Drain), Manual (watering cans), Fertigation (nutrients via irrigation) [14, 55, 89, 124, 125, 132, 133]. Method influences water use efficiency [61]. Precision irrigation with multiple small shots (P1, P2, P3 phases, Transcript P.121-125).**
  + **Irrigation Control: Timed, Manual, Sensor-driven (real-time soil moisture/EC, e.g., Growlink, Aroya, Transcript P.11, P.121-142). Automated systems (e.g., Netafim, Dosatron, Edatrons with Dilution Solutions controller, Transcript P.74, P.95, P.115, P.148) [55, 119].**
  + **Watering Frequency/Volume: Depends on medium, plant size/stage, environmental conditions [89, 136]. Overwatering leads to root/nutrient issues, disease risk (Transcript P.11, P.126) [137, 138]. Underwatering leads to dehydration [48]. Crop steering involves manipulating watering volume and drybacks (Transcript P.62, P.121-125). Hand watering once a day for some (MHigh Dave, Transcript P.157). Greenhouse irrigation frequency varies by season (3-4 times/day winter, 10-12 times/day summer, Transcript P.297-298).**
  + **Water Temperature: Optimal root zone temp: 18-24°C (65-75°F) [49, 124, 139]. Affects DO, nutrient uptake, microbial growth [49, 139-141]. Colder water at end of flower can induce color (Transcript P.14). Target 2-3°C below room temp (TH Seeds, Transcript P.324).**
  + **Water Conservation: Drip irrigation, recycling/reclamation (condensate, treated wastewater, e.g., Hydrologic skids, Transcript P.64-65), media selection (water retention) [61, 142]. Condensate can provide 40-50% of water needs in desert climates (Transcript P.65).**
  + **Drainage: Proper drainage from pots/media is critical [126, 127]. Avoid standing water [127]. Influenced by substrate properties [126, 143]. Runoff management (collection, testing, disposal/recirculation, Transcript P.64-65, P.157-158). Target 15-30% runoff (Transcript P.64, P.158, P.307).**
* **Nutrient Management:**
  + **Essential Nutrients: Macronutrients (N, P, K, Ca, Mg, S), Micronutrients (Fe, Mn, Zn, Cu, B, Mo, Si) [126, 144-146]. Calcium critical for cell wall, preventing bud rot (Transcript P.7-8).**
  + **Nutrient Ratios (NPK): Vary by growth stage [82, 146, 147]. High N / low P in vegetative. Low-to-medium N and medium-to-high P/K in flowering [146, 147]. Optimal ratios can be cultivar-specific [148, 149]. "Fade" products reduce N late flower (Transcript P.7-9).**
  + **Fertilizer Types: Organic, Inorganic/Synthetic (salts, e.g., Athena ProLine/Blended, Transcript P.7-13, P.25, P.59-63, P.116, P.157, P.175, P.184, P.221), Slow-release [150-152]. Organic inputs often have higher upfront cost [152]. Simplicity of 2-part salt lines valued (Athena, Transcript P.25, P.62). Transition from complex organic/multi-bottle lines to simpler salt lines is common (Kings Garden, Transcript P.59-63; TH Seeds, Transcript P.308).**
  + **Nutrient Solution Management (Hydroponics/Soilless): Precise control of EC/PPM, pH, temperature, DO [49, 106, 124, 128, 139]. Nutrient uptake efficiency [49, 55]. Nutrient partitioning [148]. Nutrient lockout (pH imbalances, ion competition, salt buildup from high EC/inadequate runoff, Transcript P.11, P.123, P.158) [100, 149]. Precise nutrient plans needed [153]. Athena ProLine often run at 3.0 EC (Transcript P.12, P.15, P.126, P.157, P.175, P.221). Blended line can be pushed with or without runoff (Transcript P.25).**
  + **Nutrient Application: Fertigation (via irrigation) [55, 151]. Top dressing [151]. Foliar spraying (e.g. Athena Stack, IPM, Transcript P.160, P.178) [52]. Rate depends on plant maturity, stage, other factors [69, 124]. Increase concentration with maturity, peak flowering, reduce pre-harvest [124].**
  + **Nutrient Uptake: Influenced by nutrient availability, concentration, form, pH (coco 6.0-6.2, Transcript P.158), substrate type, root health, water temperature, DO [49, 125, 126, 139, 140]. Nutrient uptake efficiency [148].**
  + **Nutrient Deficiency/Toxicity: Visual symptoms (chlorosis, necrosis, stunting, leaf deformation, tip burn) [79, 100, 154]. Can interact with pH imbalances [100]. Diagnosis requires visual cues, data (EC/PPM, pH of feed and runoff, Transcript P.11, P.157-158), tissue analysis [100, 148]. Flushing with straight RO or pulling Core nutrients too early can cause Ca deficiency/bud rot (Transcript P.7-8, P.12).**
  + **Nutrient Recycling/Recirculation: Feasibility/cost-effectiveness for large-scale operations [155]. Requires water treatment skids (Hydrologic, Transcript P.64-65). Risk of pathogen spread (Fusarium, Transcript P.84).**
  + **Biostimulants/Microbial Inoculants: Potential impact on nutrient uptake efficiency, secondary metabolism, plant performance [156]. (e.g., Mycorrhizae, Trichoderma, Bacillus, Transcript P.59-60, P.62). Can cause biofilm/clogging issues with salt nutrients (Transcript P.13, P.62, P.65).**
* **Energy Consumption:**
  + **Major Consumers: Artificial lighting (primary energy use), Climate control (HVAC - heating, cooling, ventilation, dehumidification), Water pumps, Fans [155, 157-159].**
  + **Measurement: Electricity (kWh), Natural Gas (for heating) [110]. Energy Use Intensity (kWh/kg flower; kWh/m²/yr) [61]. Power Demand (Peak kW, load factor) [61]. Lighting Efficacy (μmol/J) [61]. Electricity costs can be significant (e.g., 6-17 cents/kWh, up to 42 cents in CA, Transcript P.5).**
  + **Energy Efficiency: Energy-efficient HVAC technologies [108, 160]. LED lights (more efficient, less heat than HPS, Transcript P.61-62, P.113, P.160-161, P.202, P.223-224) [60, 61, 87, 161]. Optimized environmental control strategies [50]. Building envelope optimization (insulation, air seal) [162]. Smart control strategies (VSDs, MPC, AI/ML) [42, 160]. Water/nutrient use efficiency also contributes to energy savings [135]. Transformer ownership can reduce costs (Transcript P.5).**
  + **Energy Sources: Grid power, Generators (Diesel/Gas - backup), Battery Banks/UPS (short-term buffer), On-site renewable energy (solar) [41, 163, 164]. Co-generation plants (Transcript P.5).**
  + **Energy Costs: Major OPEX (esp. indoor/controlled GH) [61, 159]. Fluctuating energy prices [153].**
  + **Environmental Impact: GHG emissions from energy consumption [61, 157, 159].**
  + **Optimization: Strategic energy management (audits, benchmarking), optimized facility design [165].**
* **Waste Management:**
  + **Waste Streams: Plant material (leaves, stems, roots, trimmed material), Used substrates, Packaging, Consumables [163]. Failed/unsellable product (Transcript P.3, P.6-7).**
  + **Characterization/Quantification: Waste generation rate (m³/kg waste categories/kg yield) [166].**
  + **Management Practices: Composting (plant material, some substrates), Recycling, Residual value extraction, Compliant disposal (metric system tracking) [163] (Transcript P.6-7). Diversion Rates (% waste diverted from landfill) [166].**
  + **Costs: Waste management costs ($/kg yield) [166].**
  + **Integration: Waste management flow prevents contamination [34]. Designated routes/areas for waste [34].**
  + **Future Vision: Explore processing/re-using waste for beneficial byproducts [27].**

#### 3.4 Cultivation Practices and Operational Parameters

**Parameters related to the day-to-day activities, workflows, and management strategies in cultivation. SOPs are critical for consistency and scalability (Transcript P.58-59, P.67, P.199, P.215).**

* **Propagation:**
  + **Methods: Seeds (Feminized, Regular, Transcript P.153, P.168-170, P.187-189, P.309, P.318-320), Clones (Cuttings from mother plants, Transcript P.1, P.17-18, P.80-82, P.154, P.183, P.228, P.308), Tissue Culture (Micropropagation, Transcript P.17-22, P.81, P.153, P.330).**
  + **Seed Germination: Requires moisture, warmth (medium temp), darkness (usually) [90, 169]. Optimal medium temperature is critical [169, 170]. Dormancy may require protocols (scarification, stratification, GA3) [126]. Influenced by genetics, medium composition, light, pH, temperature [171]. Old seeds can have poor germination (Transcript P.168).**
  + **Cloning: Cuttings from "mother plants" or plants about to flower [35, 172, 173]. Requires rooting (rooting hormones/compounds) [174, 175]. Success rate depends on heat, humidity, light, hormone, medium [176]. Clones are genetically identical [172]. Risk of inheriting pests/diseases (HLVd spread is a major concern, Transcript P.17, P.80, P.83-84) [177, 178]. Weaker roots than seed plants [177, 179]. Requires dedicated space/infrastructure [178]. Clone shipping is evolving legally (Transcript P.1-2). VP Domes or similar high-humidity environments for rooting (Transcript P.177-178). Clone dunking in IPM solutions (e.g., Athena IPM + Stack) as preventative (Transcript P.178, P.228).**
  + **Tissue Culture: Sterile lab process [16, 168]. Excising explant (shoot tips, nodal segments, meristems), surface sterilizing [168]. Establishment in vitro on nutrient medium with PGRs [180]. Multiplication/Proliferation via subculturing [180]. Potential for pathogen eradication (HLVd, Transcript P.17-18, P.81, P.330) [181, 182]. Renews old mother stock vigor [182]. High setup cost ($5k-50k, Transcript P.18-20), technical expertise required [183]. Risks: contamination, somaclonal variation, acclimatization failure, genotype specificity, vitrification [184-186]. Multi-stage process [168, 180]. Meristem culture is key for cleaning genetics (Transcript P.17-18).**
  + **Seed vs. Clone Comparison: Seeds offer genetic diversity, stronger roots; variable growth [177, 179]. Clones offer speed, predictability, uniformity; weaker roots (Transcript P.32) [177, 179]. Cost/logistics differ [187]. Most commercial grows rely on clones for uniformity (Transcript P.17).**
* **Vegetative Growth:**
  + **Initiation: Rapid leaf/root production in seedlings/clones [188].**
  + **Duration: Depends on desired plant size, cultivar growth rate, symbiotic rotation schedule [188-190]. Prolonging veg increases plant/root size but requires more space/light/time [189]. SOG requires short veg period [191, 192]. Commercial veg times vary: 10-18 days (Transcript P.58, P.176, P.217), 14-18 days (Transcript P.300), up to 5-6 weeks (Transcript P.200). "Veg in place" in flower rooms becoming more common to save labor/time (Transcript P.175-176, P.198-200, P.300).**
  + **Requirements: Long light periods (18-24 hrs, Transcript P.181) [47, 66, 90]. High nitrogen nutrients [146, 147, 193]. Moderate humidity (60-70% RH, Transcript P.161) [48, 69]. Optimal temperature (70-85F, Transcript P.161) [47, 48, 170]. Airflow/ventilation [66, 79]. Adequate space [189]. Low PPFD (200-600, Transcript P.161) can be sufficient if DLI is met.**
  + **Daily Care: Watering/irrigation, monitoring health/environment [194, 195]. Fairly tough stage [194].**
* **Flowering Growth:**
  + **Initiation: Triggered by light cycle change (12/12 for photoperiod strains, Transcript P.115) [89, 90]. Some chemicals can induce flowering [196].**
  + **Duration: Varies by cultivar (e.g., 7-10+ weeks, Transcript P.115, P.169, P.308) [197]. Affected by genetics, environment, nutrients [47, 99]. Far-red light can shorten by a week+ (Transcript P.204). 11/13 light cycle to push finish (Transcript P.115).**
  + **Requirements: Strict 12 hrs light / 12 hrs uninterrupted dark for photoperiod strains [89-91]. Lower humidity (40-65% RH, Transcript P.15, P.161) [46, 48]. Intense light (high PPFD, 800-1500+ with CO2, Transcript P.114, P.161) [46, 86]. Higher phosphorus/potassium nutrients, lower N (e.g. Athena Fade, Transcript P.7-9) [146, 147]. Optimal temperature (65-80F, Transcript P.161) [47, 48].**
  + **Processes: Female plants produce buds/flowers [90]. Trichome development and cannabinoid/terpene synthesis occur [47, 63, 197]. Stretch period in first 1-4 weeks (Transcript P.114).**
  + **Challenges: Bud density/structure can affect airflow/mold risk (Botrytis, Transcript P.7-8, P.15) [198]. Requires robust structure/roots to support bud weight [195].**
* **Plant Training & Care:**
  + **Techniques: Topping (removes apical meristem, encourages lateral branching), Low-Stress Training (LST), Screen of Green (ScrOG - trains plants through a screen for horizontal canopy), Sea of Green (SOG - dense packing of small plants/clones for many colas), Lollipopping (removing lower branches) [53, 80, 133, 173, 190]. Techniques alter growth patterns, influence yield, morphology [53, 133]. Some growers are moving away from topping to reduce labor and stress, focusing on plant density and natural structure (Transcript P.182-183, P.200-201, P.225).**
  + **Other Tasks: Pruning/Defoliation (removes fan leaves/branches, improves airflow/light penetration, redirects energy, Transcript P.12, P.15-16, P.205) [133, 199]. Watering/substrate moisture checks (visual, meters, pot lift method, Transcript P.11) [133]. Providing plant support (stakes, trellis netting, Transcript P.200-201) [190, 200]. Transplanting (moving plants to larger containers/different zones) [90, 190, 201].**
* **Harvest and Post-Harvest Processing:**
  + **Harvest Timing: Critical for chemical profile, quality, effects [202]. Indicators: Trichome maturation (color: clear -> milky -> brown/amber, Transcript P.12, P.197), pistil color, yield/plant [197, 202-204]. Optimal timing is strain/grow-specific [205]. Monitoring trichome appearance via loupe [204]. Hash production often requires earlier harvest (Transcript P.197).**
  + **Harvesting Methodologies: Manual (whole plants vs. branches), Automated (machines) [206-208]. Sharp, sanitized tools essential [199]. Pre-harvest defoliation (large fan leaves) [199]. Organized workspace [199]. Harvest can take 2.5 days for a 7200 sq ft room (Transcript P.199-200).**
  + **Trimming: Hand trim (meticulous, preferred for quality, Transcript P.5), Automated machines (speed vs. quality trade-off) [206, 207, 209]. Wet trim (immediately post-harvest) vs. Dry trim (after drying) [207]. Dedicated trimming space [206]. Cost of hand trimming $100-150/lb (Transcript P.5).**
  + **Drying: Manual hanging/rack in dedicated space [1, 210]. Environment (temp 60F, humidity 60%RH, airflow) impacts time (7-14 days, Transcript P.22, P.298-299) /quality [199, 202, 210, 211]. Too fast -> harshness, terpene loss, uneven drying [210]. Too slow -> mold/mildew, hay smell [198, 210]. Optimal environment needed for quality preservation [202, 211]. Weight loss during drying [211]. Refrigerated trailers used by some outdoor grows (Transcript P.6).**
  + **Curing: Manual container curing (jars, "Grove Bags" / terp block bags, Transcript P.22) [1, 212]. Manual "burping" (releases moisture, exchanges air) [1, 212]. Duration (weeks to months) [212]. Environmental stability (cool, dark) crucial [212]. Target RH (container interior): 58-62% [212]. Influences aroma, flavor, smoothness [211, 212]. Automated curing (smart containers, climate-controlled rooms) [213]. Strain-specific curing may exist [213].**
  + **Bulk Storage: Preserve quality, stability, potency over time [202, 214]. Requires controlled environment (temp, light, O2, humidity) [214]. Evidence-based practices for large-scale storage [214].**
  + **Processing (Extraction/Manufacturing): Converting harvested product to other forms (oils, concentrates like rosin/hydrocarbon, edibles, topicals) [1, 215] (Transcript P.3, P.9-10). Requires specialized equipment and facilities [215].**
  + **Packaging: Preparing final product for sale/storage [215]. Weighing, containerization (bags, jars), sealing, labeling [215]. Cost of testing per batch is a factor (Transcript P.6).**
  + **Minimizing Degradation: Efficient facility layout, batch management/tracking, dedicated environmental controls, inventory management (FIFO) [216].**
* **Cleaning and Sanitation:**
  + **Importance: Prevents pest/pathogen buildup, contamination, ensures product safety/quality [133, 217-219]. Cornerstone of IPM [220]. Critical for preventing HLVd spread (Transcript P.17, P.80, P.82-83, P.341).**
  + **Practices: Routine daily cleaning (debris removal) [217]. Wet/dry cleaning [221]. Deep cleaning (between cycles, post-contamination) [29, 133]. System flushing (irrigation, tanks, HVAC) [20, 133]. Equipment-specific sanitation [20]. Personnel hygiene (handwashing, PPE, foot baths, changing clothes/gloves between rooms/plants, Transcript P.80, P.341-342) [33]. Controlled access/workflow [33]. Quarantine new materials/genetics (Transcript P.17, P.83, P.136, P.137). Sterilizing tools (bleach 10-20% for 30-60s for HLVd, Virkon S; alcohol/flame NOT effective for HLVd, Transcript P.82-83) [20, 222, 223]. Disinfectant use (concentration, contact time, rotation, e.g., Athena Reset foamer, Transcript P.117, P.199) [222, 224, 225].**
  + **Monitoring Effectiveness: Environmental monitoring (air, surface, water sampling for microbes/pathogens, e.g. EnvyCan swabs, Transcript P.341-344) [225, 226]. Rapid assessment tools (ATP bioluminescence testing, visual inspections) [227]. Data analysis for continuous improvement [228].**
  + **Integration: Sanitation protocols integrated into facility design, workflows, staff training [218]. Coordinated efforts with environmental controls [77]. Indispensable for sustainable IPM [220].**
  + **Scale Differences: Strategies, intensity, resources, regulatory pressure differ by scale (hobbyist to large commercial) [225, 229]. Cardboard is a contamination risk (Transcript P.340-341).**
* **Staff Management & Training (Abstracted for MVP):**
  + **Hiring: Finding skilled and reliable labor can be a challenge (Transcript P.2-3, P.58-59).**
  + **Training: SOPs, hygiene, cultivation tasks (Transcript P.19, P.58-59).**
  + **Team Size: Varies by facility size and automation (e.g., 4 people for 300 lights, Transcript P.4; 5 full-time for 1000 lights + floating crew, Transcript P.58; 14 trimmers + 5 cultivators for 500 lights, Transcript P.216).**
  + **Cost of Labor: Significant operational expense (Transcript P.2, P.5).**
  + **Motivation & Culture: Creating a positive work environment (Transcript P.185, P.210).**

### 4. Equipment and Tools Possibilities Parameters

**This section details parameters for various equipment and tools used in cannabis cultivation, from basic hand tools to advanced lab and facility systems. The focus is on their function, impact, cost, and progression within the game.**

#### 4.1 Cultivation & Plant Care Tools Parameters

**Parameters defining handheld tools and basic equipment used for direct plant maintenance and manipulation.**

* **Pruning and Cutting Tools: [1] Tools for trimming, cutting, and shaping plants.**
  + **Types: Bypass Pruners (Standard, Heavy-Duty) [1], Snips/Scissors (Micro-Tip, Curved/Straight, e.g., for cloning or trimming, Transcript P.80, P.82) [1], Scalpels (for TC, Transcript P.18) [1], Loppers [1], Hand Saw [1]. Large Hedge Trimmers [2].**
  + **Quality/Tier: Basic, High-quality [1].**
  + **Material: (Impacts durability, cleanliness, potential for rust) [3].**
  + **Sharpness/Condition: (Affects cut cleanliness, plant stress, disease transmission risk) [3]. Can degrade with use [3]. Requires cleaning/sterilization after use (alcohol, hydrogen peroxide, drying, BLEACH for HLVd - Transcript P.82-83) [3].**
  + **Effect on Plant: Clean cuts promote faster healing, reduce disease entry points. Rough cuts can cause stress, invite pathogens [3].**
  + **Durability: Degrades with use; may require sharpening or replacement [3].**
  + **Cost: Initial purchase cost. Varies by quality [1, 4].**
  + **Maintenance: Cleaning [3], sharpening (potential mechanic). Multiple pairs of scissors rotated through bleach for HLVd prevention (Transcript P.82).**
  + **Storage: Requires a designated clean, dry space to prevent rust and contamination [3].**
  + **Reach: Some hedge trimmers have pole extensions for reaching tall branches [2].**
  + **Cutting Area/Blade Length: (e.g., 12-24 inches for hedge trimmers) [2]. Affects trimming efficiency.**
  + **Weight: (e.g., affects worker fatigue) [2].**
* **Plant Support Tools: Tools for supporting plant structure.**
  + **Types: Trellis netting (Transcript P.200-201, P.225) [5], stakes, tie wire [5].**
  + **Functionality: Prevents lodging, supports heavy buds, helps manage canopy for light penetration [5]. Trellis can be used to spread branches [5]. Marking trellis poles for consistent height (Transcript P.300-301).**
  + **Placement/Setup: Requires setting up (e.g., installing and removing nets) [5]. Floating net designs make harvest/replanting easier [5]. One layer of trellis for untopped plants (Transcript P.201, P.205).**
  + **Material: (e.g., nylon rope for supports) [6].**
* **Clone Dunker Tool: (Craft Farmer invention, Transcript P.227-228)**
  + **Functionality: Slides through a 50-cell clone tray, snaps on, allows entire tray of clones to be inverted and submerged for IPM treatment. Has a lip for slight elevation to promote airflow when tray is upright.**
  + **Material: 3D printed / plastic injection molded.**
  + **Cost: Estimated $20 retail (Transcript P.228).**
  + **Use Case: Dunking clones in IPM solution (e.g., Athena IPM + Stack) twice during propagation as a preventative measure (Transcript P.228). Also useful for secure transport of clones in trays.**

#### 4.2 Nutrient & Irrigation Equipment Parameters

**Parameters defining equipment for storing, mixing, and delivering nutrients and water.**

* **Watering Cans/Hoses: [7] Basic tools for manual irrigation.**
  + **Capacity/Flow Rate: (Affects time taken for manual watering). Hand watering large facilities is labor-intensive but done by some (MHigh Dave, Transcript P.157; Kings Garden for resets, Transcript P.180).**
  + **Cost: Initial purchase cost [7].**
  + **Durability: Can degrade (leaks, cracks).**
  + **Impact: Manual delivery means inconsistent application compared to automated systems.**
* **Reservoirs/Tanks: [7] Containers for storing water or nutrient solution.**
  + **Types: Plastic, Poly, Stainless [7]. Common sizes: 50-gallon (Transcript P.157), 100-gallon (Transcript P.115), up to 15,000-gallon for large facilities (Transcript P.65).**
  + **Sizes: Various sizes (Small, Large, Industrial) [7]. Affects batch volume.**
  + **Material Properties: (Affects inertness, potential for chemical interaction, ease of cleaning). Stainless steel is food-grade [8].**
  + **Capacity: Volume held (e.g., affects how often refilling is needed) [7].**
  + **Cost: Varies by size and material [7].**
  + **Cleanliness: Can harbor pathogens/biofilm if not cleaned (Transcript P.13, P.62, P.65). Regular cleaning with products like Athena Cleanse or Reset (Transcript P.62, P.117).**
  + **Visual Representation: Can dynamically reflect fill levels [10].**
* **Pumps: [7] Equipment for moving water or nutrient solution.**
  + **Types: Water Pumps (Submersible, Inline), Air Pumps (for DWC) [7]. Edatrons, H&A Anderson injectors for fertigation (Transcript P.74, P.115, P.148).**
  + **Flow Rate: Volume of fluid moved per unit time (e.g., GPH) [7]. Affects irrigation speed.**
  + **Head Pressure: Maximum height fluid can be pumped. Affects system design.**
  + **Power Requirement: Electrical consumption [7, 11].**
  + **Cost: Purchase cost [7], operational cost (power).**
  + **Durability/Maintenance: Can fail [12]. Redundant pumps possible [7, 13].**
  + **Functionality: Required for reservoir systems [7], automated water flow [14].**
  + **Noise Level: (Potential factor, less critical for simulation).**
* **Plumbing: [15] Components for constructing fluid delivery networks.**
  + **Types: Pipes (PVC, PEX, Drip Line, poly tube Transcript P.52), Fittings, Valves (manual, solenoid), Filters [15]. Drippers/Emitters (e.g., Netafim 0.3 or 0.5 GPH, Transcript P.116, P.174, P.220; Octo-bubblers, Transcript P.174, P.226).**
  + **Material: PVC, PEX, etc. [15]. Impacts cost, durability, efficiency (friction loss) [16], appearance [16].**
  + **Sizing: Diameters (various diameters) [16, 17]. Impacts flow rate, capacity, pressure drop [16].**
  + **Connectivity: Requires logical source-to-endpoint connections [18]. Visual feedback for valid connections [18]. "Whip kits" for table connections (Craft Farmer, Transcript P.52).**
  + **Routing: Can be routed in 3D [16] (grid-snap or free-form) [16]. Vertical runs require specific tools/UI [19]. No auto-routing in MVP [20]. Uses segmented components for curves/bends [19].**
  + **Durability: Can degrade, leak, or clog (biofilm, salt buildup, Transcript P.13, P.49, P.62, P.65, P.221). Filters require cleaning/replacement.**
  + **Cost: Material cost per unit length/fitting [15].**
  + **Functionality: Essential for irrigation systems [15]. Used in detailed construction [15].**
  + **Pressure Simulation: Abstracted pressure loss based on layout, pump specs, pipe specs [18]. Pressure compensated drippers maintain consistent flow (Transcript P.174).**
* **Nutrient Mixing Stations/Vats: [15] Areas/equipment for preparing nutrient solutions.**
  + **Scale: Manual (hand mixing daily, MHigh Dave, Transcript P.157), Small, Large, Industrial [15].**
  + **Functionality: Used for manual nutrient mixing [15]. Requires clean tanks, measuring tools (scales, beakers), pumps/stirrers, calibrated pH/EC meters [21]. Mixing powdered nutrients (like Athena ProLine) requires specific order and agitation (Transcript P.9, P.157, P.159). Calcium chloride powder is exothermic and can melt tanks if mixed improperly (Transcript P.10).**
  + **Automation: Automation increases at later stages [15]. Full auto-dosing (e.g., Dosatron, Edatron, Dilution Solutions, Anderson Injectors, Transcript P.60, P.74, P.95, P.115, P.148) deferred post-MVP [15].**
  + **Cost: Initial purchase cost. Varies by scale/automation level.**
  + **Maintenance: Cleaning is critical to prevent precipitation and contamination [21].**
* **Automated Dosing/Fertigation Systems: [15] Systems for automated nutrient delivery.**
  + **Functionality: Links sensors (EC/pH) to pumps/valves for automated mixing and delivery based on setpoints [22, 23]. Can automate nutrient delivery schedules [24]. (e.g., Growlink with Edatrons/Anderson, Transcript P.74, P.115, P.121-142, P.148). Direct inject vs. batch tank filling (Transcript P.74, P.115).**
  + **Progression: Late-Game MVP or Post-MVP [15]. Requires advanced controllers [22]. Precision Fertigation needs data on optimal levels [25].**
  + **Precision: Offers higher consistency and efficiency than manual methods [24]. Allows for multiple recipes (Transcript P.148-149).**
  + **Cost: High initial investment [15]. Reduces labor costs [24]. Anderson skids are robust but expensive (Transcript P.148).**
* **Growing Mediums/Substrates: [15] Materials holding plants and providing root support.**
  + **Types: Soil (organic mixes, Transcript P.151, P.298), Coco Coir (straight or with perlite, Transcript P.8, P.11, P.62, P.113-114, P.126-128, P.147, P.157, P.180-181, P.194, P.219, P.298), Rockwool cubes/slabs (Transcript P.8, P.11, P.62, P.113-114, P.126-128, P.147, P.180-181, P.194, P.217, P.219, P.300), Hydroton, Peat Moss [15]. Living Soil [26]. BX ProMix, Sunshine Mix #4 (Transcript P.102, P.114).**
  + **Form: Bags/bulk [15]. Compressed coco bricks (Transcript P.181). Pre-filled coco bags/pots. Rockwool starter plugs (AOKs, Transcript P.177), 4x4x2.5 blocks, 6x6 blocks, slabs (Transcript P.114, P.127, P.180, P.217, P.220, P.300).**
  + **Properties: Water retention, aeration, nutrient availability, pH, EC, bulk density, porosity, mineral content, organic matter (living soil) [27, 28]. These properties affect root health, water/nutrient dynamics [27, 29]. Coco is more forgiving than rockwool (Transcript P.11, P.113). Rockwool provides more control but less forgiving (Transcript P.113, P.126, P.180). Channeling can be an issue in rockwool if it dries too much (Transcript P.180).**
  + **Living Soil: Includes microbial ecosystems (key groups, roles in nutrient cycling, decomposition, carbon sequestration) [26]. Can be assessed/promoted [26]. Requires specific organic amendments [26, 30].**
  + **Cost: Consumable cost [15]. Organic inputs can be higher upfront [31]. Rockwool more expensive than coco (Transcript P.113, P.181).**
  + **Depletion/Degradation: Nutrients in medium can be depleted over time. Organic matter can decompose. Structure can break down (compaction) [29].**
  + **Measurement: EC/PPM, pH, Temperature, Volumetric Water Content (VWC%) can be measured in the medium/leachate [32, 33]. (Using substrate sensors like Aroya, Growlink, Transcript P.11, P.121-142).**
* **Nutrient Containers: [34] Packaging for nutrient products.**
  + **Form: Bottles/Bags of base nutrients, additives [34]. Athena ProLine (Core, Bloom, Grow, Fade, Cleanse, Balance, Stack, IPM - Transcript P.7-16, P.25, P.62, P.115-117, P.157-160, P.178, P.221, P.228). General Hydroponics 3-part (Transcript P.103, P.116). Botanicare, House & Garden (Transcript P.60).**
  + **Cost: Consumable cost [34]. Significant operational expense.**
  + **Types: Base nutrients (N, P, K - primary macronutrients) [35], macro- (Ca, Mg, S) & micro-nutrients (Fe, Mn, Zn, Cu, B, Mo, Si) [36], additives (PK boosters, CalMag, Silica, Carbs/Sugars, Beneficials, Transcript P.11, P.60, P.115), supplements [37].**
  + **Composition: NPK Ratio (% Nitrogen, Phosphorus, Potassium) [35]. Specific concentrations (% or mg kg-1 DW) [36].**
  + **Interactions: Nutrients can interact (e.g., optimal level of one depends on others) [38]. Incompatibilities can cause precipitation [21, 26]. Mixing order important for powdered nutrients (Transcript P.9, P.159).**
  + **Mixing Requirements: Follow product-specific instructions [21]. Requires precise measurement [21].**
  + **Storage: Requires proper storage per Safety Data Sheets (SDS) [39].**
  + **SDS Information: Hazard ID, composition, PPE, handling/storage, reactivity, first aid, spill/disposal measures [39]. SDS must be accessible [39].**
  + **Impact on Plant: Affects growth, yield, cannabinoid/terpene profiles, nutrient uptake, resilience [38, 40-42]. Deficiencies or toxicities cause visual symptoms [40].**
  + **Resource Use Efficiency: Can be measured (Nutrient Use Efficiency - NUE) [38].**

#### 4.3 Environmental Control Equipment Parameters

**Parameters defining equipment for managing temperature, humidity, CO2, airflow, and light.**

* **HVAC Systems: [34] Equipment for heating, cooling, and dehumidifying.**
  + **Types: Air Conditioners (Window, Split, Mini-splits Transcript P.18) [34], Heaters (Electric, Gas) [34], Dehumidifiers (e.g., Anden, Transcript P.304) [34], Humidifiers (e.g., ultrasonic for VPD domes, Transcript P.177-178, P.299) [34].**
  + **Sizes/Capacity: Affects ability to condition a given space [34]. Oversizing can reduce efficiency [43]. Needs to match facility heat load (e.g. 0.6 tons/light, Transcript P.62) [43, 44].**
  + **Efficiency: (e.g., SEER rating for ACs, efficiency for heaters). Affects power/fuel consumption [34, 43, 45]. Can be influenced by maintenance [43].**
  + **Control: Manual [34], Timed [34], Sensor-Controlled (e.g., Growlink, Transcript P.119, P.139) [46]. Simple thermostat/humidistat in MVP [46]. Advanced/integrated controllers later [46]. Precision requires robust controls [47].**
  + **Power/Fuel Requirement: Electrical or gas consumption [34, 45].**
  + **Cost: Initial purchase cost [31, 34, 48-50]. Operational cost (utilities) [31, 34, 51]. Complex systems increase initial cost [47].**
  + **Functionality: Manages temperature and humidity [34]. Needs power [18]. Can require water (humidifiers) or generate wastewater (dehumidifiers). Projects "radius of effect" or "cone of influence" for environmental impact [52, 53].**
  + **Maintenance: Required for optimal performance and efficiency [43]. Regular calibration and maintenance [48]. Can fail [12]. AC filter changes.**
  + **Installation Complexity: More complex systems (custom design, integrated controls) have longer lead times [47]. Poor duct design can reduce effectiveness [43].**
  + **Noise Level: (Potential factor).**
* **Fans: [17] Equipment for circulating and exchanging air.**
  + **Types: Circulation Fans (Clip, Standing, Wall, V-Flow), Exhaust Fans, Inline Duct Fans [17].**
  + **Airflow Rate: Measured in CFM (Cubic Feet per Minute) [54]. Affects air exchange rate, circulation speed [18]. Needs to match room size [43].**
  + **Power Requirement: Electrical consumption [17].**
  + **Cost: Initial purchase cost [17]. Operational cost (power).**
  + **Functionality: Essential for airflow management [17]. Part of abstracted airflow physics [17]. Removes heat/humidity from lights/plants [18]. Requires power [18]. Projects "radius of effect" or "cone of influence" for environmental impact [52, 53].**
  + **Control: Manual, Timed, Sensor-Controlled [46]. Fan speed controller available [54].**
  + **Maintenance: Can fail. Cleaning fan blades.**
  + **Installation: Inline duct fans require ducting [17]. Gear board can be used to install [55].**
* **Ducting: [17] Components for air distribution networks.**
  + **Types: Flexible, Rigid (various diameters), Fittings, Filters [17].**
  + **Material: Flexible, Rigid [17]. Impacts cost, durability, efficiency (insulation, airflow friction) [16], appearance [16].**
  + **Sizing: Diameters (various diameters) [17]. Impacts airflow rate, pressure drop [16]. Fittings impact pressure drop [43]. Standard sizes (e.g., 6-inch, 8-inch) [56].**
  + **Connectivity: Requires logical connections (e.g., from fans/HVAC) [18]. Manual routing MVP [17]. Uses segmented components for curves/bends [19].**
  + **Filters: Intake filters, Carbon filters (for odor control, Transcript P.104) [57]. Requires maintenance/replacement. Carbon filters control odor [35, 57]. HEPA filters for intake (Transcript P.347).**
  + **Cost: Material cost per unit length/fitting [17].**
  + **Functionality: Needed for HVAC/exhaust systems [17]. Used in detailed construction [17]. Part of abstracted airflow physics [17].**
  + **Installation: Requires joining sections and fittings.**
* **CO2 Systems: [17] Equipment for managing carbon dioxide levels.**
  + **Types: CO2 Tanks (Visual assets), Regulators, Controllers, Generators [17].**
  + **Functionality: Increases CO2 levels for enhanced photosynthesis [18]. Requires CO2 source [18]. Target 1500ppm in flower (Transcript P.161).**
  + **Cost: Initial purchase cost (equipment) [17]. Ongoing cost (CO2 consumable) [58].**
  + **Control: Manual (likely initially) [17], Controllers for automation (e.g., Growlink, Transcript P.139) [17, 46].**
  + **Consumable: CO2 Gas (from tanks or generators) [58]. UI representation for gas levels [58].**
  + **Safety: Requires safe handling and monitoring. Alarms for high CO2 levels.**
  + **Installation: Requires regulator on tank, tubing to distribution area, potential controller integration [17].**
* **Grow Lights: [46] Artificial light sources for photosynthesis.**
  + **Types: HID (MH/HPS - e.g., Gavita, Luxx DE 1000W, Transcript P.46, P.108, P.113, P.181-182, P.202, P.223-224), LED Panels (e.g., Luxx, ThinkGrow, Fluence, Gavita LED, Transcript P.61, P.113, P.160-161, P.181-182, P.202-207, P.223-224, P.235, P.306, P.323), Fluorescent (T5/CFL, Transcript P.102) [46]. LEC (Light Emitting Ceramic) [35]. Under canopy LED bars (Craft Farmer, Transcript P.196, P.205, P.224-225).**
  + **Wattage: Power consumption (e.g., 60W, 600W, 1000W HID, 600-860W LED, 120W under canopy) [46, 59] (Transcript P.61, P.113, P.202, P.225). Affects light intensity, heat output [18, 43, 53].**
  + **Spectrum: Color of light emitted [46, 60]. Affects photosynthesis, plant morphology, cannabinoid/terpene production [42, 60]. LED panels can have adjustable spectrum control (e.g., Veg/Bloom switches, tunable reds/far-reds, Transcript P.203) [61]. Light spectrum analyzers can measure [62]. Mixed HPS/LED spectrums (Transcript P.202-203, P.206-207, P.223). Far-red for Emerson effect (Transcript P.203-204).**
  + **Light Output: Measured in PAR/PPFD (Photosynthetically Active Radiation/Photosynthetic Photon Flux Density) [62]. Affected by wattage, spectrum, fixture efficiency, reflector design, distance to canopy [46, 63]. Reflector design/materials affect coverage area/quality [56]. Target PPFDs: Veg 200-600 (Transcript P.161), Flower 800-1500+ (Transcript P.114, P.161).**
  + **Fixture Efficiency: Conversion of electrical power to usable light [43].**
  + **Power Requirement: Electrical consumption (Wattage) [11, 46]. Requires connection to electrical system [18]. High draw appliances [10].**
  + **Heat Output: Generates significant heat (HPS more than LED, Transcript P.61-62, P.113, P.202, P.223-224) [18, 43, 53].**
  + **Cost: Initial purchase cost [31, 46, 48, 50]. Operational cost (power) [31, 46, 51].**
  + **Durability/Maintenance: HID bulbs need replacement. Ballasts can fail. LEDs have lifespan. Cleaning fixtures.**
  + **Installation: Requires hanging/mounting [46, 54]. Ratchet pairs for suspension [54]. Requires connection to timer/controller/electrical system [18, 46, 55]. Ballasts should be off the floor [55]. Distance from canopy critical (Transcript P.114).**
  + **Coverage Area: Area over which light intensity is sufficient. Affected by fixture type, wattage, height, reflector design [56].**
* **Light Timers/Controllers: [46] Equipment for automating light cycles.**
  + **Types: Mechanical, Digital [64]. Strip timer/thermostat/humidistat combination [54]. Integrated controllers (Growlink, Transcript P.139).**
  + **Functionality: Turns lights on/off at set times [35, 46]. Basic automation (core MVP) [46]. Sensor-controlled/advanced automation later [46]. Can control entire lighting system [64] or multiple lamps [64]. Can have continuous power outlets [55]. Dimming capabilities.**
  + **Power Handling: Rated capacity (e.g., controls a single 1000W HID) [64].**
  + **Installation: Can be mounted on a gear board [55]. Requires connection to electrical system [18].**
  + **Cost: Initial purchase cost [46].**
* **Thermostats, Humidistats, Environmental Controllers: [46] Equipment for automating environmental parameters based on sensor readings.**
  + **Types: Simple (on/off for single parameter), Advanced/Integrated (control multiple parameters, e.g., Growlink, Transcript P.119, P.139) [46]. Controllers link sensors to equipment for IF-THEN logic [22, 23]. Can use setpoints/ranges [22].**
  + **Functionality: Automates HVAC, fans, humidifiers/dehumidifiers based on sensor input (temp, RH) [22, 61]. Reduces manual adjustments [61]. Offers precise control in varying conditions [47]. Growlink Co-Pilot for suggestions/automation (Transcript P.132-142).**
  + **Power Requirement: Electrical consumption. Requires power connection [18]. Advanced controllers require advanced electrical [65].**
  + **Cost: Initial purchase cost [46]. Advanced/integrated controllers unlock later [46]. Complex controls increase initial cost [47]. Subscription for software (Growlink, Transcript P.144).**
  + **Installation: Requires connection to sensors and controlled equipment [22]. Can be mounted on a gear board [55].**
* **Sensors: [46] Equipment for measuring environmental and substrate parameters.**
  + **Types: Environmental (Temp, RH, CO2, Light - PAR/PPFD), Substrate (Moisture, EC, pH, Temp - e.g., Aroya, Growlink, Transcript P.11, P.121-142, P.145-147). Advanced/Specialized (Leaf Temp, Inline Water, Spore Traps - Post-MVP) [66].**
  + **Tiers: Basic (standalone, manual checking), Intermediate (networked, simple controllers), Advanced (accurate, multi-functional, specialized) [66]. Research-grade reference sensors for R&D/calibration [67]. Capacitance vs TDR sensors (Transcript P.145-146).**
  + **Functionality: Provide real-time data for dashboards [46, 68]. Essential for automated control (controllers) [22, 23]. Player-placed sensors core to data collection [46]. Data is auto-logged with timestamp [112, 113]. Data used for crop steering decisions (Transcript P.11, P.62, P.121-138).**
  + **Accuracy/Precision: Varies by tier [66]. Calibration is necessary [48, 70]. Accuracy directly impacts control efficacy [44]. Sensor placement in substrate is critical (Transcript P.11, P.146-147).**
  + **Power Requirement: Electrical (batteries or wired) [46].**
  + **Cost: Initial purchase cost [46, 48, 67]. Operational cost (calibration, maintenance) [70]. Low-cost alternatives available but TCO matters [70].**
  + **Installation: Player-placed [46]. Can be networked [66].**
  + **Data Output: Provides numerical readouts [71]. Can be integrated into data platforms [69]. Graphs for trend analysis (Growlink, Transcript P.132-138).**
  + **Durability: Can be affected by harsh CEA environment (humidity, dust, chemicals) [44].**
* **Air Filters: [57] Components for cleaning intake or exhaust air.**
  + **Types: Intake filters, Carbon filters (for odor control, Transcript P.104) [57]. HEPA filters (Transcript P.347).**
  + **Functionality: Part of ducting system [57]. Improve air quality, control odor (carbon filters) [35, 57]. Removes particles [72].**
  + **Maintenance: Requires regular replacement/cleaning.**
  + **Cost: Consumable cost (replacement filters).**
  + **Installation: Installed within ducting [57].**

#### 4.4 Utility Systems & Equipment Parameters

**Parameters defining equipment for delivering power and connecting facility systems.**

* **Electrical Wiring: [57] Components for electrical networks.**
  + **Material: Conductors (copper, aluminum) [73], Insulators [73].**
  + **Sizing: Gauges (various gauges) [16, 57]. Impacts performance (resistance, voltage drop) [16, 59]. Larger gauges are less resistive, more expensive [59]. Extension cords in early game (Transcript P.108).**
  + **Connectivity: Requires logical source-to-endpoint connections [18]. Manual routing MVP [57]. Can be routed in 3D [16]. Uses segmented components [19].**
  + **Cost: Material cost per unit length [57].**
  + **Functionality: Essential for electrical system management [57], abstracted utility connections [57]. Used in detailed construction [57]. Delivers power [74].**
  + **Safety: Requires adherence to safety standards (NEC Art. 547, IEEE) [75, 76]. No contact with energized circuits, use PPE [77]. Grounding, isolation, ratings [77].**
  + **Installation: Requires stripping wires, making connections with fittings/junction boxes.**
* **Circuit Breakers / Fuse Boxes / Electrical Panels: [57] Equipment for protecting circuits from overload.**
  + **Functionality: Breaks circuit on overload [11, 18]. Essential for electrical system management [57], load balancing [57]. CT cabinet (Current Transformer cabinet, Transcript P.5).**
  + **Rated Capacity: Maximum current handled (Amps) [11]. Should not be loaded beyond 80% (80% Rule) [11].**
  + **Power Requirement: Minimal electrical consumption.**
  + **Cost: Initial purchase cost [57].**
  + **Installation: Requires integration into electrical panel [78].**
  + **Types: Panels [78], conduits, junction boxes [14].**
* **Generators (Diesel/Gas): [79] Equipment for generating backup or primary power.**
  + **Types: Diesel/Gas [79]. CoGeneration (CoGen) systems use natural gas fueled engines (Transcript P.5) [80].**
  + **Functionality: Provides backup power on grid failure [79, 80]. Can reduce utility bills [80]. Requires fuel [13, 79]. Non-instant full power (ramp-up time) [81]. Generates heat [82].**
  + **Power Output: Max power output (Watts) [81]. Limited output capacity [13].**
  + **Efficiency: Fuel to output conversion [81].**
  + **Cost: Initial purchase cost [79]. Operational cost (fuel consumption rate, periodic maintenance) [81, 83].**
  + **Progression: Late-Game MVP / Post-MVP [79]. Tiers (Basic - louder, less efficient, manual prime/start; Advanced - quieter, efficient, auto transfer switches) [13].**
  + **Installation: Requires connection to electrical system (auto transfer switch) [13].**
  + **Environmental Impact: Can cause pollution [84].**
* **Battery Banks / UPS: [79] Equipment for storing electrical energy.**
  + **Functionality: Provides short-term power buffer for critical systems [13, 79]. Can be a main source [80].**
  + **Capacity: Amount of energy stored (kWh) [10].**
  + **Charge/Discharge Rate: Speed of energy transfer.**
  + **Cost: Initial purchase cost [79].**
  + **Progression: Late-Game MVP / Post-MVP [79]. Part of advanced risk management [79].**
* **Main Power Grid Connection Point (Abstracted): [79] Represents drawing power from an external source.**
  + **Functionality: Provides stable power [84]. Abstracted power draw [79]. Primary vs. Secondary power (owning transformer vs. direct from pole, Transcript P.5).**
  + **Capacity: Amount and type of power allocated based on service contract, equipment, infrastructure [85]. Capacity of existing electrical service and unused capacity from nearby transformers determine potential size/scope [85]. Some grows require new substations (Transcript P.5).**
  + **Cost: Metered cost (utility bill, e.g., 6-42 cents/kWh, Transcript P.5) [51, 83].**
  + **Risk: External disruption risk [84]. Power loss can occur [80].**
  + **Progression: Base power source for MVP [79]. Requires connection to circuit breaker/panel [78].**
  + **Voltage: Provides specific voltage (e.g., 120V) [11, 86]. Transformers convert high to low voltage [85].**
* **Water Supply Connection Point (Abstracted - Tap, RO, Treated): [79] Represents drawing water from an external source.**
  + **Types: Tap, RO (Reverse Osmosis), Treated [79]. RO/Treated might be later upgrades [89]. RO water requires Cal-Mag/pH management (Transcript P.8, P.87, P.115).**
  + **Functionality: Provides water source [18]. Abstracted water source [79].**
  + **Cost: Metered cost (utility bill) [51, 83]. RO systems have costs (power, wastewater) [83].**
  + **Quality: Varies by source [87, 88]. Tap water can contain contaminants (chlorine, sediment, rust, VOCs, bacteria, iron, sulfur, fluoride, high Ca/Mg) [88]. Quality impacts plant growth/health [88]. Requires pre-filtration (sediment/carbon) [87]. Disinfection (UV or Ozone) may be needed [87].**
  + **Progression: Base water source for MVP [79]. RO/Treated might be later upgrades [89].**

#### 4.5 Pots, Containers, & Growing Surfaces Parameters

**Parameters defining containers holding plants and growing medium.**

* **Pots: [90] Containers for plants.**
  + **Types: Standard Pot, Grow Bag [90], Tray [90], Slab [90]. Fabric grow bags [90].**
  + **Sizes: Various sizes (Small, Medium, Large) [90]. 1-gallon, 1.5-gallon, 1.7-gallon, 2-gallon, 3-gallon, 5-gallon common in coco (Transcript P.127-128, P.157, P.181, P.219, P.298). Affects root space, plant size potential [91]. Used for transplanting as plants grow [90]. Smaller pots (1-2 gal) for more control with frequent irrigation (Transcript P.127).**
  + **Material: Plastic, Fabric, Ceramic [90]. Affects cost, durability, aeration (fabric pots), appearance, cleanliness.**
  + **Cost: Initial purchase cost [90].**
  + **Functionality: Hold plants and medium [90].**
  + **Root Health: Can affect root health (e.g., root binding). Substrate properties are key [29].**
* **Fabric Grow Bags: [90] Containers made of fabric.**
  + **Functionality: Container variation [90]. Offers better aeration than plastic pots.**
  + **Material: Fabric [90].**
  + **Sizes: Various sizes [90].**
  + **Cost: Initial purchase cost [90].**
* **Trays / Flats (Seedling, Propagation): [90] Shallow containers for starting seeds or clones.**
  + **Types: Seedling, Propagation [90]. (e.g., 50-cell, 72-cell clone trays, Transcript P.228-229). Ihort pre-filled trays (Transcript P.342).**
  + **Sizes: Varies [92]. Choice influenced by greenhouse space, crew availability, transplant timing flexibility, desired plant size [92]. Need to fit in greenhouse [92]. Crew size/equipment affects how many can be handled/transplanted in time [92].**
  + **Cost: Initial purchase cost [90].**
  + **Functionality: For starting seeds/clones [90].**
  + **Materials: Plastic, other materials.**
* **Rockwool Cubes / Slabs: [90] Growing medium/container type often used in hydroponics.**
  + **Functionality: Growing medium and container type, esp. for hydro/coco [90]. Common sizes: 4x4x2.5 starter blocks, 6x6x6 blocks, 3ft slabs (Transcript P.114, P.127, P.180, P.217, P.220, P.300).**
  + **Cost: Consumable cost [90]. Can be more expensive than coco (Transcript P.113, P.181).**
  + **Properties: Inert, requires specific nutrient management. Good for crop steering due to quick dry-downs (Transcript P.113, P.126). Channeling can occur if dried too much (Transcript P.180). Requires weekly hand soaks to reset (Transcript P.180, P.194).**
* **Hydroponic/Aeroponic Systems: [90] Systems for growing plants without soil.**
  + **Types: Basic Ebb/Flow (flood & drain tables, Transcript P.102, P.108, P.113), DWC buckets [90], NFT, Aeroponics [27, 41]. DWC reservoirs [93]. Recirculating systems (Transcript P.84, P.174).**
  + **Functionality: Provides nutrients and water directly to roots [27]. Requires profound plant physiology understanding, precise control of nutrient solution chemistry/environmental parameters [27].**
  + **Cost: Initial purchase cost [31, 90]. Can be DIY or pre-built [31].**
  + **Progression: MVP for basic hydro options [90]. Complex systems (aeroponic) might be later MVP/Post-MVP [90].**
  + **Buffering: Lacks natural buffering compared to soil [27]. Sensitive to management [27].**
  + **Efficiency: Offers higher resource use efficiency/productivity if optimally managed [27].**
  + **Measurement: Nutrient solution pH, EC, DO, temperature must be monitored [33, 93].**
  + **Nutrient Solution Dynamics: Precipitation, pH drift can occur over time [26]. Requires frequent monitoring/precise nutrient plan [48]. Pathogen spread risk in recirculating systems (Fusarium, Transcript P.84).**
  + **Root System: Directly exposed to solution, impacts root health and development.**

#### 4.6 Pest and Disease Management Tools Parameters

**Parameters defining tools and equipment for identifying and treating pests and diseases.**

* **Scouting Tools: Tools for inspecting plants for issues.**
  + **Types: Loupes [30], Handheld Microscopes [8], Benchtop Microscopes [8].**
  + **Functionality: Detailed inspection of pests, pathogens, trichomes [8, 94]. Helps identify "hot spots" for targeted resource allocation [95]. Essential for early detection [95, 96]. (e.g., for HLVd symptoms, Transcript P.17, P.80).**
  + **Cost: Initial purchase cost [8].**
  + **Progression: Unlocked via Science skill tree [8].**
  + **Skill Requirement: Requires skill/understanding for effective use [97].**
* **Application Tools: Equipment for applying treatments.**
  + **Types: Sprayers (hand, backpack) [98, 99], Integrated Spraying Systems (automated) [22]. Foggers (e.g., for Athena Reset, Transcript P.117).**
  + **Functionality: Applies approved fungicides/pesticides/biologicals [22, 96, 98]. Foliar feeding (Athena Stack, Transcript P.178).**
  + **Cost: Initial purchase cost [30].**
  + **Maintenance: Cleaning is important to prevent contamination.**
  + **Installation: Automated systems require fixed nozzles [22].**
  + **Placement: Requires proper spacing for access (e.g., leaving beds open for tractor sprayers) [99].**
  + **Risk: Misconfigured automated spraying carries risks (too close to harvest, plant stress) [22].**
  + **Consumables: Approved pesticides/fungicides/biological control agents [96, 98]. Requires understanding application timing/methods [98]. Biologicals need specific environmental conditions [96]. (e.g., Athena IPM, Transcript P.178-179, P.228). Sulfur for broad/russet mites (Transcript P.179).**
* **Identification/Diagnostic Aids: In-game resources/tools assisting identification.**
  + **Types: In-game "Plant Problems Guide" UI/Asset [8], guides for interpreting visual symptoms [100].**
  + **Functionality: Helps diagnose nutrient issues, pest ID, link symptoms to causes/solutions [8, 100].**
  + **Progression: Unlocked via Science skill tree [8].**
* **Monitoring Tools: Tools for tracking pest/disease presence and levels.**
  + **Types: Traps (e.g., sticky traps) [30].**
  + **Functionality: Helps answer: what, where, how much, what stage [95]. Enables monitoring to find initial outbreaks [95]. Provides objective data [9]. Early warning system [9].**
* **Lab Testing Services for Pathogens: (e.g., Tumi Genomics, MyFloraDNA, Transcript P.17, P.76-85, P.325-331).**
  + **Functionality: PCR-based testing for HLVd, Fusarium, other viruses/pathogens. Critical for confirming infections, especially asymptomatic HLVd.**
  + **Cost: Per sample (e.g., $15/sample for HLVd, Transcript P.327).**
  + **Sample Submission: Leaf tissue, petiole, root samples. Multiple samples per plant recommended for HLVd due to uneven distribution (Transcript P.81).**
  + **Turnaround Time: Typically 2-5 days (Transcript P.327).**

#### 4.7 Harvesting & Processing Equipment Parameters

**Parameters defining tools and equipment for harvesting and post-harvest processing.**

* **Harvesting Tools: [8] Tools for cutting down plants.**
  + **Types: Large Trimming Shears [8], HD Loppers [8], Hand Saw [1]. Hedge Trimmers [2].**
  + **Functionality: Cutting down plants [8], removing branches [2], harvesting buds or ripe parts of buds [2].**
  + **Material: (Impacts durability, cleanliness).**
  + **Sharpness: (Affects cut cleanliness, efficiency). Requires cleaning/sterilization [3].**
  + **Cost: Initial purchase cost [8].**
  + **Maintenance: Cleaning [3], sharpening.**
  + **Reach: Some have pole extensions [2].**
  + **Cutting Area/Blade Length: (e.g., 12-24 inches for hedge trimmers) [2].**
  + **Weight: (Affects worker fatigue) [2].**
  + **Safety: Risk of injury when working at height [2].**
* **Trimming Tools: [101] Tools for manicuring harvested material.**
  + **Types: Trim Scissors (Micro-tip, types, e.g., Chikamasa, Transcript P.174, P.180) [101], Trim Bins/Trays (kief screens) [101]. Isopropyl Alcohol/Wipes (cleaning), Rags [101]. Bowl Trimmers (Manual, Electric) [101]. Automated Trimming Machines [101]. Tools that assist hand trimmer (electrically operated, manually controlled) [102].**
  + **Functionality: Removing excess leaves from buds [101]. Manual (hand trim preferred for quality, Transcript P.5) [101], semi-automated [101], fully automated [101]. Automated trimming machines can be adjusted for aggressiveness (speed vs. quality trade-off) [103]. Can trim wet or dry buds [102].**
  + **Cost: Initial purchase cost [101]. Automated machines are high-tier equipment [101]. Hand trim labor cost $100-150/lb (Transcript P.5).**
  + **Maintenance: Requires cleaning (Isopropyl Alcohol/Wipes) [101].**
  + **Progression: Bowl trimmers Mid-Late MVP / Post-MVP [101]. Automated trimming machines Late-Game MVP / Post-MVP [101]. Requires Harvest skill/research unlocks [101, 103].**
  + **Efficiency: Automated tools save time/labor [102].**
  + **Quality Impact: Aggressiveness of trimming affects final bud appearance and potentially yield (if over-trimmed).**
  + **Yield By-product: Kief screens collect trichomes (kief) [101].**
* **Drying Racks / Clotheslines & Hangers: [101] Equipment for drying harvested material.**
  + **Functionality: Provides structure for hanging/placing harvested material to dry [101]. Needs to be in a dedicated dry space with controlled environment (60F/60%RH, Transcript P.22, P.298-299) [101]. Requires airflow/humidity control in the space [97, 101].**
  + **Cost: Initial purchase cost [101].**
  + **Capacity: Amount of material that can be dried at once. Varies by size/number. Larger options for bulk processing [104].**
  + **Installation: Requires setup [101, 105].**
  + **Impact on Product: Environment of drying space impacts time (7-14 days, Transcript P.22, P.298-299) and quality (terpene preservation, Transcript P.179, P.298-299) [97, 101, 106]. Controlled drying is important for quality preservation [97]. Slow, controlled drying is key [97].**
* **Curing Containers (Jars, Buckets, Bags): [101] Containers for curing harvested material.**
  + **Functionality: Provides sealed environment for curing (jars, Grove Bags/terp block bags, Transcript P.22) [106]. Requires manual "burping" [106].**
  + **Cost: Initial purchase cost [101].**
  + **Capacity: Amount of material held. Varies by size. Larger options for bulk processing [104].**
  + **Material: Glass (jars), plastic (buckets), specialized bags (Grove Bags) [101].**
  + **Impact on Product: Environment (stable humidity/temperature) is crucial for proper curing [104]. Affects flavor, aroma, smoothness. Target 58-62% RH in container.**
  + **Maintenance: Requires cleaning.**
* **Weighing & Measuring: [107] Equipment for measuring mass.**
  + **Types: Digital Pocket Scales (Precision), Digital Bench Scales (Larger capacity) [107]. Industrial (Platform, Floor scales) [107]. Calibration Weights [107, 108].**
  + **Functionality: Essential for yield tracking [107], meeting contract specifications [107], inventory management [107]. Different scales for different needs/scales [107].**
  + **Accuracy/Precision: Varies by type (Precision scales for small amounts) [107]. Requires calibration [108].**
  + **Cost: Initial purchase cost [107].**
  + **Maintenance: Calibration [108].**
  + **Data Output: Provides numerical readout. Data should be logged [107].**
* **Transporting Equipment: [109] Equipment for moving harvested material.**
  + **Types: Baskets, hand-drawn garden cart, small motorized transport, portable conveyor belt [109]. Baker's racks for moving plants/trays (Transcript P.300).**
  + **Functionality: Moves material from field to processing [109]. Can transport equipment, plants, tools [110]. Can save labor [110].**
  + **Cost: Initial purchase cost [109].**
  + **Efficiency: Saves labor by transporting items without manual carrying [110]. May allow elimination of walkways [110].**
* **Cold Storage: [109] Equipment for keeping harvested material cool.**
  + **Functionality: Keeps buds cool and turgid while awaiting processing or fresh-frozen capabilities [109]. Important for material intended for fresh frozen or high terpene retention [105]. Refrigerated trailers for outdoor harvests (Transcript P.6). Labs refrigerate samples before THC testing, potentially affecting moisture/potency (Transcript P.22).**
  + **Types: Refrigerators, freezers.**
  + **Temperature Control: Maintains specific low temperatures.**
  + **Cost: Initial purchase cost [109]. Operational cost (power).**

#### 4.8 Data Collection & Lab Equipment Parameters

**Parameters defining equipment for collecting and analyzing data about plants, environment, and product.**

* **Handheld Meters (Visual): [111] Portable tools for manual data acquisition.**
  + **Types: EC/PPM, pH, Temp Probe, Soil Moisture, Simulated Chlorophyll Content, PAR/PPFD, Infrared Thermometer, VPD Meter [111]. (Transcript P.11, P.157-158, P.161).**
  + **Functionality: Basic data collection tools [111]. Player uses in "Action Mode" on target asset [112, 113]. Provides numerical readout [112, 113]. Data is auto-logged with timestamp [112, 113]. Essential for early manual data collection loop [112]. Validating automated sensor data (Transcript P.11).**
  + **Accuracy: Varies by type/tier. Requires calibration [21, 114].**
  + **Cost: Initial purchase cost [111].**
  + **Progression: Unlocked via Science skill tree [111].**
  + **Battery Life: (Potential factor).**
* **Benchtop Meters/Analyzers (Visual): [111] Lab-grade equipment for more accurate or detailed analysis.**
  + **Types: Lab-grade EC/pH meter, Spectrophotometer (simulated use) [111]. ICP (Inductively Coupled Plasma) assay for mineral content [28]. HPLC (High-Performance Liquid Chromatography) [115-117], GC-MS (Gas Chromatography-Mass Spectrometry) [115, 117, 118], LC-UV/LC-MS [115, 116]. MIR (Mid-Infrared) spectroscopy [119, 120]. NIR (Near-Infrared) spectroscopy [121]. Elemental analyzer (dry combustion for Total N/C) [36].**
  + **Functionality: Advanced tools for higher-tier data analysis/research [111]. Simulated lab analysis (nutrient levels, cannabinoid/terpene profiles) [32, 122]. Provides objective chemical analysis [65]. Quantifies cannabinoid content (THC, CBD, etc.) [116, 119]. Quantifies terpene content [115]. Analyzes mineral content [28, 36]. Can identify/quantify multiple cannabinoids [116]. Can identify pesticides [115]. Can analyze soil/substrate mineral content [28]. Some methods require sample preparation (extraction) [123]. Some methods provide rapid, on-site detection [124]. Some methods (IR spectroscopy) are promising for Process Analytical Technology (PAT) for continuous monitoring [119, 120, 125]. State-mandated testing labs use these (Transcript P.22, P.336).**
  + **Accuracy/Precision: Generally higher than handheld meters. Can be affected by sample complexity, limited samples, variability of origin/maturity, non-uniformity [120]. Requires method validation [116]. Prediction ability assessed by statistics (SEC, R2, SECV, R2CV, SEP, slope, RSQ, RPD) [121]. Inconsistencies between labs are a major issue (Transcript P.17, P.22).**
  + **Cost: Higher initial purchase cost [111]. Operational cost (reagents, gases, maintenance, lab access/services) [126, 127]. HPLC, GC-MS are relatively slow and costly [123]. Analytical services can be outsourced [126].**
  + **Progression: Mid-Late MVP / Post-MVP [111, 122]. Tied to Quantitative Analysis skill node [122]. Requires in-house analytics software integrating with sensor networks [65].**
  + **Data Output: Provides numerical values (%, mg kg-1 DW) [36, 119]. Can provide profiles (charts, graphs) [122]. Can provide reports [122]. Raw data (e.g., mass spectra, chromatograms) [117, 128].**
  + **Maintenance: Requires regular calibration/maintenance. Analytical standards/Certified Reference Materials (CRMs) needed for calibration [126].**
  + **Sample Requirements: Specific sample preparation methods needed [116, 118, 123]. Different sample types (plant flowers, extracts, body fluid, raw product) [116, 117]. Sample representativeness is a limitation for end-point testing [123]. Lab sampling protocols (e.g., lab picks samples in MI/NV, Transcript P.22).**
* **Data Logging & Interface (Visual): [108] Equipment representing systems for viewing and interacting with simulation data.**
  + **Types: Laptop, Tablet, Desktop (Monitor, Keyboard, Mouse) [108]. Industrial (Server rack, large control displays) [108]. Clipboard, Pens, Whiteboard [108]. Smartphones for remote monitoring (Transcript P.11).**
  + **Functionality: Visual representation of UI/Data Viz systems [108]. Interface for dashboards, logs [108], sensor/controller management (e.g., Growlink, Transcript P.11, P.129-142) [129], grow cycle comparison [130], lab analysis interface [122]. Can display real-time data, historical trends, reports [68, 122, 130]. Can be used for manual data logging [131].**
  + **Progression: MVP [108]. Industrial versions likely later [108]. Advanced analytics software integrates with these interfaces [65].**
  + **Data Storage: Data logged should be stored (secure digital DB, physical backups) [132]. Cannabis software (MES, AROYA, Growlink) can provide integrated data management [132]. Growlink data stored in Azure cloud, option for private server (Transcript P.141-142).**
* **Calibration Weights: [108] Used for calibrating scales.**
  + **Functionality: Essential for ensuring accuracy of scales [108]. Part of a calibration routine mechanic if implemented [108].**
  + **Cost: Initial purchase cost [108].**
* **Simulated Lab Analysis Interface: [122] In-game system for managing samples and viewing lab results.**
  + **Functionality: Manages sample submission, time, costs [122]. Views Reports [122]. Provides results for cannabinoid/terpene profiles, tissue nutrient analysis, water quality [122]. Allows comparison to optimal/previous results [122].**
  + **Cost: Simulated cost for analysis [83, 122]. Varies by type of analysis.**
  + **Progression: Mid-Late MVP / Post-MVP [122]. Tied to Quantitative Analysis skill node [122].**

#### 4.9 Advanced Breeding & Lab Equipment Parameters

**Parameters defining high-tier equipment for advanced breeding techniques and genetic research.**

* **Tissue Culture Station: [133] Sterile setup for micropropagation.**
  + **Components: Sterile Work Area/Hood (Laminar Flow, Transcript P.18) [133], Autoclave [133], Incubator [133], Microscope (Dissecting, Transcript P.19) [133], Racks for Culture Vessels, Culture Vessels [133]. pH meter [134], analytical balance [134], glassware [134], sterilizable tools (scalpels, forceps, spatulas) [134], Bunsen burner/glass bead sterilizer [134], refrigerators/freezers [134].**
  + **Functionality: Sterile multiplication of genetic material [133]. Potential for cleaning genetics (pathogen eradication, e.g., HLVd, viruses, Transcript P.17-18, P.81, P.330) [133, 135]. Long-term genetic preservation in vitro (Transcript P.21-22) [133, 136]. Allows rapid cloning [136]. Various techniques possible (nodal/shoot tip, meristem, callus, somatic embryogenesis, anther/microspore) [135]. Meristem culture for HLVd eradication (Transcript P.17-18).**
  + **Cost: High initial setup cost [49]. Equipment: $50-$300/sq ft, Construction: $100-$300/sq ft [49]. Initial investment substantial ($5k-$50k for a lab, Transcript P.18-20) [134]. Consumable costs (specialized media, sterile consumables, energy) [137].**
  + **Progression: Post-MVP [133]. Part of "Advanced Propagation (Tissue Culture & Micropropagation)" skill node [133]. Requires sterile technique understanding [133, 138]. Requires a clean lab space [133, 138]. Tiered labs (Basic, Advanced, Specialized Biotech) [139].**
  + **Technical Expertise: Requires high skill/knowledge [49]. Meticulous sterile techniques, media prep, PGR understanding, troubleshooting [49]. Specialized expertise for meristem dissection, protoplast isolation [49]. Challenging rooting/acclimatization needs experience [49]. Success can be chance-based (staff/player skill) [137]. Undergrads can be taught (Transcript P.19).**
  + **Success Rate: Can have low success rates initially [138]. Influenced by genotype/protocol [135, 140]. Requires optimization per strain [140]. HLVd eradication not 100%, depends on genotype (Transcript P.17-18, P.81).**
  + **Contamination: Risk if unmaintained [141] or technique is poor [142]. Reduced by aseptic technique skills [142].**
  + **Media Requirements: Specialized media [137]. pH 5.7-5.8 before autoclaving [134]. Requires Plant Growth Regulators (PGRs) [49]. Media imbalance or old/unvented vessels can cause vitrification [140]. Requires specific reagents (agar, hormones, cryoprotectants, enzymes) [139, 141].**
  + **Vitrification/Hyperhydricity: Physiological disorder if media imbalanced (wrong PGRs, high ammonium), old/unvented vessels, long culture without subculturing [140]. Can be mitigated (anti-vitrification additives, vented vessels, bottom cooling) [140].**
  + **Data Logging: Need to track culture details.**
  + **Research: "Media Optimization Trials" per strain can be research projects [140].**
* **Lab Furniture: [143] Specialized furniture for lab environments.**
  + **Types: Specialized Benches (Stainless/Chemical Resistant), Storage Cabinets (Chemical/Flammable), Lab Sinks [143].**
  + **Cost: Initial purchase cost [143].**
  + **Installation: Requires a dedicated lab space [143]. Research Lab facility Future (Post-MVP) [144].**
  + **Functionality: Provides workspace, storage, safety for lab operations [143]. Supports Cleanliness aesthetic [107].**
* **Cryopreservation Unit: [143] Equipment for long-term genetic archiving.**
  + **Functionality: Long-term storage of genetic material (free up mother plant space, secure genetics) [136, 143].**
  + **Progression: Post-MVP [143]. Very high-tier/specialized [143]. Linked to long-term genetic archiving [143].**
  + **Components: Freezers, LN₂ tanks, straws/vials [139].**
  + **Cost: High initial cost [139]. Operational cost (LN₂ supply) [141].**
  + **Installation: Requires a dedicated storage facility [142].**
* **Advanced Genetic Modification Equipment: (CRISPR-like System) [145] Equipment for direct genetic manipulation.**
  + **Functionality: High-risk, high-reward direct genetic manipulation [145]. Target genes for specific traits (THCAS, CsTPS, disease susceptibility, e.g. PM resistance genes Transcript P.79) [146]. Introduce specific alleles [147]. Precise trait modification (high-CBG, disease resistance) [148].**
  + **Types: Electroporator/Gene Gun [139].**
  + **Cost: Substantial prerequisite research/investment [136]. High-cost [149].**
  + **Progression: Potential future expansion, not core launch feature [145]. Very late-game [145]. Requires specialized lab interface [145] and dedicated lab space [142].**
  + **Technical Expertise: Requires specialized expertise [49]. Success can be chance-based [137].**
  + **Risk: High-risk [136, 145]. Off-target effects possible [146]. Regeneration from transformed tissue challenging [135]. GMO perception (Transcript P.79).**
  + **Regulation: Subject to regulation [148].**
  + **Protocols: Requires optimization for selected genotypes/explants [146]. Transformation protocols (Agrobacterium-mediated or alternative) [146].**
* **Bioinformatics Tools/Software: Tools for analyzing genetic/genomic data.**
  + **Functionality: Analyze sequencing data (QC, alignment, variant calling, filtering) [150]. Imputation, population structure analysis, kinship calculation [151]. Linkage mapping [151]. GWAS (Association Mapping) [151]. Genomic Selection (Model train/validate) [151]. Identify markers for desirable traits (SSRs, SNPs) [148]. Pangenome analysis [152]. Functional annotation (BLAST, InterProScan, GO enrichment), pathway comparison [153]. Candidate gene identification [153]. DNA Fingerprinting (MyFloraDNA CCI, Transcript P.331-334).**
  + **Types: FastQC, Trimmomatic, BWA/Bowtie2 [150]. GATK, FreeBayes, VCFtools [150]. Beagle, STRUCTURE, PCA [151]. TASSEL, PLINK, R (adegenet) [151]. JoinMap, R/qtl, QTL Cartographer [151]. TASSEL, GAPIT, GEMMA, FarmCPU [151]. R (rrBLUP, BGLR) [151]. R (lme4, agricolae, GGEBiplotR) [150]. RicePilaf, Biomercator [153]. PEST, SUFI2 (with SWAT) [154]. R/Python optimization libraries [154]. Python (NumPy, SciPy, Pandas) [155]. JAX [155]. PyBrOpS [156]. ChromaX [156]. MoBPS [157].**
  + **Cost: Software licenses, HPC access [50, 126, 158].**
  + **Technical Expertise: Requires bioinformatics skills [159].**
  + **Data Requirements: High-density genotyping data (GBS) [160], WGS for key parents [160], real genotype data [161], phenotype data [162], environmental data [161]. Phased haplotypes often necessary/desirable [163]. Genome assembly/genetic map [163]. QTL information [163].**
  + **Integration: Needs integration with genetic/phenotypic data [164]. Can interface with other software (CGMs) [165].**
  + **Performance: Can be computationally intensive (large scenarios, dense markers) [166]. HPC/GPU (ChromaX) can improve speed [156, 166].**
  + **Usability: Varies by software. MoBPSweb enhances usability [157, 165]. Python packages developing usability [165, 167].**

#### 4.10 Consumable Resources (Abstract/UI Representation) Parameters

**Parameters defining resources that are consumed during cultivation and need to be tracked and managed. Represented abstractly in UI, but may have visual models for bulk storage.**

* **Water: [89] Consumed for irrigation.**
  + **Types: Tap, RO, Treated [89]. RO/Treated might be later upgrades [89].**
  + **Supply Source: Abstracted connection point [79].**
  + **Storage: Tanks, Reservoirs [89]. Visual models possible [89].**
  + **Consumption Rate: Varies with plant size, growth stage, environment, irrigation system efficiency [32]. Metered cost [83].**
  + **Cost: Operational cost (utility bill) [51, 83].**
  + **Quality: Varies by source [87, 88]. Impacts plant health [88]. Can require pre-filtration/disinfection [87].**
  + **Measurement: UI representation [89], consumption meter [10], water usage dashboard [10].**
* **Power: [89] Consumed by electrical equipment.**
  + **Supply Source: Grid, Generator Fuel, Battery Charge [89]. Abstracted connection point [79]. Linked to Generators/Batteries (Late-Game MVP / Post-MVP) [89].**
  + **Consumption Rate: Varies with active equipment, wattage [11, 32]. Metered cost [83]. High consumption from lights/HVAC [51, 63, 168]. Electricity cost a major factor (Transcript P.5).**
  + **Cost: Operational cost (utility bill) [51, 83]. Can be significant [31, 51, 168].**
  + **Measurement: UI representation (meter) [89], consumption meter [10], power usage dashboard [10]. Utility usage can be broken down by room, equipment category [10].**
  + **Voltage/Amperage: Required by equipment [11, 86]. Circuit load is important [11, 57].**
* **Nutrients: [89] Consumed by plants from growing medium/solution.**
  + **Form: Packaged Fertilizers (e.g., Athena ProLine bags, Blended bottles, Transcript P.9, P.25, P.159), Mixed Solution (Reservoir) [89].**
  + **Consumption Rate: Varies with plant size, growth stage, genetics, environment [32]. Affects concentration in medium/solution over time [169]. Metered cost [83].**
  + **Cost: Operational cost (purchase) [31, 51, 83].**
  + **Measurement: UI representation [89], consumption meter [10]. Nutrient management interface [170]. EC/PPM/pH readouts [170]. Nutrient composition displays [170]. Runoff/Substrate test results [170]. Can be measured in plant tissue [36].**
* **CO2: [58] Consumed by plants for photosynthesis.**
  + **Form: CO2 Tanks (Visual), CO2 Gas (UI) [58]. From tanks or generators [58].**
  + **Consumption Rate: Varies with plant size, growth stage, environment (light, temperature). Metered cost [83].**
  + **Cost: Operational cost (purchase/generation) [83].**
  + **Measurement: UI representation [58], tank levels [10], consumption meter [10].**
* **Building Materials: [58] Consumed for facility construction.**
  + **Types: Walls, Floors, Pipes, Wires, Ducting [58].**
  + **Form: UI representation [58], pallet/stack models possible [58].**
  + **Consumption Rate: Used during construction based on placed objects.**
  + **Cost: Material cost [50, 83]. Varies by material/type [16, 171].**
* **Seeds/Clones: [58] Consumed for starting new plants.**
  + **Form: Strain-specific Seeds (Visual), Clones (Propagation) [58].**
  + **Consumption Rate: Used when starting a new grow cycle.**
  + **Cost: Acquisition costs (NPC vendors, special events) [83]. Varies by strain/source [172, 173]. Quality is important [173]. Can be made in-house (clones) [174]. Cost of elite cuts can be high.**
  + **Measurement: UI inventory representation [58].**
* **Finances: [58] In-game currency.**
  + **Functionality: Used for purchases, paying costs [83]. Earned from sales/contracts [83].**
  + **Measurement: UI representation [58]. Ledger for income/major expenses [175]. Budget, Costs, Revenue, Profit/Loss displays [130, 176]. Financial reports [10]. Understanding Cost of Production (CoP) is critical (Transcript P.2-3).**

#### 4.11 Facility Furniture & Fixtures Parameters

**Parameters defining functional items providing workspace, storage, and supporting the facility aesthetic.**

* **Workbenches: [107] Provides a surface for tasks.**
  + **Types: Various Sizes, materials [107].**
  + **Functionality: Workspace [107].**
  + **Cost: Initial purchase cost [107].**
* **Shelving: [107] Provides storage.**
  + **Types: HD Shelving (Metal, Wire, e.g., for drying racks, clone racks, Transcript P.21, P.177) [107]. Stackable [177]. Wall-mounted [177].**
  + **Functionality: Storage [107]. Supports Cleanliness aesthetic (item storage) [107, 178].**
  + **Cost: Initial purchase cost [107].**
* **Storage Cabinets: [107] Provides enclosed storage.**
  + **Types: Metal, Plastic, Lockable [107]. Chemical/Flammable storage [143].**
  + **Functionality: Storage [107]. Supports Cleanliness aesthetic (item storage) [107, 178]. Specific storage for chemicals [143].**
  + **Cost: Initial purchase cost [107].**
  + **Security: Lockable options [107].**
* **Rolling Utility Carts: [107] Provides portable workspace/storage.**
  + **Functionality: Portable workspace/storage [107]. Supports Cleanliness aesthetic (item storage) [107, 178]. Cloning carts (Transcript P.199).**
  + **Cost: Initial purchase cost [107].**
* **Seating: [107] Provides resting spots.**
  + **Types: Chairs, Stools, Folding Chairs [107].**
  + **Cost: Initial purchase cost [107].**
* **Waste Disposal Assets: [179] Containers for generated waste.**
  + **Types: Dumpsters, Trash Cans [179].**
  + **Functionality: Players transport generated waste (pruned leaves, used media) to these [179].**
  + **Capacity: Can be upgraded [179].**
  + **Cost: Initial purchase cost [179]. Upgrade costs [179]. Potential minor cost for waste disposal [83].**
  + **Visuals: Can be upgraded in visuals [179].**

### 5. Gameplay Systems & Simulation Mechanics

**This section outlines parameters for core gameplay systems including economy, player progression, data interfaces, time mechanics, and the underlying knowledge base that informs the simulation.**

#### 5.1 Economy & Market Dynamics Parameters

**Parameters defining the economic interactions, costs, revenues, and market forces within the simulation. The MVP focuses on an NPC-driven economy, with a player-driven market as a post-MVP goal. Market conditions are volatile, with prices fluctuating based on supply, demand, quality, and trends (Transcript P.2-6, P.42-44, P.71-73, P.91-93, P.156, P.239, P.275).**

* **NPC-Driven Economy (MVP):**
  + **Cultivation Contracts:**
    - **Issuers: NPCs (e.g., dispensaries, processors, research institutions).**
    - **Requirements: Specific strain (chemovar/genetic profile), quantity (lbs/kg), quality tiers (e.g., A-grade, B-grade, C-nugs/trim, processing grade, Transcript P.4, P.6), THC/CBD/terpene levels, visual appeal, cure quality, contaminant-free (passing tests).**
    - **Deadlines: Time limits for contract fulfillment.**
    - **Rewards: Currency, Reputation Points, Research Points, rare genetics/equipment blueprints.**
    - **Penalties: For failure to meet quality/quantity/deadline (reduced payment, reputation loss).**
    - **Contract Negotiation (Simplified MVP): Basic acceptance/rejection. (Advanced: price negotiation, milestone payments - Post-MVP).**
    - **Market Price Fluctuation: Contract prices influenced by simulated supply/demand for specific strains/qualities. "Fire" with a brand commands higher prices than unbranded or "mids" (Transcript P.2-4, P.42). Mids market often flooded ($600-1200/lb, Transcript P.2, P.4). Packaged eighths wholesale for $25 ($3200/lb, Transcript P.4-5).**
  + **Direct Sales to NPC Buyers:**
    - **Buyer Types: Limited NPC buyers with specific preferences (e.g., bulk flower, trim for extraction, specific chemovars).**
    - **Pricing: Influenced by quality, quantity, relationship with buyer, current market conditions. White labeling for other brands is an option (Transcript P.6).**
  + **Operational Costs (OPEX):**
    - **Utilities: Electricity (major cost, varies by region/source, e.g., 6-42 cents/kWh, Transcript P.5), Water, Gas.**
    - **Consumables: Nutrients (significant cost, depends on line/complexity, Transcript P.10-11, P.25, P.59-63), Growing Mediums (coco, rockwool, soil), CO2, Pest/Disease Control products, Cleaning supplies, Packaging materials.**
    - **Labor (Abstracted MVP): Simulated cost based on facility size/tasks. (Real-world: $100-150/lb trim cost, Transcript P.5; Cultivation staff, Transcript P.4, P.58, P.216).**
    - **Testing Costs: Mandatory state/contract testing (potency, microbial, pesticides, heavy metals, Transcript P.6, P.22, P.336-340). HLVd/pathogen testing (Transcript P.17, P.82-84, P.327). Cost per batch (e.g., $350/5lb lot in NV, Transcript P.6, P.336).**
    - **Licensing/Permits (Abstracted MVP): Fees for facility operation, research. (Real-world: cultivation taxes vary by state, e.g., 18% in NV, 0% in MI, Transcript P.4). 280E tax implications (Transcript P.4).**
    - **Maintenance/Repairs: For equipment.**
    - **Logistics/Shipping: For seeds/clones (Transcript P.1-2), finished product.**
    - **Cost of Production (CoP): Critical metric for players to track ($/lb or $/g). Varies greatly by facility type, scale, efficiency (e.g., $250-300/lb Black Market, $456/lb MI Legal, $750/lb NV Legal with tax, Transcript P.5-6). Understanding CoP is vital for profitability (Transcript P.2-3).**
  + **Capital Expenditures (CAPEX):**
    - **Facility Construction/Upgrades: Costs for building/expanding rooms, installing utilities.**
    - **Equipment Purchase: Lights, HVAC, irrigation, benches, tools, lab equipment.**
* **Market Influences (Simulated for NPC Economy):**
  + **Supply & Demand: For specific strains, product types (flower, rosin, hydrocarbon extracts, Transcript P.3), quality tiers. Oversupply drives prices down (e.g., Michigan market, Transcript P.2, P.5-6).**
  + **Trends & Hype: Popularity of certain terpene profiles ("candy," "gas," Transcript P.152, P.172, P.187) or genetic lines (Runtz, Zkittlez, Cookies, Transcript P.115-116, P.192, P.196, P.241). Influencers can drive trends (Transcript P.67).**
  + **Regional Variation (Abstracted MVP): Different markets (states/countries simulated via NPC buyers) may have different price points and preferences (e.g., Europe terpene focus, Transcript P.192; NY demand, Transcript P.6).**
  + **Quality Premiums/Discounts: Higher quality (potency, terpenes, bag appeal, cleanliness) commands better prices. "Fire" vs. "Mids" (Transcript P.2-4).**
  + **Brand Reputation: Player's brand (developed through consistent quality, successful contracts) influences prices and contract availability (Transcript P.3).**
  + **Seasonality (for outdoor/greenhouse): Outdoor harvests can flood the market and depress prices (Transcript P.5-6, P.42-43).**
  + **Regulatory Changes (Simulated Events): Changes in simulated local/state regulations affecting taxes, licensing, testing requirements (Transcript P.2, P.5, P.71-73, P.88-93, P.269-275, P.276-283, P.287-295).**
* **Player-Driven Marketplace (Post-MVP):**
  + **Tradable Items: Genetics (seeds, clones, tissue culture), Equipment, Consumables, potentially Harvested Product.**
  + **Mechanisms: Listings, Bids, Direct Trades.**
  + **Fees: Marketplace tax, listing fees (currency sinks).**
  + **Reputation System: For buyers/sellers, impacting trust and prices.**
  + **Data Analysis: Market history, price trends (potential skill unlock).**
* **Financial Management:**
  + **Ledger: Tracking income, expenses, profit/loss.**
  + **Budgeting Tools: Planning for operational costs, investments.**
  + **Loans/Investors (Potential Post-MVP): Options for capital infusion with associated risks/obligations. Banking is a major challenge in the real world (Transcript P.2).**
  + **Insurance (Potential Post-MVP): For crop loss, facility damage.**

#### 5.2 Player Progression Systems Parameters

**Parameters defining how players advance, unlock new capabilities, and achieve goals.**

* **Skill Tree ("The Tree"):**
  + **Categories (Leaves): Genetics, Cultivation, Environment, Construction, Harvest, Science, Business.**
  + **Nodes (Skills/Concepts): Specific abilities or knowledge unlocks within categories.**
    - ***Genetics:* Basic Pollination, Cloning, Pheno Hunting SOPs, Sex Reversal (STS), Advanced Breeding Techniques (Backcrossing, S1, F2+), Tissue Culture Basics, Genetic Marker Intro, Genome Editing Intro.**
    - ***Cultivation:* Basic Watering, Nutrient Mixing Level 1, Plant Training (Topping, LST), IPM Basics, Substrate Management, Advanced Irrigation (Crop Steering Intro, Transcript P.62, P.121-125), Harvest Timing.**
    - ***Environment:* Basic Climate Control, VPD Understanding, CO2 Enrichment, Advanced Airflow, Spectrum Manipulation (Far-red, Transcript P.203-204).**
    - ***Construction:* Basic Room Building, Electrical Level 1, Plumbing Level 1, HVAC Setup, Greenhouse Construction, Lab Construction.**
    - ***Harvest:* Basic Drying/Curing, Hand Trimming, Machine Trimming Intro, Rosin Pressing Intro, Hydrocarbon Extraction Intro.**
    - ***Science:* Basic Microscopy, Pathogen ID (HLVd, PM, Botrytis), Nutrient Deficiency ID, Lab Testing Interpretation (Potency, Terpenes), Data Logging & Analysis.**
    - ***Business:* Basic Contracts, Budgeting, NPC Vendor Relations, Marketing Intro.**
  + **Skill Point Acquisition: Completing objectives/tasks (ADA guidance, Transcript P.VI), successful harvests (quality/yield based), research breakthroughs.**
  + **Unlocking Philosophy: Nodes introduce concepts/mechanics; mastery often tied to equipment/tool upgrades.**
* **Research System:**
  + **Funding: Research Points (from contracts, data analysis, breeding breakthroughs, selling rare genetics).**
  + **Projects: Available after relevant Skill Tree nodes unlocked.**
    - **Examples: New Equipment Blueprints (e.g., advanced lights, automated fertigation systems like Growlink/Dilution Solutions, Transcript P.74, P.119-149), Technique Refinements (e.g., optimized drying/curing protocols, advanced cloning methods), Genetic Insights (e.g., marker discovery for specific traits, understanding HLVd resistance mechanisms), Facility Upgrades (e.g., energy efficiency improvements, advanced clean room designs), Business Development (e.g., new market access, branding strategies).**
  + **Outcomes: Unlocks, efficiency bonuses, new information in Knowledge Base.**
  + **Risk/Failure: Some research projects may have a chance of failure or suboptimal results.**
* **Narrative Milestones & Objectives (ADA Guided):**
  + **Structure: Guides player through development stages (Early, Mid, Late game).**
  + **Examples:**
    - ***Early:* First successful harvest, Unlock Warehouse map, Secure first large contract.**
    - ***Mid:* Develop a specific high-THC/CBD/CBG strain, Achieve GACP/GMP-like certification (simulated), Establish a stable mother room with clean genetics (HLVd-free).**
    - ***Late:* Pioneer a novel genetic line with unique traits, Dominate a specific market segment, Unlock advanced research lab/technologies.**
  + **Rewards: Skill Points, Research Points, Currency, Unique Equipment/Genetics, New NPCs/Factions, Access to new map areas/facility types.**
* **Equipment & Resource-Based Progression:**
  + **Acquisition: Purchasing from NPC vendors, unlocking via research/skill tree.**
  + **Tiers: Equipment exists in tiers (Basic, Intermediate, Advanced, Experimental), affecting efficiency, capacity, durability, features, cost. (e.g., basic hand tools to automated trimmers, simple timers to Growlink controllers).**
  + **Upgrades: Some equipment can be upgraded (e.g., pump flow rate, HVAC capacity).**
  + **Resource Quality: Higher quality inputs (nutrients, medium) can improve outcomes but cost more.**
* **Reputation System:**
  + **Player Reputation: Influenced by contract fulfillment (quality, timeliness), product quality in direct sales, ethical choices.**
  + **Impact: Affects NPC interactions (contract availability/terms, prices from buyers/vendors), access to rare genetics/equipment, potential for future player market interactions. A good brand name is crucial for better prices (Transcript P.3).**
* **Meta-Progression (Potential):**
  + **Persistent Genetic Library: Player-bred strains tied to account, usable across playthroughs.**
  + **Starting Conditions: Unlocking different starting scenarios/facility types for new games.**

#### 5.3 Data, UI, and Feedback Systems Parameters

**Parameters defining how simulation data is collected, presented to the player, and used for decision-making. Emphasis on intuitive, actionable information.**

* **Data Points & Collection:**
  + **Environmental: Real-time sensor data (Temp, RH, VPD, CO2, PAR/PPFD) from player-placed sensors (Growlink, Aroya, Transcript P.11, P.121-147). Data logging for historical trends.**
  + **Growing Medium: Manual sampling (EC/PPM, pH, Temp, VWC%) using handheld meters. Automated substrate sensors (EC, VWC, Temp). Runoff collection and testing (EC, pH, volume, Transcript P.157-158).**
  + **Plant Data: Visual inspection (health, stage, structure, color, pest/disease symptoms, HLVd symptoms Transcript P.17, P.80). Manual sampling (simulated chlorophyll meters). Harvest data (wet/dry weight, trim weight).**
  + **Lab Analysis (Simulated): Potency (THC, CBD, CBG, etc.), Terpene profiles, Microbial loads (yeast/mold, E.coli, Salmonella, Aspergillus), Pesticides, Heavy Metals, HLVd/Pathogen tests (Transcript P.6, P.12-13, P.17, P.22, P.76-85, P.152, P.160, P.170, P.197, P.325-340, P.336-340). Moisture content, water activity.**
  + **Operational: Resource consumption (water, power, nutrients, CO2), costs, task times, yields.**
  + **Genetic: Phenotypic data from hunts, pedigree information, simulated genetic marker results.**
* **Data Presentation & UI:**
  + **Dashboards: Customizable displays for key environmental, substrate, and plant metrics. Real-time and summarized views.**
  + **Graphs & Charts: Historical trends for all logged data (e.g., VPD over 24hrs, substrate EC fluctuations, Transcript P.132-138). Multi-variable plotting for correlations.**
  + **Simulated Lab Reports: Clear presentation of potency, terpene, contaminant results. Comparison to acceptable limits/contract requirements.**
  + **Breeding Interface: Tools for managing pedigrees, comparing traits, planning crosses, tracking pheno hunt data.**
  + **Facility Management Overlays: Utility View ("X-Ray" mode for pipes, wires, ducts), Zoning View, Resource Inventory levels.**
  + **Operational/Financial Reports: Cost of Production (CoP) breakdowns, Profit/Loss statements, sales history, contract status.**
  + **Alerts & Notifications: Tiered system (Blue/Info, Yellow/Warning, Red/Critical) for environmental deviations, equipment malfunctions, pest/disease outbreaks, low resources, task reminders. Visual and audio cues. (e.g., Growlink alerts, Transcript P.137).**
  + **Historical Logs & Notes: Automated logging of key events (harvests, system changes, alerts). Player-creatable notes for observations, plans.**
* **Manual Data Acquisition & Plant Work Loop:**
  + **Process: Player identifies need -> Selects tool from inventory -> Clicks target asset (plant, substrate, room) -> Enters "Action Mode" (tool-specific zoomed view/UI) -> Observes readout/animation -> Data auto-logged.**
  + **Examples: Using handheld EC/pH meter on runoff, using loupe to inspect trichomes or pests, taking leaf sample for HLVd test.**
* **Knowledge Base (In-Game Encyclopedia/ADA Guidance):**
  + **Content: Information on plant biology, genetics, cultivation techniques, equipment operation, pest/disease management, market dynamics. Unlocked via skill tree, research, discoveries.**
  + **Presentation: ADA provides contextual help and tutorials. Dedicated UI for browsing discovered knowledge.**
  + **Realism Data: Grounded in real-world science and best practices, cross-referenced from reputable sources. Simplified for gameplay but maintains authenticity. (Transcript P.23-25, P.60, P.68-70, P.76-85, P.118, P.121-149, P.178-180, P.235-237, P.269-275, P.298-299, P.323-348).**

#### 5.4 Time Mechanics Parameters

**Parameters governing the in-game passage of time and its effects.**

* **Time Scale Control: Player can accelerate/decelerate time (e.g., 1x, 2x, 5x, 10x, Pause).**
* **Transition Inertia: Initiating a time scale change requires confirmation and locks further changes for a "transition duration" proportional to the speed change. Prevents rapid cycling/exploits.**
* **Time Scale-Dependent Variables (Subtle):**
  + **Genetic Expression Potential: Slower speeds might offer slightly higher maximum quality potential for sensitive traits (requires more nuanced management).**
  + **Stress Event Probability: Faster speeds might slightly increase base probability/severity of minor stressors if systems are not perfectly optimized or if player is not attentive to alerts.**
  + **Resource Consumption Rates: Directly tied to time scale (e.g., electricity use per in-game hour is constant, but real-time cost accrues faster at higher time scales).**
* **Offline Time Progression: Player chooses time scale (including pause) for offline periods. Events/alerts are queued for review upon return.**
* **Scheduled Events: Calendar system for recurring tasks (e.g., weekly mom refresh, HLVd testing schedule, harvest schedules based on flowering times, Transcript P.59, P.183, P.302). Linked to ADA reminders.**

#### 5.5 Regulatory & Compliance Parameters (Abstracted for Gameplay)

**Parameters simulating the impact of external rules and standards on the player's operation.**

* **Simulated State/Local Regulations:**
  + **Licensing: Initial license to operate. Potential for different license tiers (cultivation, processing, retail - post-MVP) with varying costs/requirements. Moratoriums on new licenses can occur as a market event (Transcript P.5).**
  + **Taxation: Cultivation taxes (per sq ft, per lb, % of revenue), sales tax, 280E implications (abstracted). Tax rates can change via simulated events (Transcript P.4, P.71-73, P.88-91).**
  + **Testing Requirements: Mandatory tests for specific compounds/contaminants (potency, microbial, pesticides, heavy metals). Batch sizes for testing (e.g., 5lb lots in NV, up to 50lb in MI, Transcript P.6, P.336). Testing labs have variable accuracy/turnaround times. Cost of testing (Transcript P.6).**
  + **THC Limits: For hemp vs. drug-type classification (<0.3% Δ⁹-THC for hemp, Transcript P.2, P.276-277). Total THC calculations (THCA\*0.877 + THC).**
  + **Waste Disposal: Rules for disposing of plant waste (metric tracking, Transcript P.6-7).**
  + **Facility Compliance: Building codes, safety inspections (fire, electrical).**
* **Contract Compliance: Meeting terms of NPC contracts (strain, quantity, quality, deadline). Failure impacts reputation and finances.**
* **Audits/Inspections (Simulated Events): Random or triggered events where player facility is "inspected."**
  + **Triggers: Poor reputation, repeated contract failures, "whistleblowers."**
  + **Checks: Environmental logs, cleanliness, SOP adherence, license validity, tax payments.**
  + **Outcomes: Fines, temporary shutdown, license suspension/revocation for severe/repeated violations.**
* **Product Recalls (Simulated Events): If a sold batch is later found to be contaminated (e.g., failed retest by NPC buyer), triggering financial loss and reputation damage.**