



Parts List for iCIDER

Archita Gupta, Arvind Thevathasan, Anthony Lee, Bertrand Chandany, Harsh Agrawal,
Natalie Goh, and Ryan Boey

Supervisors: Luiz Araujo, Prof. Mark Isalan, Prof. Geoff Baldwin, Dr. Simon Moore

Contents

1	Introduction	3
2	Other Applications of iCIDER	3
3	Chassis	4
4	Circuit Design	5
4.1	Phytohormone Sensor	5
4.2	NIMPLY Gate	5
4.3	Activator Module	7
4.4	Repressor Module	8
4.5	Cassette Module	9
5	Assembly Method	10
5.1	Formatting of parts	10
5.2	Assembly logic	10
5.3	<i>In vivo</i> Characterisation	12
6	Level 0 Parts	13
6.1	Promoters	13
6.2	Kozak Sequences	17
6.3	Protein Coding Sequences (CDS)	17
6.4	Terminators	23
6.5	Spacers	25
6.6	Regulatory Elements	25

7 Responsible Research and Innovation	26
7.1 Biocontainment	26
7.2 Compliance and Regulation	27
7.3 Stakeholders	28
Appendix	37
A Modelling	37
B Codon Optimization Script and CellDesigner Files	40

1 Introduction

Harvested plant tissues represent an under-explored frontier for biotechnology. Despite being detached from the parent plant, they remain metabolically active, maintaining the transcriptional and enzymatic capacity required for complex biosynthesis. Recent efforts in plant synthetic biology have successfully engineered autonomous regulation using endogenous signal sensing during the plant growth phase. For example, Ge et al. [26] designed synthetic abscisic acid (ABA)-responsive promoters (Ap , Dp and $ANDp$) to drive the expression of ABA-signalling genes such as *CARK1* and *RCAR11*. Similar approaches have demonstrated programmable ligand sensing via synthetic histidine-kinase signalling pathways and jasmonate-responsive activation of defence metabolite production [5, 71].

We aimed to extend this paradigm into the post-ripening phase. This allows us to engineer valuable compounds like peptides, vitamins, small-molecule drugs, etc., which are less dependent on external inputs that are highly variable during the growth phase of plants. To achieve robust post-harvest control, we identified two hormones with a unique regulatory relationship - ethylene and gibberellins.

Ethylene functions as the master transcriptional regulator of fruit ripening [35, 67]. It activates large transcription factor networks controlling cell wall remodelling, sugar metabolism, and volatile production. Critically, ethylene levels increase dramatically — often by orders of magnitude — following harvest [19]. This transition reflects a regulatory switch from autoinhibitory basal synthesis to autocatalytic positive feedback, creating a sharp and reliable temporal signal marking entry into the ripening phase.

In contrast, gibberellins act as master regulators of fruit growth and developmental expansion programmes. Gibberellin signalling declines substantially as the fruit transitions from growth to ripening [19]. Importantly, reduced gibberellin signalling can promote ethylene biosynthesis, while ethylene signalling does not directly restore gibberellin levels.

To exploit this, we developed iCIDER, a synthetic biology platform that converts endogenous post-harvest ethylene-gibberellin dynamics into programmable gene expression outputs. At the core of iCIDER is a NIMPLY logic gate, where expression is activated only when ethylene is present and gibberellin is absent. This architecture enables temporal filtering of expression such that gene activation occurs only once tissues have fully transitioned into the post-harvest ripening state. By tuning circuit parameters such as repressor binding affinity and enzyme degradation rate, we achieve control over both the magnitude and duration of expression, generating a transient post-harvest pulse of gene activity.

As a proof of concept, we applied iCIDER to regulate pyruvate decarboxylase (PDC) and alcohol dehydrogenase 1 (ADH1) expression, driving ethanol production in apples. Ethanol biosynthesis was selected because it is a two-step pathway drawing directly from central carbon metabolism [51], minimising metabolic burden relative to more complex secondary metabolite pathways. The modular architecture of iCIDER allows straightforward replacement of output cassettes and incorporation of additional or inverted sensing modules, positioning this framework as a general strategy for programmable post-harvest traits in agriculture.

2 Other Applications of iCIDER

Apple production faces significant losses from a range of biotic stressors like pests and abiotic factors including post-harvest degradation and environmental contamination, leading to an approximate 13-54% fruit loss before packaging [11]. Current management strategies utilise exogenous chemical treatments to reduce post-harvest degradation [21]. Pesticides like terpenoids act through direct insecticidal activity on top of volatile anti-herbivory effects as well [1] [56]. Despite this, their high volatility and low solubility in water [22] make it challenging to use as a topical insecticide. Therefore, terpenoids endogenously produced in fruits could be used to

alleviate these challenges and provide a strategy for pest-resistance. However, as terpenoid synthesis is toxic and metabolically expensive, continued synthesis post-harvest would deplete sugar stores and decrease fruit quality. By inverting the phytohormone sensing module in iCIDER, we could inhibit terpenoid synthesis post-harvest to maintain pest protection pre-harvest and preserve quality post-harvest.

Additionally, maximising farming yield and efficiency will be crucial to meet future global demand and allow adaptation to a changing environment. Expansins, for example, promote faster fruit growth and higher quality when expressed pre-harvest [11]. However, increased post-harvest expression accelerates tissue softening and quality deterioration [60]. Our system could be employed here to promote expression during growth while triggering an off-state after harvesting to increase yield without compromising shelf-life.

3 Chassis

The modular platform was developed to work in post-harvest plants, with the ripening-induced expression gated by endogenous hormone signals. As such, the chosen chassis was required to remain metabolically active after harvest, possess native ethylene and gibberellin signalling networks, and provide sufficient internal carbon to support biosynthesis. Our chosen chassis is apples (*Malus domestica*), specifically the cultivar Winston.

Apples are climacteric fruits that undergo a well-characterised ripening process driven by a sharp ethylene burst and transition from the basal autoinhibitory system 1 to the autocatalytic system 2 ethylene production following harvest [35]. This transition causes transcriptional changes that lead to tightly regulated hormonal cross-talk, including interaction with gibberellins. These features provide a robust, endogenous signalling framework that can be repurposed for conditional gene expression without the need for external inducers.

Following harvest, apples remain metabolically active for extended periods while being physically separated from the parent plant, enabling the synthetic gene circuit to operate without impacting plant growth or development. During fruit development, apples accumulate sugar to approximately 10 – 11 g of sugar per 100g of fruit tissue [32]. This provides an internal carbon source that can support autonomous biosynthesis without external nutrient supply. The combination of sustained metabolic activity, endogenous signalling and carbon availability allows the harvested fruit to function as a self-contained bioreactor. These autonomous behaviours are a key requirement of the proposed platform, enabling inducible expression in a physically contained system.

In addition to these biological advantages, apples are the third most produced fruit globally, with approximately 149 megatons harvested in 2023 and a market value of around 148 billion USD, representing a 37% increase in production since 2010 [24] [23]. This sustained growth and established post-harvest infrastructure support the relevance of apples as a scalable chassis for a harvest-inducible platform, rather than being limited to laboratory-scale deployment.

From an engineering perspective, apples provide a tractable and modular chassis for implementing hormone-gated synthetic gene circuits. Ethylene and gibberellin signalling act through native promoter architecture, enabling synthetic modules to interface directly with endogenous regulatory networks rather than relying on orthogonal inducers. Crucially, many potential platform applications, including alcohol, terpenoid and expansin biosynthesis, are native apple pathways that are naturally regulated during development and ripening. This allows flux to be modulated through existing metabolic pathways rather than introducing entirely heterologous pathways, reducing metabolic burden and design complexity. As a result, output modules can be readily exchanged while preserving the same sensing module.

4 Circuit Design

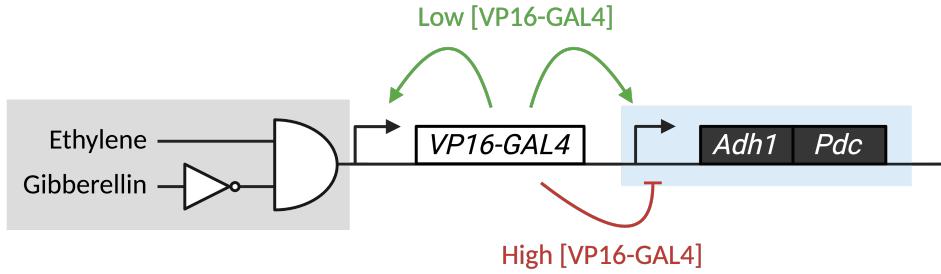


Figure 1: **Circuit overview**. Input module is shown in grey. The ethanol-producing cassette is shown in blue. Self-amplification and cassette expression are depicted in green, and circuit repression is shown in red.

The circuit has four modules (Figure 1): the plant hormone (phytohormone) sensor in the form of a NIMPLY gate, the activation module which drives strong biosynthesis of the cassette, the repression module which suppresses the circuit, and the cassette module. Currently, temporal dynamics are cassette-dependent and adjusting the activation-repression delay remains a limitation.

4.1 Phytohormone Sensor

For our proof of concept, we aimed to express PDC and ADH1 for ethanol biosynthesis post-harvest by exploiting the endogenous fruit ripening mechanism. We decided on ET as it is the most studied phytohormone regulating ripening in climacteric fruit, including apples [35, 67]. Studies showed that ethylene production in *M. domestica* increases 1000-fold post-harvest and cold-storage [19], making it an ideal candidate as a post-harvest indicator. However, ET is highly volatile and is prone to stochastic changes from abiotic and biotic stresses [48], which can cause premature activation of our circuit. Therefore, a secondary ripening signal was introduced to enhance robustness to our circuit by providing redundancy and protecting activation from stochastic fluxes of ET.

The secondary phytohormones considered were auxin and gibberellins. Studies showed that auxin and ethylene have an inter-dependent relationship featuring complex crosstalk. In apples, auxin has been shown to regulate ethylene in fruit ripening [66], while ET modulates auxin to restrict plant growth in *Arabidopsis* [57]. GA on the other hand is unaffected by ET; exogenous treatment with ET does not reverse the ripening inhibition induced by GA [63]. Additionally, GA accumulates during fruit growth and declines during ripening [33, 39]. Put together, we decided to use the presence of ethylene and the absence of gibberellin as our indicator for post-harvest ripening.

To detect ethylene's presence, we decided to use P_{MdERF3} , the promoter for ethylene response factor 3 (MdERF3) in *M. domestica*. Ethylene activates MdEIL1 to induce MdMYB1, subsequently inducing MdERF3 [61, 3]. For gibberellins, we decided to use PMdGA2ox6, a promoter for gibberellin 2 oxidase 6 (GA2ox6) in *M. domestica* as the GA2ox family was found to be upregulated after GA treatment [70]. MdGA2ox6 was specifically found to be the most differentially expressed between 100 days post-anthesis and harvest conditions [65].

4.2 NIMPLY Gate

To achieve activation when ET is high and GA is low, we implemented a NOT-GA AND ET (NIMPLY) logic function (Figure 3). When both inputs are satisfied, the split GAL4 and VP16

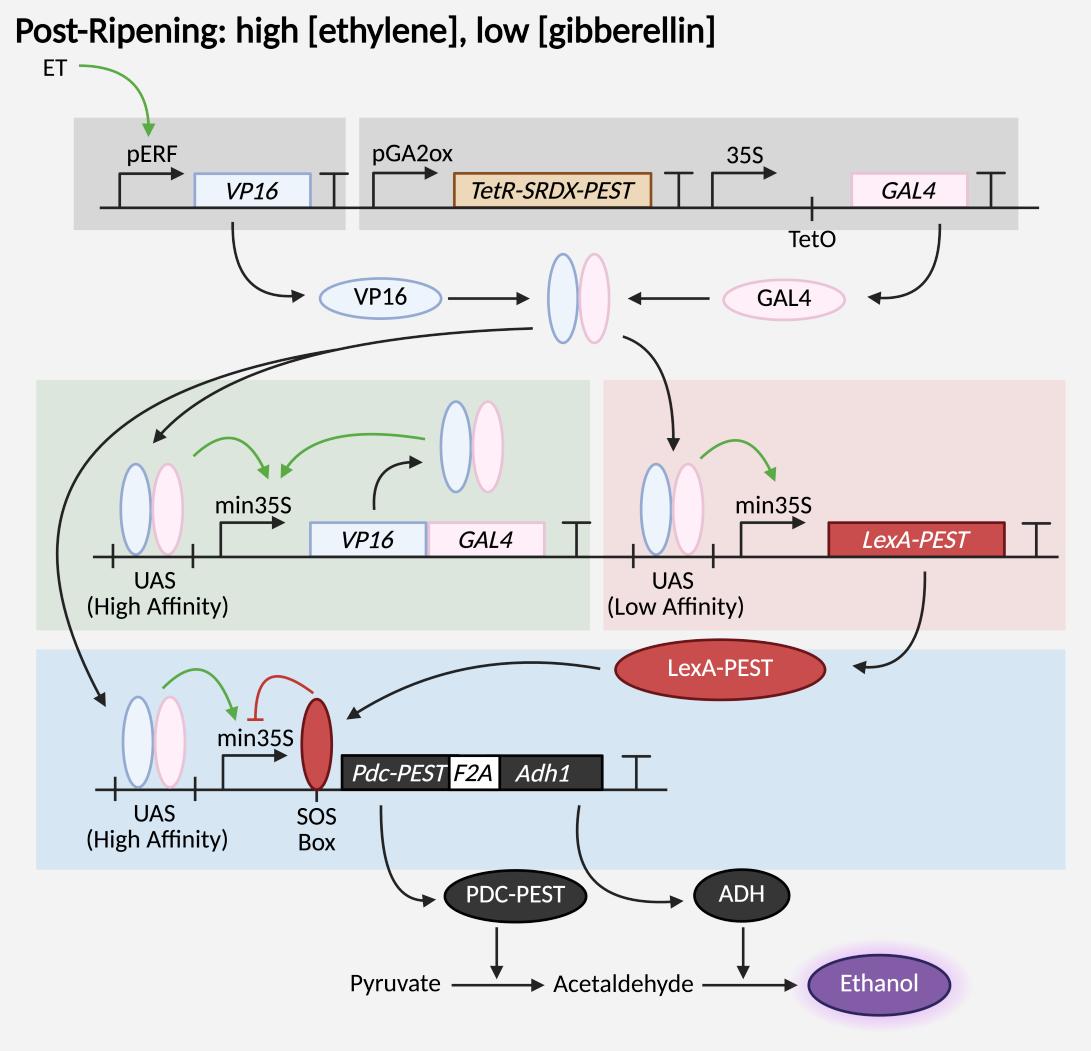
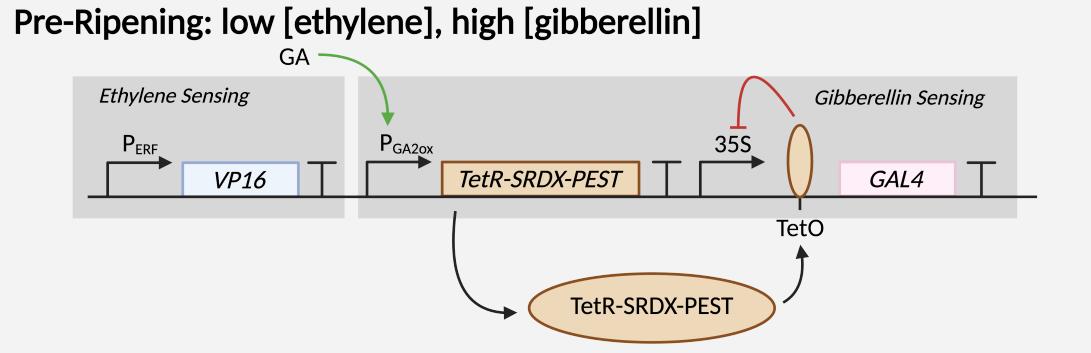


Figure 2: **Detailed circuit.** Activation is shown by green arrows whilst inhibition is shown by red inhibition arrows. The phytohormone sensor, activator module, repressor module and cassette module are shown in grey, green, red and blue boxes respectively. Conversion of pyruvate to ethanol, with associated enzymes, are shown at the bottom.

fragments are expressed and associate via heterodimerising leucine zippers to reconstitute a functional activator for downstream expression.

Gibberellin induces the expression of TetR–SRDX–PEST via PMdGA2ox6, which binds TetO sites and, via its SRDX repression domain, inhibits the expression of GAL4, which is downstream

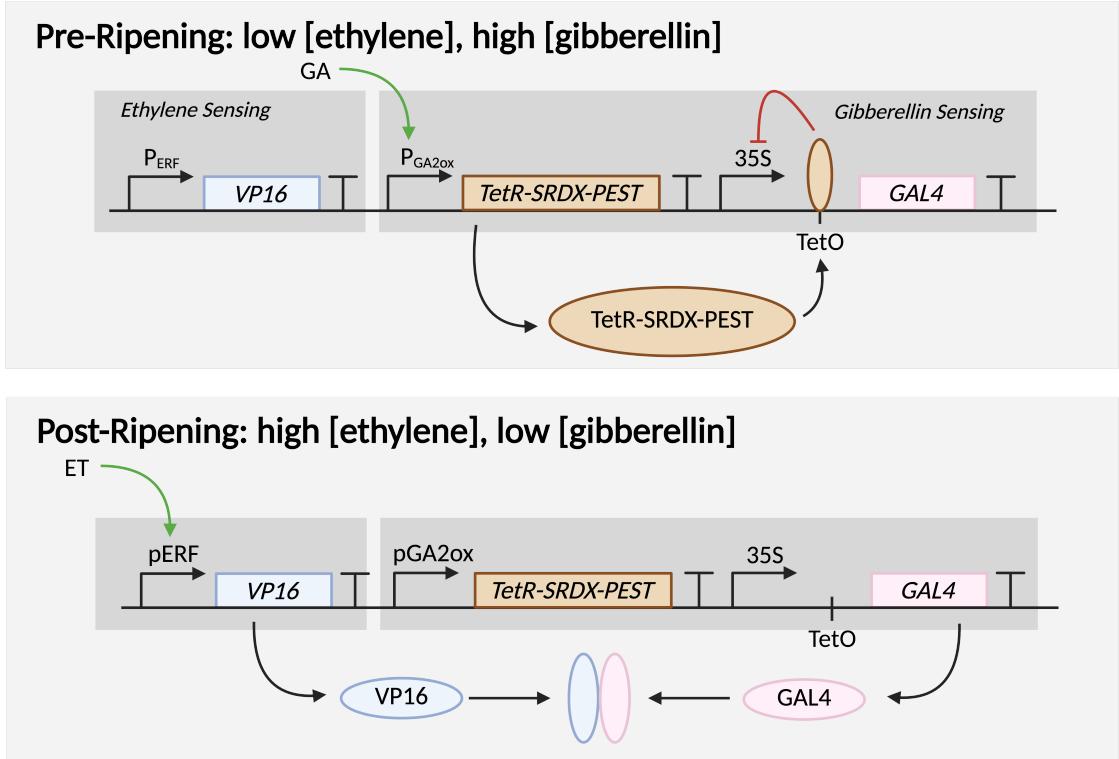


Figure 3: Sensor modules. Top panel shows the module behaviour during pre-ripening conditions, where ethylene is low and gibberellin is high. Bottom panel shows post-ripening behaviour, where the presence of ethylene and absence of gibberellin induces the expression of VP16 and GAL4. ET: ethylene. GA: gibberellin.

of the constitutive 35S promoter. The SRDX domain, derived from the plant EAR motif family, is a well-characterised and highly potent repressor in plants [36]. EAR/SRDX domains have been shown to outperform non-EAR repression domains, including bacterial repressors like TetR, which, on their own, bind DNA but generally fail to recruit plant co-repressors efficiently [44]. Consequently, fusing SRDX to DNA-binding domains has been widely demonstrated to enhance repression strength in plants [54, 20]. Therefore, the strong repression of SRDX improves the robustness of the NIMPLY gate by reducing stochastic derepression events. The PEST tag is a eukaryotic degradation signal that accelerates protein turnover and provides enhanced temporal control and reactivity of the circuit. This improves temporal precision, as, without the PEST tag, inhibition by TetR–SRDX may persist even when gibberellin is absent. Ferreira et al. demonstrated that fusions of a bacterial DNA-binding repressor (FapR) with SRDX and PEST improve the efficiency of Boolean gate designs in plants [20]. Together, these mechanisms minimise leaky expression of the NOT gate.

Once both VP16 and GAL4 are available, their association is catalysed by $RR_{1234}L$ and $EE_{1234}L$, two halves of a synthetic heterodimerising leucine zipper. Crucially, $RR_{1234}L$ and $EE_{1234}L$ exhibit a low dissociation constant of $K_D \approx 10^{-15}$ M, indicating an immediate and strong association [17, 40]. This architecture allows the gate to operate predictably within the complex endogenous signalling environment of ripening fruit.

4.3 Activator Module

The activator module is made of a high affinity UAS site upstream of a min35s promoter and GAL4-VP16 fusion activator gene, as shown in Figure 4A. The min35S promoter, derived from

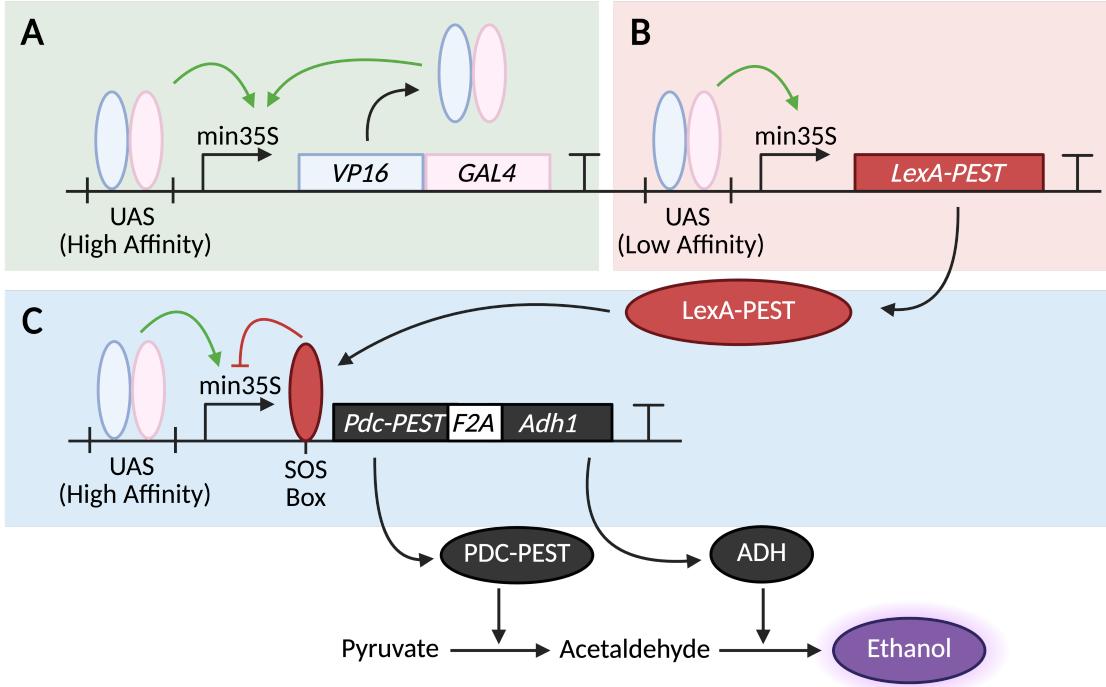


Figure 4: **Downstream VP16-GAL4-induced modules.** (A) Self-activation module. (B) Repressor module. (C) Cassette module which produces enzymes for ethanol conversion.

the Cauliflower mosaic virus (CaMV) 35S promoter, is transcriptionally inactive in isolation and requires upstream enhancer elements for activation [14, 2]. The enhancer sequence used is from the UAS/GAL4 system which has also been proven to work in plants [29, 59]. The specific high affinity UAS site used is taken from the promoter of the yeast *gal3* gene [13]. Self-amplification is activated by associated GAL4-VP16 inducing the expression of additional GAL4-VP16 fusion proteins. This feedback binarises ethylene signals upon reaching a threshold.

4.4 Repressor Module

The repressor module regulates the system to generate pulse-like expression of the cassette module. It comprises a low affinity UAS site upstream of a min35s promoter regulating the expression of LexA, which represses the cassette module, as shown in Figure 4B. The UAS site is derived from the fourth tandem UAS upstream of the yeast *gal10* gene and has a higher K_D than the high affinity UAS site used in the activator module [13]. This reduced binding affinity introduces a delay in repressor expression, ensuring that repression only occurs after an initial phase of cassette module expression. A prokaryotic repressor was intentionally chosen as it is less efficient in eukaryotic systems (LINK). LexA binds to LexA operator sites or SOS boxes [73]. Crucially, LexA is orthogonal to TetR, making it appropriate for our system. Repression strength can be further tuned by fusing LexA to the plant-derived SRDX, WRKY7 repression domain [30, 28, 64], or by altering LexA binding affinity through SOS boxes mutations ([?]), enabling more efficient transcriptional silencing, thereby lowering the system's output. The ability to tune output levels is especially important as factors such as metabolic burden or product toxicity may necessitate different repressor strengths. Thus, the optimal strength of the repressor module depends on the specific cassette module. For the context of ADH1 and PDC expression, our modelling suggests that weak repression is required, hence, we chose to use LexA in isolation.

4.5 Cassette Module

The cassette module is positioned downstream of all regulatory elements and is fully interchangeable. For our proof-of-concept, as shown in Figure 4C, the cassette encodes ADH1 and PDC, linked by an F2A peptide to enable polycistronic expression from a single transcript via ribosomal skipping [68]. This results in approximately equimolar concentrations of ADH1 and PDC. Modelling indicated that the production of ADH1 and PDC without active degradation led to uncontrolled ethanol production. However, the addition of a PEST tag to both ADH1 and PDC led to the accumulation of acetaldehyde which is highly toxic and carcinogenic [51]. Therefore, a PEST tag was added to PDC only to promote its degradation for controlled ethanol production without acetaldehyde accumulation.

5 Assembly Method

To assemble the level 0 parts in our circuit, we will be using Golden Braid (GB) 3.0 in *Escherichia coli*, before using Agrobacterium-mediated delivery into the *in vivo* host, *Nicotiana benthamiana*.

GB 3.0 is a modular cloning system designed for rapid assembly of multiple gene parts specifically for genetic modification in plants, and benefits from established parts and vector libraries [58]. We use *E. coli* as the standard propagation host for the GB vectors, as it grows quickly, gives high plasmid yields [18] and requires a straightforward protocol to isolate verified constructs.

5.1 Formatting of parts

GB 3.0 constructs are made up of "levels". Level 0 involves individual parts e.g. promoters, coding sequences (CDS), and terminators. Level 1 constructs are assembled from level 0 parts to form transcriptional units (TU). Level 2 are multi-TU constructs.

Each GB 3.0 level 0 part is formatted into plasmids according to the PhytoBrick standard where each part type (promoter, CDS, terminator) is flanked by specific Type IIS restriction enzyme sites that generate overhangs. Promoters are flanked by 5' GGAG and 3'AATG slots, CDS are flanked by 5'AATG and 3'GCTT slots, and terminators are flanked by 5' GCTT and 3' CGCT, such that the 3' slot of one part is complementary to the 5' slot of its adjacent part [49]. To prevent off-target cleavage, each part was screened for internal type IIS *BsaI* and *BsmBI* restriction sites.

Once formatted, part sequences can be obtained by PCR amplification or by DNA synthesis if required. Level 0 parts are then cloned into level 1 vectors, ready for downstream α and ω assembly into level 2 vectors.

5.2 Assembly logic

Unlike traditional cloning, our assembly approach follows the recursive logic of GB 3.0, which allows level 0 parts to be combined into complex multi-gene circuits using alternating Type IIS restriction enzymes (see Figure 5). Each assembled construct retains its terminal restriction sites, enabling further rounds of assembly. However, if the same enzyme was used in consecutive steps, it would cut previously assembled products. Therefore, by alternating enzymes and using matching vector overhangs, the integrity of each assembled module is maintained throughout the process.

Figure 5A illustrates how level 1 vectors, prepared in the PhytoBrick format, are assembled into a pDGB1 $_{\alpha}$ destination vector using *BsaI*. This yields three separate plasmids: the sensor plasmid (α 1), containing the circuit's sensing components, the feedback plasmid (α 2), which holds regulatory elements, and the cargo plasmid (α 3), carrying the interchangeable cassette. This modular design permits individual modification of any of α 1, α 2, or α 3 without the need to reassemble the entire construct.

Figure 5B depicts the Ω -assembly step, where a second reaction using *BsmBI* combines α 1 and α 2 into the pDGB1 $_{\Omega}$ vector, resulting in the stable modular construct pCIDER $_{\alpha}$ that encodes the core circuitry of iCIDER.

Figure 5C shows the final integration step, in which either an α 2-assembly or the Ω -assembly product is merged with the cargo plasmid (α 3) to produce a binary vector. This final binary vector is flanked by left and right border (LB/RB) T-DNA sequences required for Agrobacterium-mediated plant transformation.

After each α 2- or Ω -assembly, *E. coli* transformants are plated with the antibiotic corresponding to the resistance marker in the destination backbone, to select for correctly assembled constructs. Multiple colonies are then screened by colony PCR, with primers that span the new junctions formed between level 0 parts, to confirm correct part order and orientation. Restriction

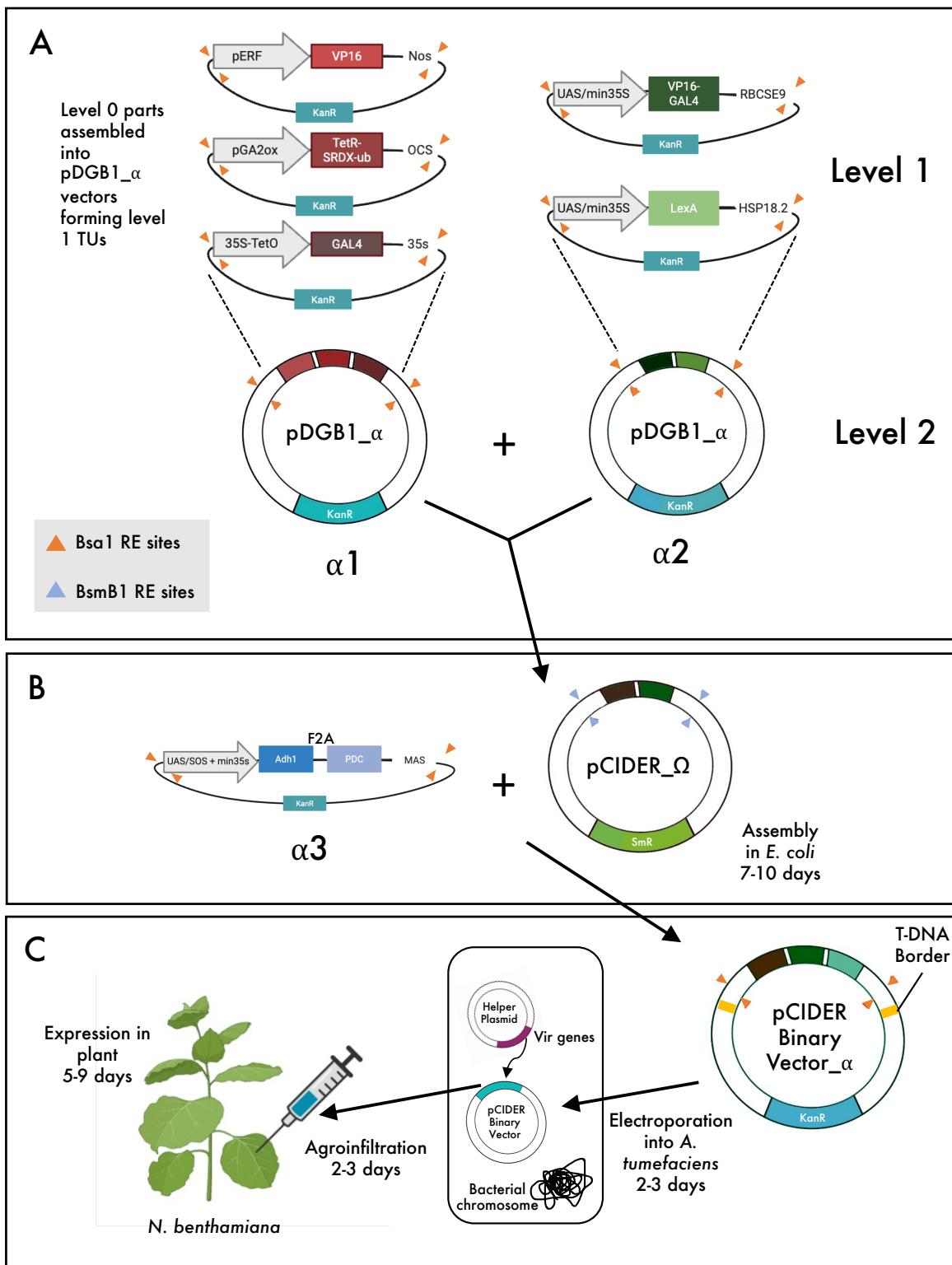


Figure 5: **iCIDER circuit assembly using GoldenBraid3.0.** BsaI and BsmBI restriction enzyme (RE) sites are shown as orange and grey triangles respectively. Plasmids carry kanamycin resistance (KanR; light blue) and omega plasmids carry streptomycin resistance (SmR; light green). Following construction and verification in *E. coli*, the final pCIDER binary vector is electroporated into *Agrobacterium tumefaciens* (with a helper plasmid providing *vir* genes) for DNA transfer and transient expression in *Nicotiana benthamiana* via agroinfiltration.

digest profiling and Sanger sequencing can be used to identify any mutations before the final binary vector is electroporated into *Agrobacterium tumefaciens*.

5.3 *In vivo* Characterisation

Agrobacteria-mediated delivery is a well-established rapid protocol for genetic modification in plants [4]. Wounded plant tissues induce the activation of virulence (*vir*) genes, which transfer LB/RB-flanked T-DNA into plant cells via the type IV bacterial secretion system [27]. For proof-of-concept, *N. benthamiana* will be used as our chassis as it is highly amenable to Agrobacterium-mediated agroinfiltration delivery [7]. Following validation in *N. benthamiana*, the system will be translated to *M. domestica*, from which stable transgenic lines will be made, enabling evaluation in apples. Finally, ethanol production will be quantified by gas chromatography-mass spectrometry [41] using Imperial's facilities. This can help us validate circuit function and gene expression.

6 Level 0 Parts

6.1 Promoters

Table 1: List of promoters with corresponding sequences, descriptions, and sources.

Promoter	Sequence	Description	Source/Part ID
PERF	ACTTAGCATTACTCTTAGGTTAAAGACTGAAATT TTAGACTTAGGTTAGAGTGGAACACATACTTT CTATGTAACATAATTATAACAATTTACTATACAT ATACATATATAATCGGGTCGAGTTGAATTAATC AAGAATGAAAATACCATCATGGCGACTCAGATT TTCAAAAAGTCCTGAACCTGTCCAGTACTCGTG TACTATCCACCATAACCACCGTGTAGGATTGGG TATCAACAAATACCCAATTCTGGGGGGTTTTT GTCATCCCCATCCTGTTGGCCCCACCAAGCACG AAAGAGAAAACCTACGAAGGTGAATATGAGTCGAT GTGTTGGAACCTAACGCATGCCGTATCCTAACCTG AAGTATTGTCATGGGCTTGAATGGCATGTCCTA GCACATTTGATCTTGCAAGTAGCTATTGGGT GAACGTAATTGATTTATTAGCATCAGAACAA ATTAATCTGGCTCGTCGCACATTTTTTACAT TACGAAGTACCAACCTCAAAAACCACTTCAAGTA ATAGCAACGAAGGGTTGCCAATACTCTTGGCC ATTCATCACCGATGGCGCTCTCAAGGCTATAC TTGCATGATTTGGTAGCCGTTGAAAAGCACCAA TATGAACCGCAGCCTCTATGGAAATACNTAA AAAAAAAAATAAGCCNGCCTCCAGCCCTCTAGCC CTCTCCGATCCCGTGTGGCCCTCCATATCCAG AGCCATCTGCCCTAGCCCTCGTTGGAGACGGTT TTAGGGCTATTCGGCCCCYCTGGCCCTCTGG CCCTCGGTTGGAGATGCCCTAACGCATGCCCTAT CCTAACCTGAAGTATTGTCATGGGCTTGAATGG CATGTCTTAGCACATTTGATCTTGCAAGTAG CTATTGGGTGAACGTAATTGATTTATTAG CATCAGAACAAATTAAATCTGGCTCGGTACACATT TTTTTACATTACGAAGTACCAACCTCAAAAACC ACTTCAAGTAATAGCAACGAAGGGTTGCCAATA CTCTTGGCCAGTTCATCACCGATGGCGCTCTC AAGGCTATACTTGCATGATTTGGTAGCGGTTGA AAAGCACCAATATGAACCGCAGCCTCTMTGTGT TGCTAACATTGCTGCTAATTATGTATATGAATC TTGATAAAGATCTCTGCTCTAACAACTAACCC GTGAACCTACCAACTATTGTTTATAAAAAGA ATTATTAGTTAGATTGGTTATTATAAAAATGCA TAAATTAAATTATAATGTAAGTGATTAAAAAAA TTGTGTCAAATTGTCAGAATGACGAGTTAAAAGC TTCTTCTAAAGATATCAATATTATTCATTT GATAATTATTACATGTATAATTACCAATAATAC AATTATTGCTWAAAACCTCGGTATTAGTTGTT AAACCAATAGTCGCGCATTATGAACCTTTGG GTTGTCGAAGTGCACCTGTTGGTTGCATATCG ATTATGGATAAAGCAAAGAGAC	Promoter taken from the MdERF3 gene in Malus domestica, demonstrated to be induced by ethylene.	An et al. 2018 [3]

Promoter	Sequence	Description	Source/Part ID
	AAAAAAAAAAATGCGTGGAAAGCAAAGCGACACAA CAAGAACGTGCACTTGCTGCTGTAACAGGATGA CATCACGCTTCTCTCAATCCAACCCAAAACCAA CGTGATTAATTGAAAACGGRCCCCACAACACAAT TTGCACACTAAAGAAAATTCAAAGCAGCCGACTTC GACATCGACATCAACTAAAAATAAATAAAAAAAAT ATCGGCCGCTAAAAATAAAAATAATAATATAT TAAATACCGAAAATATCCATCCGGTTGAAGTGTG CATGAACCTTCTCACCTATTTAACCTTCATCTC TTCAAATCCCAGAAGAAATCCAAAATCTCAACAA ATATAAGACTCTCTCTCTCTCTCTCTCTCTCT CTCTCTCTACACTTCAAACACATTCGGT TTAAGACCCGGACCCGAATTTTTGGTTTTGG CTGCGAA		

Promoter	Sequence	Description	Source/Part ID
pGA2ox	TGTTGAGTACTTCATAACCTCATCTGGTATTCTTACGATAATTACCTGTAAGCATATGGTTTACCTTGTCTCGTAAAAAGAACGGTATTAAATTATGCCCATCTCGATGTCATCGTCTTATTATAGTTAATCTTAACAATGACATTCCCTAATTAGATTACATTGGAACTTACACTTCTGTTAGGTTGTTACCGAGAATAATAATCCTTTGTTGCTATATATATA CGAAGTCTTCGATGATATTAGTGGCGGAAGATGTTCTTTGTTATTCACTCGCGGACACTATATTTGGTCTAATGCGGTAGGACTCCGATAAAAAATTATAAAGACTTTCTCAATTGGATGAGCTGTTACATAGCCTTGGTTTACCTAGATAAAACAAGGCCCTCTCTAAACTCTATTGAATGTTGTTTAGTGCTTCCACGATTATGAGGTTAGAGTTGCTGATGACATCAATAATTCACATTAGATTATTGAAAATACGATA GATTAAGTTTGACTAACTATACAATCATTGATTCTAACTGCGAGGTTCCCTACATAAAAGTATAACATGATTGAGTACCTTCTCCTAATAGCTTTAAGATTAAACAATGAATATCCAGGGTTAATAACTATAAGAA AATTGATTGAGGCTAATAGTACATGATGAGATT TAGGATGAAAGCAATTGGGTGGTGGTCTCAAAGTTCTTCAAAACCCATCTAAAGT AGCAAAGAGGCAGATAAGCAGCTTAGCTTATAA CTGTCAGCCACTGTTGCAATATGTATGGCATTGGAATTATGCTCTTGTCAATATTTGAGTTAACCTTCGAAGCCGACTTGAGTGGAAAGTTAACCTCAATTACATGATCTTAAATATCATCATT TTATTGTCATTCTGCAACATTCTATCCGTAGTACTCTCCATTACATCTTGGACTGGGT CACCAAATAGTACCGAATGCTTGCTGATCTGATGATCGGGCATGTGATGACCTTGACATGACTGCTTGGATCGACCTTATATATACATTCTTGCAACTGATTAAATTGAGTTGATCATATGAGTAAAATGAAACCACGTTAACCCAGGCATCGAGTTACATCGAGTACAAAGAGAAAGACATT ATATATATATGTACACACACACACACACACACAGAGGCAGGCTTGCATTGGTCCACATTGGGACTCCCACTTTGGCGGCAGCTAGGGCCA GATAGTTATTGTTGAAATAGTGAGCCAATTAAACCCCTAATCATGAAATATATATATATATA GCTAGAAGTGTAGGTCAACAAATTAAAAATAGAT AAAAGAGAATTGTTAACACTTAATACCACAGGTTAGTTAACAGTTTATGAGGATGAATTATGTTGGTACAAATGGATATAGTACCAAACAATAACTAGTAA	pMdGA2ox is the promoter taken from the GA2 oxidase gene from <i>M. domestica</i> . The promoter is the 1500bp region upstream of the GA2ox gene and contains a gibberellin responsive element. There are 17 MdGA2ox genes. This promoter has been specifically taken from MdGA2ox6, as it has been shown to have the biggest difference in expression between pre- and post-harvest.	Chr09:36,563,197-36,564,697 (+), Apple genome GDDH13 v1.1 [65]

Promoter	Sequence	Description	Source/Part ID
p35S	GGAGGTATTCCAATCCCACAAAAATCTGAGCTTA ACAGCACAGTGCTCCTCTCAGAGCAGAATCGGG TATTCAACACCCTCATATCAACTACTACGTTGTG TATAACGGTCCACATGCCGTATATACGATGACT GGGGTTGTACAAAGCGGCAACAAACGGCGTTCC CGGAGTTGCACACAAGAAATTGCCACTATTACA GAGGCAAGAGCAGCAGCTGACGCGTACACAACAA GTCAGCAAACAGACAGGTTGAACCTCATCCCCAA AGGAGAACGCTCAACTCAAGCCCCAAGAGCTTGCT AAGGCCCTAACAAAGCCCACCAAAGCAAAAGCCC ACTGGCTCACGCTAGGAACCAAAAGGCCAGCAG TGATCCAGCCCCAAAGAGATCTCCTTGCCCCG GAGATTACAATGGACGATTTCTCTATCTTACG ATCTAGGAAGGAAGTTCGAAGGTGAAGGTGACGA CACTATGTTACCACTGATAATGAGAAGGTTAGC CTCTTCATTTCAAGAAAGAATGCTGACCCACAGA TGGTTAGAGAGGCCCTACGCAGCAAGTCTCATCAA GACGATCTACCCGAGTAACAATCTCAGGAGATC AAATACCTCCCAAGAAGGTTAAAGATGCACTCA AAAGATTCAAGGACTAATTGCATCAAGAACACAGA GAAAGACATATTCCTCAAGATCAGAAGTACTATT CCAGTATGGACGATTCAAGGTTGCTTCATAAAC CAAGGCAAGTAATAGAGATTGGAGTCTCTAAAAAA GGTAGTTCTACTGAATCTAAGGCCATGCATGGA GTCTAAGATTCAAATCGAGGATCTAACAGAACTC GCCGTCAAGACTGGCGAACAGTTCTACAGAGTC TTTACGACTCAATGACAAGAAAGAAAATCTCGT CAACATGGTGGAGCACGACACTCTGGTCTACTCC AAAAATGTCAAAGATACAGTCTCAGAAGATCAA GGGCTATTGAGACTTTCAACAAAGGATAATTTC GGGAAACCTCCTCGGATTCCATTGCCAGCTATC TGTCACTTCATCGAAAGGACAGTAGAAAAGGAAG GTGGCTCCTACAAATGCCATATTGCGATAAAGG AAAGGCTATCATTCAAGATCTCTGCGACAGT GGTCCCAAAGATGGACCCCCACCCACGAGGAGCA TCGTGGAAAAAGAAGAGGTTCCAACCACGCTAC AAAGCAAGTGGATTGATGTGACATCTCACTGAC GTAAGGGATGACGACAATCCCACTATCCTTCGC AAGACCCCTCCTCTATATAAGGAAGTTCATTTCA TTTGGAGAGGACACGCTCGAGTATAAGAGCTCAT TTTACAAACAATTACCAACAACAAACAAACAA ACAACATTACAATTACATTACAATTATCGATAC AATG	35S promoter is a regulatory sequence from Cauliflower Mosaic Virus and has been extensively used for constitutive expression of transgenes in plants. The chosen sequence was used by the NRP-UEA iGEM team in 2014 in argobacterium-based transformation of <i>N. benthamiana</i> . It is compatible with Golden Braid 3.0 genomic assembly method as it is free from internal BsaI and BpiI restriction sites.	BBa_K1467101 [2]
pMin35S-1	GCAAGACCCCTCCTCTATATAAGGAAGTTCATTT CATTGGAGAGG	Fragment of the 35S core promoter that has very low to zero expression activity of transgenes in plants. Insertion of upstream enhancers has shown to increase transcriptional activity.	BBa_K5223011 [2]

6.2 Kozak Sequences

Kozak sequences are eukaryotic regions upstream of the CDS where the ribosome binds, functionally analogous to prokaryotic ribosome-binding sites. These sequences are regions directly upstream of *Arabidopsis* genes that have been shown to affect translational efficiency. Kim et al. [31] quantified the efficiency of various sequences using a GFP reporter construct, and the most optimal sequences were selected.

Table 2: List of Kozak sequences with corresponding loci and sources.

Protein	Sequence	Locus	Source
VP16	ATTATTACATCAAAACAAAAAA	AT1G58420	Kim et al. [31]
TetR	AACACTAAAAGTAGAAGAAAAA	AT1G35720	Kim et al. [31]
Gal4	CGTTCTTCCCACACAAAAAAA	AT5G44520	Kim et al. [31]
VP16/GAL4	CTCAGAAAGATAAGATCAGCC	AT5G45900	Kim et al. [31]
LexA	CATTTTCATTTCATAAAAC	AT5G45900	Kim et al. [31]
ADH1/2a/PDC	CACAAAGAGTAAAGAAGAAC	AT1G67090	Kim et al. [31]

6.3 Protein Coding Sequences (CDS)

Sources are listed in the order of the part sequence, with components separated by ";". Start and stop codons are highlighted in bold. Many parts were derived from bacterial or yeast genes and have been codon-optimised for plant expression, except SRDX, PEST, and LexA, which already had plant-compatible sequences. Codon optimisation was performed using the NovoPro Labs codon optimisation tool [42] or, if not specified, by an in-house R script (see Appendix B) implementing *Arabidopsis thaliana* codon usage preferences as described by Sahoo, Das & Rakshit [47].

Table 3: List of proteins with corresponding sequences, descriptions, and sources.

Part	Sequence	Description	Source/Part ID
RR1234L- VP16	ATGAAGGGAGGAGGACTCGAGATTAGAGCTGCTTCC <u>CAGAAGAACACAGCTCTCAGAACAGAGTTGCTG</u> <u>AGCTCAGACAAAGAGTTCAAAGACTCAGAACATTGTT</u> <u>TCTCAATACGAGACAAGATAACGGACCCTCAGTACAGC</u> <u>ACCTCCAACCGATGTAAGCCTGGCGATGAGCTCCATT</u> <u>TGGATGGAGAAGATGTTGCAATGGCTACGCAGATGCC</u> <u>CTTGATGATTTGACCTCGATATGTTGGAGATGGCGA</u> <u>TTCCGCTGGTCCAGGTTCACTCCTCACGACTCTGCTC</u> <u>CTTACGGCGCACTTGATACTGCAGATTCGAGTTCGAG</u> <u>CAAATGTTCACTGATGCCCTCGGCATTGATGAATACGG</u> TGGTTAG	Codon optimised RR1234L is the basic half of the split coiled-coil dimerization motif, needed for VP16-GAL4 fusion. VP16 is a widely used strong activation domain that efficiently recruits eukaryotic transcriptional machinery and has been shown to function in plants. Codon optimised using NovoPro.	RR1234L [40], VP16 (BBa_K3242005)

Part	Sequence	Description	Source/Part ID
TetR-Linker-SRDX-PEST	ATGGCTAGACTCAACAGAGAGTCTGTTATTGATGCTGC TCTCGAGCTCCTCAACGAGACAGGAATTGATGGACTCA CAACAAGAAAAGCTCGCTCAAAAGCTCGGAATTGAGCAA CCAACACTCTACTGGCACGTTAAGAACAAAGAGAGCTCT CCTCGATGCTCTCGCTGTTGAGATTCTCGCTAGACACC ACGATTACTCTCTCCCAGCTGCTGGAGAGCTTGGCAA TCTTCCTCAGAAACAACGCTATGTCTTCAGAACAGAC TCTCCTCAGATACAGAGATGGAGCTAAGGTTCACCTCG GAACAAAGACCAGATGAGAACAAATACGATAACAGTTGAG ACACAACTCAGATTCAATGACAGAGAACGGATTCTCTCT CAGAGATGGACTCTACGCTATTCCTGCTGTTCTCACT TCACACTCGGAGCTGTTCTCGAGCAACAAGAGCACACA GCTGCTCTCACAGATAGACCAGCTGCTCCAGATGAGAA CCTCCCACCACTCCTCAGAGAGGCTCTCCAAATTATGG ATTCTGATGATGGAGAGCAAGCTTCCTCACGGACTC GAGTCTCTCATTAGAGGATTCGAGGTTCAACTCACAGC TCTCCTCCAAATTGTTGGAGGAGATAAGCTCATTATTC CATTCTGC GGATCTGGATTGGACCTTGATCTTGAATTG AGACTTGGTTTGCATCGGGTCCGGCAGCCACGGTTT TCCACCTGAGGTCGAGGAACAGGCCAGGAACCCCTGC CCATGTCCCTGCGCTCAGGAGTCTGGTATGGACAGACAT CCCGCTGCATGTGCAAGCGCCAGAATTACGTGTAG	<p>TetR is a transgenic bacterial repressor that binds and inhibits the TetO operator. It is widely used in synthetic biology as a NOT gate and has been demonstrated to function in plant systems. Codon optimised. The Gly-Ser-Gly (GSG) linker has been demonstrated to link protein domains without interfering with function or folding. Codon optimised.</p> <p>SRDX is a plant repression domain derived from plant transcriptional repressors to silent gene expression.</p> <p>PEST degradation tags are used in plant synthetic biology to accelerate protein turnover. An additional stop codon has been added.</p>	TetR from UniProt P0ACT4, GSG linker [69], SRDX and PEST [20, 49], Genbank JQ437371.1

Part	Sequence	Description	Source/Part ID
GAL4-EE1234L	ATGAAGTTGCTCTCTAGCATAGAACAGCTTGCATAT CTGTCGACTCAAGAAGTTGAAGTGTCCAAGAAAAAGC CTAAATGCGCAAAGTGCCTTAAGAATAATTGGGAATGC AGGTACTCACAAAGACTAAAAGAAGCCATTGACACG AGCTCATTTGACTGAGGTCGAAAGTCGTTGGAGAGAT TAGAACAGCTTTTGTTGATCTCCCTCGTGAAGAT CTTGACATGATCTTGAAGATGGACTCTTACAAGACAT CAAAGCACTGCTCACAGGTCTGTTGTCCAGGACAACG TTAACAAAGGACGCAAGTGAACAGACTGCTTCAGTC GAAACAGATATGCCATTGACTTTGCGTCAGCATAGGAT ATCCCGACGTCTTCTTCTGAGGAAAGTAGCAATAAAG GGCAACGACAGTTGACTGTTCTCGAGATTGAGGCTGCT <u>TTCCTCGAGCAAGAGAACACAGCTCTCGAGACAGAGGT</u> <u>TGCTGAGCTCGAGCAAGAGGTTCAAAGACTCGAGAACAA</u> <u>TTGTTTCTCAATACGAGACAAGATA CGGACCACTCGGA</u> <u>GGAGGAAAGTAG</u>	GAL4 is widely used in synthetic biology alongside VP16 as a split transcription factor and has been demonstrated to work in plants. Codon optimised using NovoPro. EE1234L constitutes the acidic half of the split coiled-coil dimerization motif, needed for GAL4/VP16 association. An additional stop codon has been added. Codon optimised.	GAL4 from BBa_K3242004, EE1234L [40]
GAL4/VP16 fusion	ATGAAGCTCCTGTCCTCCATCGAGCAGGCCCTGCACAT CTGCCGCTCAAGAAGCTCAAGTGTCTGAAGAACAACTGGGAGGT CGCTACTCTCCCCAAACCAAGCGCTCCCCGCTGACCCG CGCCCACCTCACCGAAGTGGAGTCCCGCCTGGAGCGCC TGGAGCAGCTTCCCTCTGATCTCCCTCGAGAGGAC CTCGACATGATCTGAAAATGGACTCCCTCCAGGACAT CAAAGCCCTGCTACCGGCCTTCTCGTCCAGGACAACG TGAACAAAGACGCCGTACCGACCAGCCTGGCCTCCGTG GAGACCGACATGCCCTCACCGCAGCAGCAGCGCAT CAGCCGACCTCCCTCGGAGGAGAGCAGCAACAAGG GCCAGCGCCAGTTGACCGTCTCGACGGCCCCCGACC GACGTCAGCCTGGGGACGAGCTCCACTTAGACGGCGA GGACGTGGCGATGGCGATGCCGACGCCAGCGCTAGACGATT TCGATCTGGACATGTTGGGGACGGGGATTCCCCGGGG CCGGGATTTACCCCCCACGACTCCGCCCCCTACGGCGC TCTGGATA CGGCCGACTTCGAGTTGAGCAGATGTTA CCGATGCCCTTGAATTGACCGAGTACGGTGGGTAG	A hybrid transcription factor used by UGA iGEM team in 2019 for agrobacterium-based transformation of <i>N. benthamiana</i> .	BBa_K3242006

Part	Sequence	Description	Source/Part ID
LexA- PEST	ATGAAAGCGTTAACGCCAGGCAACAAGAGGTGTTGA TCTCATCCGTGATCACATCAGCCAGACAGGTATGCCG CGACCGTGCGGAAATCGCGAGCGTTGGGTTCCGT TCCCCAAACCGCGCTGAAGAACATCTGAAGGCCTGGC ACGCAAAGCGTTATTGAAATTGTTCCGGCGCATCAC GCGGGATTCTGTCGAGGAGAAGAGGAAGGGTTG CCGCTGGTAGGTCGTGTCGCTCGGGTCCGGCAG CCACGGTTTCCACCTGAGGTGAGGAACAGGCGCAG GAACCCCTGCCATGTCCTGCCCTCAGGAGTCTGGTATG GACAGACATCCCCCTGCATGTGCAAGGCCAGAATTAA CGTGTAA	The Addgene-derived LexA module encodes a bacterial DNA-binding protein (LexA) that recognizes and binds LexO operator sites in plant systems. This part is derived from the GoldenBraid plant synthetic biology framework. PEST tag included. An additional stop codon has been added.	Addgene #68184 [49], PEST from Genbank JQ437371.1
ADH1- F2A-PDC- PEST	ATGTCTAATACTGCTGGTCAGGTCATACGCTGCAGAGC TGCTGTAGCTGGAAAGCAGGGAAAGCCACTGGTGATTG AAGAAGTTGAGGTGGCACCACCAAGCAAATGAAGTT CGCATAAAGATCCTTTTACATCTTGTCGCCACACTGA TGTCTACTTCTGGAAAGCCAAGGGACAAAACCCTTAT TTCCCTAGAATTATGGTCATGAGGCAGGGAGGTG GAGAGTGTGGTGAGGGCGTGACGGATCTGAAAGCCGG CGATCATGTCCTGCCGGTGTACAGGGGAATGCAAGG ACTGCGCTCACTGCAAATCAGAAGAGGAAACATGTGT GACCTCCTCAGGATAAAACACTGACAGGGAGTGATGCT CAGTGTGGAAAATCAAGATTTCATCAAAGGCAAGC CTATCTACCATTGTTGGACTTCCACCTTCAGCGAG TACACTGTTGTCACGTTGGCTGCCCTGCCAAGATCAA TCCCTCGGCGCCTCTAGACAAAGTCTGTCCTCAGTT GTGGAATCTCCACAGGTCTGGAGCTACTCTAAATGTT GCAAAACCAAAAAAGGGATCAACCGTGGCTTGGG ATTGGGAGCTGTAGGCCTTGCAGCTGCTGAAGGAGCCA GGTTGTCTGGCGCTTCAAGAATTATCGGTGTTGATTG CATTCCGACAGATTGAAAGAACAAAAAGTTGGCGT GACAGAATTCTGTAACCCAAAAGCCACGAAAAACAG TTCAAGAGGTGATTGCTGAGTTGACGAATCGAGGAGTG GACAGAAGCATTGAATGTACAGGAAGCACTGAAGCCAT GATATCTGCATTTGAATGTGTCATGATGGTTGGGTG TTGCTGTTCTGTTGGAGTACCAACACAAAGATGCCGT TTCAAGACGCATCCGGTTAACCTTCTGAATGAGAGGAC TCTCAAGGGTACATTCTCGAAACTACAAGACTCGAA CGGACATTCCCTCTGCTGGAGAAGTACATGAACAAAG GAACCTGGAGCTAGAGAAATTCAACCAAGGACATTGAGT GTTCTCAGAAATCAACAAGGACATTGAGTACATGCTTA AAGGGGAAGGTCTCGTTGCATAATCCGATGGAGGAA TGACAACTCCTCAACTTCGATCTCCTCAAGCTCGCTGG AGATGTTGAGTCTAACCCAGGACCA		

Part	Sequence	Description	Source/Part ID
	ATGGACACCAAAATTGGTTCGCTTGACGTCTGCAAGCC TACGTGCACCGGGCGTCGGCAGCCTACCGAACGGCGCCG CTTAGCAATCAAAGCTCTGCCCTCCCTCATCAAC TCCTCTGACGCCACTCTGGGTGGCACATCGCCCGCCG ACTTGCTCAAATCGCGTCACGGACGTGTTACTGTCC CAGGTGACTTTAACTTAACCCCTCTAGACCACCTCATT GCCGAGCCTGGGCTACCAACATCGGCTGCTGCAACGA ACTCAATGCCGGTACGCTGCTGACGGCTACGCTCGGT CGCAGGGAGTCGGGCGTGTGTTACTTCAGTGTG GGTGGGCTCAGTGTCTCAATGCTATGCCGGAGCTTA CAGTGAGAGTCTGCCATTGATTTGTATAGTTGGAGGAC CCAACTCGAATGATTACGGGACGCACAGGATTCTTCAC CACACTATTGGGTACCGGATTTAGCCAAGAGTTGAC ATGCTTCCAGACCGTCACTTGCTATCAGGCTGTGGTAA ATAATCTGGAAGATGCTCATGAAATGATTGATAACCGCA ATTCAACCGCCTTGAAAGAAAGCAAGCCTGTTATAT CAGCATAAGCTGCAACTTGGCTGGAATTGCTCATCCAA CTTTAGCCTGGATCCTGTTCCCTCTCATGTCTCCA AGATTGAGTAATCTTGGGTTAGAGGCTGCCGTGGA GGCGGCTGCAGAGTTCTTAACAAGGCAGTGAAGCCGG TTATGGTAGGGGGCCTAAACTTCGAGTTGCACATGCT GGCGATGCCCTTGTGAACTAGCAGATGCTAGTGGTTA TGCCTCGCTGTATGCCATCTGCAAAGGGCTTGTGC CAGAGCACCACCCCCATTGATTGAAACATACTGGGT GCTGTGAGCACTGCCCTTGGCCGAGATTGTGGAGTC CGCAGATGCATACTTGGTGTGGACCAGATTTCATG ACTACAGCTCTGGATACTCTCTGCTTCAAGAAA GAGAAGGCAATTGTTGTCAGCCTGATCACGTGACCAT AGCAAATGCCCTCATTTGGTTGTGTTCTCATGAAGG ATTTCCTCCGAGCTCTGCAAAGAGGCTCAAGCACAAAC AAAAGTCTCATGAGAAACTACAGCAGGATCTTGTCC CAACGGACACCCCTAAAGTCTGCACCGAAAGAACCTT TGAGGGTTAATGTTGTTCCACCATCCAGAATATG CTGTCAAGTGAAGACTGCTGTGATTGCTGAGACAGGGGA CTCATGGTTAACTGCCAGAAACTGAAATTGCCGGCTG GTTGCCGGTATGAGTCCAAATGCACTATGGATCAATT GGTTGGTCAGTGGAGCTACTCTGGGTATGCTCAAGC TGTTACTGAGAACGGTGTGATTGCTTCTCATGGCGATG GGAGTTCCAGGTGACTGTTCAAGATGTGTCACCATG ATCCGAAATGGCAGAAGAACATCATCTTGTGATAAA CAACGGCGGATAACACAATTGAGGTGGAGATCCATGACG GACCATAACATGTGATCAAGAAACTGGAACACTACTGGA CTAGTTGATGCCATCCACAACGGGGAGGGCAAGTGCTG GACAACCAAGGTCGTTGCGAAGAGGAGCTGATTGAAG CGATTGAGACTGCAACAGGGCGAAGAAGGAGTAGCTG TGCTTCATTGAGGTGATAGCCCACAAGGACGATACCAAG CAAAGAGTTGCTTGAGTGGGGTCTAGGGTTCTGCTG CCAACAGCCGCCACCCAGCCCTCAG		

Part	Sequence	Description	Source/Part ID
	TCGGGGTCCGGCAGCCACGGTTTCCACCTGAGGTCGA GGAACAGGCAGGCAACCTGCCATGCTCGCTCGCTC AGGAGTCTGGTATGGACAGACATCCCGCTGCATGTGCA AGCGCCAGAATTAAACGTGTAA	ADH1 protein sequence from Granny Smith from ATG to Stop codon. F2A linker for polycistronic expression. PDC sequence from <i>M. domestica</i> . PEST degradation tag included. An additional stop codon has been added.	ADH1 from UniProt P48977, F2A [8], PDC from KEGG 103425939
kan ^R	ATGAGCCATATTCAACGGAAACGTCTTGCTCGAGGCC GCGATTAATTCCAACATGGATGCTGATTTATATGGGT ATAAAATGGGCTCGCGATAATGTCGGGCAATCAGGTGCG ACAATCTATCGATTGTATGGAAAGGCCGATGCGCCAGA GTTGTTCTGAAACATGGCAAAGGTAGCGTTGCCAATG ATGTTACAGATGAGATGGTCAGACTAAACTGGCTGACG GAATTATGCCTTCCGACCACATCAAGCATTATCCG TACTCCTGATGATGCATGGTTACTCACCACTGCGATCC CCGGAAAACAGCATTCCAGGTATTAGAAGAATATCCT GATTCAAGGTAAAAATTGTTGATGCGCTGGCAGTGT CCTGCGCCGGTTGCATTGATTCCTGTTGTAATTGTC CTTTAAACAGCGATCGGTATTCGTCTGCTCAGGG CAATCACGAATGAATAACGGTTGGTTGATGCGAGTGA TTTGATGACGAGCGTAATGGCTGGCCTGTTGAACAAG TCTGAAAGAAAATGCATAAGCTTTGCCATTCTACCG GATTCAAGTCGTCACTCATGGTATTTCTCACTTGATAA CCTTATTTTGACGAGGGAAATTAATAGGTTGATTG ATGTTGGACGAGTCGGAATCGCAGACCGATACCAGGAT CTTGCATCCTATGGAACTGCCTCGGTGAGTTTCTCC TTCATTACAGAAACGGTTTTCAAAAATATGGTATTG ATAATCCTGATATGAATAAAATTGCAAGTTGATTCATTGATG CTCGATGAGTTTCTAA	Kanamycin resistance gene for selection of the construct during Golden braid assembly.	BBa_K3447004

Part	Sequence	Description	Source/Part ID
smrR	ATGCGCTCACGCAACTGGTCAGAACCTTGACCGAACG CAGCGGTGTAACGGCGCAGTGGCGTTTCATGGCTT GTTATGACTGTTTTGGGTACAGTCTATGCCTCGG GCATCCAAGCAGCAAGCGCGTACGCCGTGGTCGATG TTTGATGTTATGGAGCAGCAACGATGTTACGCAGCAGG GCAGTCGCCCTAAAACAAAGTTAAACATCATGAGGGAA GCGGTGATGCCGAAGTATCGACTCAACTATCAGAGGT AGTTGGCGTCATCGAGGCCATCTGAACCGACGTTGC TGGCCGTACATTGATCGGCTCCGCAGTGGATGGCGC CTGAAGCCACACAGCGATAATTGATTTGCTGGTTACGGT GACCGTAAGGCTTGATGAAACAACGCGGAGCTTTGA TCAACGACCTTGGAAACTTCGGCTCCCTGGAGAG AGCGAGATTCTCCCGCCTGAGAAGTCACCATTGTTG GCACGACGACATCATTCCGTGGCGTTATCCAGCTAAC GCGAAGTCAATTGGAGAATGGCAGCGCAATGACATT CTTGCAGGTATCTCGAGCCAGCAGTCGACATTGA TCTGGCTATCTTGCTGACAAAAGCAAGAGAACATAGCG TTGCCCTGGTAGGTCCAGCGCGGAGGAACCTTTGAT CCGGTTCTGAACAGGATCTATTGAGGCCTAAATGA AACCTTAACGCTATGAACTCGCCGCCGACTGGGCTG GCGATGAGCGAAATGTAAGTGCCTACGTTGCCCCGATT TGGTACAGCGCAGTAACCGGAAAATCGCGCCGAAGGA TGTGCGCTGCCACTGGCAATGGAGCGCCCTGCCGCC AGTATCAGCCCGTCATACTTGAAGCTAGACAGGCTTAT CTTGGACAAGAAGAAGATCGCTTGGCCTCGCGCAGA TCAGTTGAAAGAATTGTCCTTACGTAAAAGGCGAGA TCACCAAGGTAGTCGGCAAATAA	Streptomycin resistance gene for selection of constructs during Golden Braid assembly.	BBa_K4818060

6.4 Terminators

Table 4: List of terminators with corresponding sequences, descriptions, and sources.

Name	Sequence	Description	Source/Part ID
tNOS	CGTTCAAACATTGGCAATAAAGTTCTTAAGATTGAAT CCTGTTGCCGGTCTTGCATGATTATCATATAATTCTG TTGAATTACGTTAACGATGTAATAATTAAACATGTAATGC ATGACGTTATTATGAGATGGGTTTTATGATTAGAGTC CCGCAATTATACATTAAACGCGATAGAAAACAAAATA TAGCGCGAAACTAGGATAAATTATCGCGCGCGGTGTCA TCTATGTTACTAGATCGGG	Stands for nopaline synthase terminator. Derived from Agrobacterium tumefaciens and it is a commonly used terminator for expression system in plants.	BBa_K1537031

Name	Sequence	Description	Source/Part ID
tOCS	CTGCTTTAATGAGATATGCGAGACGCCTATGATCGCATG ATATTGCTTCATTCTGTGTCACGTTGTAACAAAC CTGAGCATGTAGCTCAGATCCTTACCGCCGGTTTCGG TTCATTCTAATGAATAATATCACCGTTACTATCGTATT TTATGAATAATATTCTCCGTTCAATTACTGATTGTACC CTACTACTTATATGTACAATATTAAAATGAAAACAATAT ATTGTGCTGAATAGTTTATAGCGACATCTATGATAGAG CGCCACAATAACAAACAATTGCGTTTATTATTACAAAT CCAATTAAAAAGCGGCAGAACCGGTCAAACCTAA AGACTGATTACATAATCTTATTCAAATTCAAAAGGCC CCAGGGCTAGTATCTACGACACACCGAGCGGCGAAGTA ATAACGTTCACTGAAGGAACTCCGGTCCCCGCCGGCG CGCATGGTGAGATTCTGAGTTGAGTATTGGCCGTC CGCTTACCGAAAGTTACGGCACCAATTCAACCCGGTCC AGCACGGCGGCCGGTAACCGACTTGCTGCCCCGAGAAT TATGCAGCATTTTTTGGTGTATGTGGGCCCAAATGAA GTGCAGGTCAAACCTTGACAGTGACGACAAATCGTGGG CGGGTCCAGGGCGAATTTCGCACAAATGTCGAGGCTC AGCA	Stands for octopine synthase terminator. It is derived from <i>Agrobacterium tumefaciens</i> . Like NOS, it is also commonly used for transgenic plants.	Addgene #71268
t35S	CTAGAGTCCGCAAAAATCACCAAGTCTCTCTACAAATC TATCTCTCTATTCTCCAGAATAATGTTGAGTAG TTCCCAAGATAAGGAAATTAGGGTTCTTATAGGGTTTCGC TCATGTGTTGAGCATATAAGAAACCTTAGTATGTATT GTATTGTTAAATACTTCTATCAATAAAATTCTAATT CTAAACCAAAATCCAGTGACC	Derived from Cauliflower Mosaic Virus (CaMV). Also deemed to be frequently used in transgenic plants.	BBa_K1159307
tRBCS E9	CAGGCCTCCCAGCTTCGTCGTATCATCGTTTCGACA ACGTTCGTCAAGTCAATGCATCAGTTCATGCCAC CACCAAGATCCTACTAAGTTGAGTATTATGGCATTGGA AAAGCTTTCTCTATCATTGTTCTGCTTGTAAATT ACTGTGTTCTTCAGTTTGTGACATCAAATG CAAATGGATGGATAAGAGTTAATAATGATATGGCCTT TTGTTCAATTCTCAAATTATTATTATCTGTTTTTACT TTAATGGTTGAATTAAAGTAAGAAAGGAACAAACAGTCTT TGATATTAAAGGTGCAATGTTAGACATATAAAACAGTCTT TCACCTCTCTGGTATGTCTGAATTGGTTGTTCT TCACTTATCTGTGTAATCAAGTTACTATGAGTCTATGA TCAAGTAATTATGCAATCAAGTTAAGTACAGTATAAGGCT TT	Stands for ribulose-1,5-bisphosphate carboxylase small subunit (rbcS) gene, clone E9 terminator. Derived from <i>Pisum sativum</i> (peas). Extracted from Plant expression vector pZG159 at position 1882–2176 base pairs.	GenBank MW026669.1
tHSP 18.2	TATGAAGATGAAGATGAAATATTGGTGTGCAAATAAA AAGCTTGTGCTTAAGTTGTTTTCTGGCTTG TTGTGTTATGAATTGTTGGCTTTCTAATATTAAATGA ATGTAAGATCTCATTATAATGAATAAACAAATGTTCTA TAATCCATTGTGAATGTTGTTGGATCTCTGCAGC ATATAACTACTGTATGTGCTATGGTATGGACTATGGAAT ATGATTAAAGATAAG	Stands for heat shock protein 18.2 terminator. Derived from <i>Arabidopsis thaliana</i> .	Addgene #68186
tMAS	CTTGGACTCCCATGTTGGCAAAGGCAACCAAACAA TGAATGATCCGCTCTGCATATGGGGCGGTTGAGTATT TCAACTGCCATTGGGCTGAATTGTAGACATGCTCCTGT CAGAAATTCCGTATCTACTCAATATTCAAGTAATCTCG GCCAATATCCTAAATGTGCGTGGCTTATCTGTCTTGT ATTGTTCATCAATTGATGTAACGTTGCTTTCTTATG AATTTCAAATAATTAT	Stands for mannopine synthase terminator. Derived from <i>Agrobacterium tumefaciens</i> .	Addgene #153381

6.5 Spacers

Spacer sequences are placed between terminators and the promoter of subsequent genes that produce a strong secondary structure to prevent transcriptional readthrough. These sequences are based on the 10 helical secondary structure that forms in the 5' external transcribed spacer of yeast pre-rRNA.

Table 5: List of spacers with corresponding sequences, descriptions, and sources.

Name	Sequence	Description	Source
H1	TGC GAA AGC AGT TGA AGA GAC AAG TCG AAA AGA GAT TGG AAA CGA ATT CGA GTAGG CTT GTC GTT ATG TTT TGTA	Between VP16 terminator and pGA2ox	Chen et al. [10]
H2	GTC AAC AGT GGAGAGAGTCGCTAGGTGATCGTCAGATCTGC CTAGTCTCTATAACAGCGTGTAAATTGAC	Between TetR-SRDX-PEST terminator and p35S	Chen et al. [10]
H3	ATGGGTTGATGCGTATTGAGAGATACAATTTGGGAAGAAAAT TCCCAGAGTGTGTTCTTTGCGTTAACCTG	Between Gal4 terminator and UAS	Chen et al. [10]
H6	GGGGAAATGCCCTGTTGAATAGCCGGTCGCAAGACTGTGATT CTTCAAGGTACCTCC	Between Gal4 terminator and low affinity UAS	Chen et al. [10]
H7	AATCAGCGATATCAAACGTACCATTCCGCTGAAACACCGGG GTACTGTTGGTGGAACCTGATT	Between LexA-SRDX terminator and high affinity UAS	Chen et al. [10]
H10	GAAGAGGGAATAGGTGGAAAAAAAAAGATTTCGGTTTC TTTCTTTTACTGCTTGTGCTTCTTC	After the ADH1-2a-PDC cassette	Chen et al. [10]

6.6 Regulatory Elements

Regulatory elements are DNA sequences that control gene expression by serving as binding sites for transcriptional regulators. These include upstream activating sequences (UAS) for GAL4 binding, SOS boxes for LexA binding, and tetracycline operators (TetO) for TetR binding.

Table 6: List of regulator elements with corresponding sequences, descriptions, and sources.

Name	Sequence	Description	Source
UAS (high affinity)	CGGTCCACTGTGTGCCG	UAS site of GAL3 gene	[13]
UAS (low affinity)	AGGAAGACTCTCCTCCG	The fourth UAS repeats of GAL10 gene	[13]
SOS box	CTGTATATATATACAG	Originated from Escherichia coli that LexA recognises	[55]
TetO	TCTCTATCACTGATAGGGA	Tetracycline operator originating from transposon Tn10 in Escherichia coli	[46]

7 Responsible Research and Innovation

7.1 Biocontainment

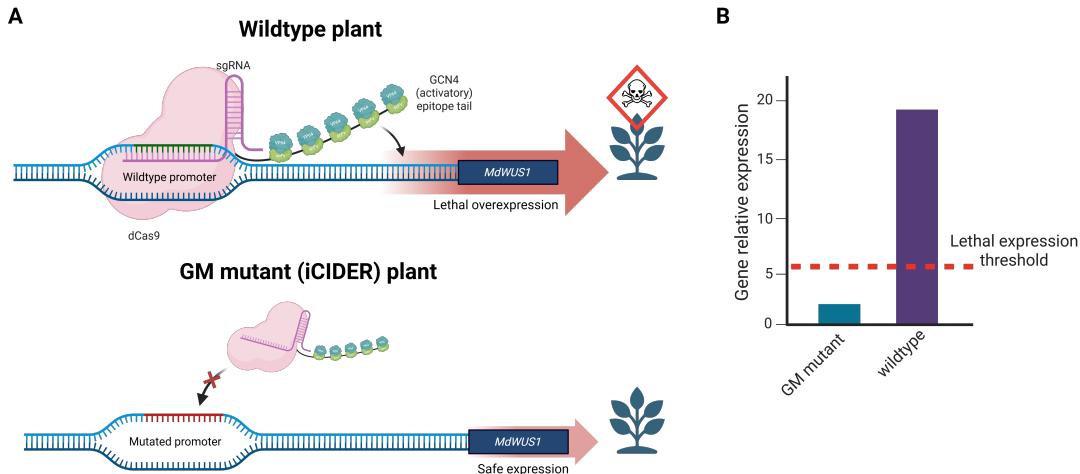


Figure 6: Graphical figure of proposed engineered genetic incompatibility mechanism. (A) dCas9 is used alongside a GCN4 epitope tail fused to VP64 activatory domains to promote lethal overexpression of tightly regulated genes like *MdWUS1*. (B) Representative data on relative gene expression showing lethal overexpression of genes and death in wildtype but not our genetically modified iCIDER plant. dCas9: dead Cas9; sgRNA: single guide RNA; GCN4: General Control Nondepressible 4; *MdWUS1*: *Malus domestica* *WUSCHEL* 1.

Biocontainment is a critical consideration for iCIDER, as it is essential to prevent the genetic spread of genetically engineered apples into the environment. There are two main concerns: out-crossing, where iCIDER genes spread into wild apple populations, and in-crossing, where wild apple pollen fertilizes iCIDER trees and could dilute our introduced traits.

Designing effective biocontainment strategies first requires an understanding of apple reproduction and commercial practices. Fruit production requires male pollen to fertilise the female stigma. Most apples promote heterozygosity in the population by exhibiting self-incompatibility, meaning they cannot fertilise themselves [9]. However, this poses a challenge for us in both the dilution of our introduced genes and the potential risk of out-crossing which could spread modified genes into the environment.

While most apple cultivars are self-incompatible, a potential work around is to use a subset of *M. domestica* cultivars that are self-compatible, such as the Winston cultivar [53, 52]. Alternatively, inhibiting gametophytic incompatibility, by deleting pollen tube degrading S-locus genes could be used to promote self-compatibility [43]. Using self-compatible cultivars allows fruit production without relying on pollen from neighbouring trees, enabling us to employ other strategies to isolate our plants and reduce the risk of out-crossing and in-crossing.

To prevent out-crossing, physical barriers could be used for biocontainment; previous studies have shown that spatial separation between apple orchards with perimeter nets could reduce cross-pollination to 1% at 8 m and 0.1% at 100 m [50].

Alternative genetic strategies, like engineered genetic incompatibility for hybrid lethality, could also be used to help prevent out-crossing from our plants. Specifically, the use of programmable transcriptional activators (PTAs) for the overexpression of tightly regulated genes to drive lethality only in wild-type plants [72]. Previously shown in a range of organisms [37, 38], PTAs are made of dead Cas9 (dCas9) fused to epitope tails with binding sites for activator domains like VP64 [72], as shown in Figure 6. By targeting PTAs to wild-type promoters, overexpression of tightly regulated endogenous genes can be driven leading to lethality in wild-type plants. On the other hand, silent mutations in the promoter sequence of our GM plants can prevent recognition by PTAs and subsequent overexpression. In apples, previous studies showed that overexpressing MdWUS-1 increased oxidative stress and led to cell death, perhaps presenting a potential candidate gene for PTA targeting [34]. While promising, in some cases, candidate genes in other plants did not lead to hybrid lethality, highlighting that stringent selection of genes is crucial for successful implementation.

To prevent our modifications from being diluted over multiple generations, clonal propagation through grafting or other vegetative techniques [12] could be employed. This would help ensure that progeny are genetically identical and can reliably produce fruit every year, whilst maintaining their genomic modifications.

Taken together, cultivating self-compatible cultivars within netted perimeter fences, engineering genetic incompatibility and clonal propagation provide a set of robust strategies that ensure reliable fruit production while preventing unintended gene flow into or from surrounding apple populations.

7.2 Compliance and Regulation

Here, our project confronts a significant regulatory limitation. If these apples were submitted as a genetically modified (GM) food intended for direct human consumption in the UK, approval would be highly unlikely. This is because GM foods are subject to additional regulatory barriers under the UK Food Standards Agency [25], and the proposed product fails to meet several key criteria, as listed below.

Nutritional disadvantage: The diversion of endogenous sugars into ethanol reduces the nutritional value of the fruit, while ethanol itself provides no nutritional benefit.

Toxicological concerns: Alcohol is explicitly classified by the World Health Organization as a toxic, psychoactive, dependence-producing carcinogen [62], placing alcohol-apples at a substantial disadvantage during safety assessment.

Consumer expectation mismatch: Another requirement for GM food approval is that products must not mislead consumers. Apples are widely consumed across all demographics, including children, and are not expected to contain psychoactive compounds. This fundamental mismatch between product identity and consumer expectation would make regulatory approval extremely challenging.

However, iCIDER is not an innovation limited to the production of alcoholic apples. In principle, iCIDER could be used to generate apples with enhanced nutritional value, or to repurpose apples as plant-based bioreactors, where the target product is extracted post-harvest rather than consumed directly. From the perspective of apples functioning as bioreactors, deployment would most likely fall under Directive 2001/18/EC (“Deliberate Release”), which governs the intentional introduction of GMOs into the environment where no specific containment measures are used to fully prevent their spread [15]. While a range of biocontainment strategies could be implemented to minimise gene flow, it is currently unclear whether such measures would be sufficient to qualify the system under Directive 2009/41/EC (“Contained Use”), which requires defined physical, chemical, or biological barriers to limit environmental exposure [16].

Consumer safety is our highest priority. If approved, iCIDER-derived alcoholic apples would feature clear labelling indicating both their GM status and alcohol content, ensuring informed choice. Placement in retail outlets would align with existing alcoholic beverages to reduce accidental consumption, particularly by minors [25]. Communicating these risks responsibly through outreach and education initiatives will be critical for public trust and adoption.

7.3 Stakeholders

Beyond direct consumers, our project considers farmers and growers. Although apple farmers are experienced in cultivation cycles, they may lack familiarity with synthetic biology techniques. The iCIDER platform is therefore designed for ease of use, requiring minimal on-field monitoring or technical intervention. Its modular architecture also ensures that trained synthetic biologists can understand and troubleshoot the system, supporting transparency and training.

References

- [1] Chiara Agliassa and Massimo E. Maffei. Origanum vulgare terpenoids induce oxidative stress and reduce the feeding activity of spodoptera littoralis. *International Journal of Molecular Sciences*, 19(9):2805, September 2018. ISSN 1422-0067. doi: 10.3390/ijms19092805. URL <http://dx.doi.org/10.3390/ijms19092805>.
- [2] Stephanie C. Amack and Mauricio S. Antunes. Camv35s promoter - a plant biology and biotechnology workhorse in the era of synthetic biology. *Current Plant Biology*, 24:100179, December 2020. ISSN 2214-6628. doi: 10.1016/j.cpb.2020.100179. URL <http://dx.doi.org/10.1016/j.cpb.2020.100179>.
- [3] Jian-Ping An, Xiao-Fei Wang, Yuan-Yuan Li, Lai-Qing Song, Ling-Ling Zhao, Chun-Xiang You, and Yu-Jin Hao. Ein3-like1, myb1, and ethylene response factor3 act in a regulatory loop that synergistically modulates ethylene biosynthesis and anthocyanin accumulation. *Plant Physiology*, 178(2):808–823, August 2018. ISSN 1532-2548. doi: 10.1104/pp.18.00068. URL <http://dx.doi.org/10.1104/pp.18.00068>.
- [4] Sylvester Anami, Elizabeth Njuguna, Griet Coussens, Stijn Aesaert, and Mieke Van Lijsebettens. Higher plant transformation: principles and molecular tools. *The International Journal of Developmental Biology*, 57(6-7-8):483–494, 2013. ISSN 0214-6282. doi: 10.1387/ijdb.130232mv. URL <http://dx.doi.org/10.1387/ijdb.130232mv>.
- [5] Mauricio S. Antunes, Kevin J. Morey, J. Jeff Smith, Kirk D. Albrecht, Tessa A. Bowen, Jeffrey K. Zdunek, Jared F. Troupe, Matthew J. Cuneo, Colleen T. Webb, Homme W. Hellinga, and June I. Medford. Programmable ligand detection system in plants through a synthetic signal transduction pathway. *PLoS ONE*, 6(1):e16292, January 2011. ISSN 1932-6203. doi: 10.1371/journal.pone.0016292. URL <http://dx.doi.org/10.1371/journal.pone.0016292>.
- [6] Mehmet Fikret BALTA, Orhan KARAKAYA, Mehmet YAMAN, Hüseyin KIRKAYA, and İzzet YAMAN. Sugar and biochemical composition of some apple cultivar grown in the middle black sea region. *Journal of Agricultural Faculty of Gaziosmanpasa University*, September 2022. ISSN 1300-2910. doi: 10.55507/gopzfd.1113864. URL <http://dx.doi.org/10.55507/gopzfd.1113864>.
- [7] Konstantina Beritza, Emma C. Watts, and Renier A. L. van der Hoorn. Improving transient protein expression in agroinfiltrated nicotiana benthamiana. *New Phytologist*, 243(3):846–850, June 2024. ISSN 1469-8137. doi: 10.1111/nph.19894. URL <http://dx.doi.org/10.1111/nph.19894>.
- [8] Stefan Burén, Cristina Ortega-Villasante, Krisztina Ötvös, Göran Samuelsson, László Bakó, and Arsenio Villarejo. Use of the foot-and-mouth disease virus 2a peptide co-expression system to study intracellular protein trafficking in arabidopsis. *PLoS ONE*, 7(12):e51973, December 2012. ISSN 1932-6203. doi: 10.1371/journal.pone.0051973. URL <http://dx.doi.org/10.1371/journal.pone.0051973>.
- [9] Radosav Cerović, Milica Fotirić Akšić, Marko Kitanović, and Mekjell Meland. Abilities of the newly introduced apple cultivars (*malus × domestica* borkh.) ‘eden’ and ‘fryd’ to promote pollen tube growth and fruit set with different combinations of pollinations. *Agronomy*, 15(4):909, April 2025. ISSN 2073-4395. doi: 10.3390/agronomy15040909. URL <http://dx.doi.org/10.3390/agronomy15040909>.
- [10] Jing Chen, Liman Zhang, and Keqiong Ye. Functional regions in the 5' external transcribed spacer of yeast pre-rrna. *RNA*, 26(7):866–877, 2020. doi: 10.1261/rna.074807.120. Epub 2020-03-25.

- [11] Yan-hui CHEN, Bin XIE, Xiu-hong AN, Ren-peng MA, De-ying ZHAO, Cun-gang CHENG, En-mao LI, Jiang-tao ZHOU, Guo-dong KANG, and Yan-zhen ZHANG. Overexpression of the apple expansin-like gene mdexlb1 accelerates the softening of fruit texture in tomato. *Journal of Integrative Agriculture*, 21(12):3578–3588, December 2022. ISSN 2095-3119. doi: 10.1016/j.jia.2022.08.030. URL <http://dx.doi.org/10.1016/j.jia.2022.08.030>.
- [12] Judit Dobránszki and Jaime A. Teixeira da Silva. Micropropagation of apple — a review. *Biotechnology Advances*, 28(4):462–488, July 2010. ISSN 0734-9750. doi: 10.1016/j.biotechadv.2010.02.008. URL <http://dx.doi.org/10.1016/j.biotechadv.2010.02.008>.
- [13] Benjamin T Donovan, Anh Huynh, David A Ball, Heta P Patel, Michael G Poirier, Daniel R Larson, Matthew L Ferguson, and Tineke L Lenstra. Live-cell imaging reveals the interplay between transcription factors, nucleosomes, and bursting. *The EMBO Journal*, 38(12), May 2019. ISSN 1460-2075. doi: 10.15252/embj.2018100809. URL <http://dx.doi.org/10.15252/embj.2018100809>.
- [14] Cawas B Engineer, Karen C Fitzsimmons, Jon J Schmuken, Stan B Dotson, and Robert G Kranz. Development and evaluation of a gal4-mediated luc/gfp/gus enhancer trap system in arabidopsis. *BMC Plant Biology*, 5(1), June 2005. ISSN 1471-2229. doi: 10.1186/1471-2229-5-9. URL <http://dx.doi.org/10.1186/1471-2229-5-9>.
- [15] European Parliament and Council of the European Union. Directive 2001/18/EC of 12 March 2001 on the deliberate release into the environment of genetically modified organisms and repealing Council Directive 90/220/EEC. Official Journal of the European Union L 106, 17.4.2001, pp. 1–39, 2001. URL https://www.legislation.gov.uk/eudr/2001/18/pdfs/eudr_20010018_adopted_en.pdf. Accessed: 2026-02-11.
- [16] European Parliament and Council of the European Union. Directive 2009/41/EC of 6 May 2009 on the contained use of genetically modified micro-organisms. Official Journal of the European Union, L 125, pp. 75–97, 2009. URL <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:125:0075:0097:EN:PDF>. Accessed: 2026-02-11.
- [17] Ben Ewen-Campen, Haojiang Luan, Jun Xu, Rohit Singh, Neha Joshi, Tanuj Thakkar, Bonnie Berger, Benjamin H. White, and Norbert Perrimon. split-intein gal4 provides intersectional genetic labeling that is repressible by gal80. *Proceedings of the National Academy of Sciences*, 120(24), June 2023. ISSN 1091-6490. doi: 10.1073/pnas.2304730120. URL <http://dx.doi.org/10.1073/pnas.2304730120>.
- [18] Md. Fakruddin, Reaz Mohammad Mazumdar, Khanjada Shahnewaj Bin Mannan, Abhijit Chowdhury, and Md. Nur Hossain. Critical factors affecting the success of cloning, expression, and mass production of enzymes by recombinante. coli. *ISRN Biotechnology*, 2013:1–7, September 2013. ISSN 2090-9403. doi: 10.5402/2013/590587. URL <http://dx.doi.org/10.5402/2013/590587>.
- [19] Pablo Fernández-Cancelo, Paula Muñoz, Gemma Echeverría, Christian Larrigaudière, Neus Teixidó, Sergi Munné-Bosch, and Jordi Giné-Bordonaba. Ethylene and abscisic acid play a key role in modulating apple ripening after harvest and after cold-storage. *Postharvest Biology and Technology*, 188:111902, June 2022. ISSN 0925-5214. doi: 10.1016/j.postharvbio.2022.111902. URL <http://dx.doi.org/10.1016/j.postharvbio.2022.111902>.
- [20] Savio S. Ferreira and Mauricio S. Antunes. Genetically encoded boolean logic operators to sense and integrate phenylpropanoid metabolite levels in plants. *New Phytologist*, 243(2): 674–687, May 2024. ISSN 1469-8137. doi: 10.1111/nph.19823. URL <http://dx.doi.org/10.1111/nph.19823>.

- [21] FIXME: Author needed. FIXME: Article title needed. *International Journal of Agricultural Science and Food Technology*, 2022. ISSN 2455-815X. doi: 10.17352/ijasft. URL <http://dx.doi.org/10.17352/ijasft>. INCOMPLETE REFERENCE - needs proper author and title.
- [22] FIXME: Author or editor needed. *FIXME: Chapter title needed*, pages 239–288. Elsevier, 2025. ISBN 9780443491504. doi: 10.1016/b978-0-443-49150-4.00008-0. URL <http://dx.doi.org/10.1016/B978-0-443-49150-4.00008-0>. INCOMPLETE REFERENCE - needs proper author and chapter title.
- [23] Food and Agriculture Organization of the United Nations. Agricultural production statistics 2010–2024. Faostat analytical brief 121, Food and Agriculture Organization of the United Nations, 2025. URL <https://openknowledge.fao.org/server/api/core/bitstreams/23eaa328-ac5a-444e-ac62-80a636acd81f/content>. This brief summarizes trends in global agricultural production and harvested areas from 2010 to 2024; it reports, for instance, that the harvested area for main primary crops reached 1.5 billion hectares in 2024 and that oil crops and cereals recorded the largest production increases:contentReference[oaicite:1]index=1.
- [24] Food and Agriculture Organization of the United Nations. FAOSTAT Statistical Database, 2026. URL <https://www.fao.org/faostat/en/#home>. FAO. 2026. FAOSTAT Statistical Database. Accessed on 11 Feb 2026. Licence: CC-BY-4.0.
- [25] Food Standards Agency. Genetically modified foods — how gm foods are labelled. Food Standards Agency guidance page, 2026. URL <https://www.food.gov.uk/safety-hygiene/genetically-modified-foods#how-gm-foods-are-labelled>. Accessed: 2026-02-11.
- [26] Hu Ge, Xiaoyi Li, Shisi Chen, Mengru Zhang, Zhibin Liu, Jianmei Wang, Xufeng Li, and Yi Yang. The expression of cark1 or rcar11 driven by synthetic promoters increases drought tolerance in arabidopsis thaliana. *International Journal of Molecular Sciences*, 19(7):1945, July 2018. ISSN 1422-0067. doi: 10.3390/ijms19071945. URL <http://dx.doi.org/10.3390/ijms19071945>.
- [27] Louis-Philippe Hamel. Nicotiana benthamiana's responses to agroinfiltration, a treasure grove of new avenues to improve protein yields in plant molecular farming. *Plant Biotechnology Journal*, 24(1):5–17, December 2025. ISSN 1467-7652. doi: 10.1111/pbi.70460. URL <http://dx.doi.org/10.1111/pbi.70460>.
- [28] Keiichiro Hiratsu, Kyoko Matsui, Tomotsugu Koyama, and Masaru Ohme-Takagi. Dominant repression of target genes by chimeric repressors that include the ear motif, a repression domain, in arabidopsis. *The Plant Journal*, 34(5):733–739, May 2003. ISSN 1365-313X. doi: 10.1046/j.1365-313x.2003.01759.x. URL <http://dx.doi.org/10.1046/j.1365-313x.2003.01759.x>.
- [29] Sergio Iacopino, Francesco Licausi, and Beatrice Giuntoli. *Exploiting the Gal4/UAS System as Plant Orthogonal Molecular Toolbox to Control Reporter Expression in Arabidopsis Protoplasts*, pages 99–111. Springer US, 2022. ISBN 9781071617915. doi: 10.1007/978-1-0716-1791-5_6. URL http://dx.doi.org/10.1007/978-1-0716-1791-5_6.
- [30] Kang-Chang Kim, Baofang Fan, and Zhixiang Chen. Pathogen-induced arabidopsis wrky7 is a transcriptional repressor and enhances plant susceptibility to pseudomonas syringae . *Plant Physiology*, 142(3):1180–1192, September 2006. ISSN 1532-2548. doi: 10.1104/pp.106.082487. URL <http://dx.doi.org/10.1104/pp.106.082487>.

- [31] Younghyun Kim, Goeun Lee, Eunhyun Jeon, Eun ju Sohn, Yongjik Lee, Hyangju Kang, Dong wook Lee, Dae Heon Kim, and Inhwon Hwang. The immediate upstream region of the 5' utr from the aug start codon has a pronounced effect on the translational efficiency in arabidopsis thaliana. *Nucleic Acids Research*, 42(1):485–498, September 2013. ISSN 0305-1048. doi: 10.1093/nar/gkt864. URL <http://dx.doi.org/10.1093/nar/gkt864>.
- [32] Yajing Li, Hongxia Sun, Jindong Li, Shu Qin, Wei Yang, Xueying Ma, Xiongwu Qiao, and Baoru Yang. Effects of genetic background and altitude on sugars, malic acid and ascorbic acid in fruits of wild and cultivated apples (*malus* sp.). *Foods*, 10(12):2950, November 2021. ISSN 2304-8158. doi: 10.3390/foods10122950. URL <http://dx.doi.org/10.3390/foods10122950>.
- [33] Shijiao Lin, Mingyang Xu, Yuling Liang, Mingqian Wang, Yunyan Peng, Yanan Wang, Weiting Liu, Aide Wang, and Yinglin Ji. The gibberellin-activated transcription factor mdravl1 regulates ethylene biosynthesis to suppress apple fruit ripening. *Plant Physiology*, 199(2), September 2025. ISSN 1532-2548. doi: 10.1093/plphys/kiaf436. URL <http://dx.doi.org/10.1093/plphys/kiaf436>.
- [34] Lin Liu, Yafei Shu, Yue Wang, Mingyue Liu, Shuxin Xu, Xiaofan Lu, Yu Zhang, Luyao Yu, Ze Tao, Jiale Wang, Bingkun Ge, Pengzhen Cui, Changai Wu, Jinguang Huang, Kang Yan, Chengchao Zheng, Guodong Yang, Xin Tian, and Shizhong Zhang. The pan genome analysis of wox gene family in apple and the two sides of mdwus-1 in promoting leaf-borne shoot. *Horticulture Research*, 12(8), July 2025. ISSN 2052-7276. doi: 10.1093/hr/uahf117. URL <http://dx.doi.org/10.1093/hr/uahf117>.
- [35] Mingchun Liu, Julien Pirrello, Christian CHERVIN, Jean-Paul Roustan, and Mondher Bouzayen. Ethylene control of fruit ripening: revisiting the complex network of transcriptional regulation. *Plant Physiology*, page pp.01361.2015, October 2015. ISSN 1532-2548. doi: 10.1104/pp.15.01361. URL <http://dx.doi.org/10.1104/pp.15.01361>.
- [36] Kasey Markel, Jean Sabety, Shehan Wijesinghe, and Patrick M. Shih. Design and characterization of a transcriptional repression toolkit for plants. *ACS Synthetic Biology*, 13 (10):3137–3143, September 2024. ISSN 2161-5063. doi: 10.1021/acssynbio.4c00404. URL <http://dx.doi.org/10.1021/acssynbio.4c00404>.
- [37] Maciej Maselko, Stephen C. Heinsch, Jeremy M. Chacón, William R. Harcombe, and Michael J. Smanski. Engineering species-like barriers to sexual reproduction. *Nature Communications*, 8(1), October 2017. ISSN 2041-1723. doi: 10.1038/s41467-017-01007-3. URL <http://dx.doi.org/10.1038/s41467-017-01007-3>.
- [38] Maciej Maselko, Nathan Feltman, Ambuj Upadhyay, Amanda Hayward, Siba Das, Nathan Myslicki, Aidan J. Peterson, Michael B. O'Connor, and Michael J. Smanski. Engineering multiple species-like genetic incompatibilities in insects. *Nature Communications*, 11(1), September 2020. ISSN 2041-1723. doi: 10.1038/s41467-020-18348-1. URL <http://dx.doi.org/10.1038/s41467-020-18348-1>.
- [39] Peter McAtee, Siti Karim, Robert Schaffer, and Karine David. A dynamic interplay between phytohormones is required for fruit development, maturation, and ripening. *Frontiers in Plant Science*, 4, 2013. ISSN 1664-462X. doi: 10.3389/fpls.2013.00079. URL <http://dx.doi.org/10.3389/fpls.2013.00079>.
- [40] Jonathan R. Moll, Sergei B. Ruvinov, Ira Pastan, and Charles Vinson. Designed heterodimerizing leucine zippers with a range of pis and stabilities up to 10-15 m. *Protein Science*, 10(3):649–655, March 2001. ISSN 1469-896X. doi: 10.1110/ps.39401. URL <http://dx.doi.org/10.1110/ps.39401>.

- [41] Ramasamy Neelamegam and BagavathiPerumal Ezhilan. Gc-ms analysis of phytocomponents in the ethanol extract of polygonum chinense l. *Pharmacognosy Research*, 4(1):11, 2012. ISSN 0974-8490. doi: 10.4103/0974-8490.91028. URL <http://dx.doi.org/10.4103/0974-8490.91028>.
- [42] NovoPro Bioscience. Codon optimization tool (expoptimizer), n.d. URL <https://www.novoprolabs.com/tools/codon-optimization>. Accessed 11 February 2026.
- [43] Kazuma Okada, Taku Shimizu, Shigeki Moriya, Masato Wada, Kazuyuki Abe, and Yutaka Sawamura. Alternative splicing and deletion in s-rnase confer stylar-part self-compatibility in the apple cultivar ‘vered’. *Plant Molecular Biology*, 114(6), October 2024. ISSN 1573-5028. doi: 10.1007/s11103-024-01514-0. URL <http://dx.doi.org/10.1007/s11103-024-01514-0>.
- [44] Malla Padidam. Chemically regulated gene expression in plants. *Current Opinion in Plant Biology*, 6(2):169–177, April 2003. ISSN 1369-5266. doi: 10.1016/s1369-5266(03)00005-0. URL [http://dx.doi.org/10.1016/S1369-5266\(03\)00005-0](http://dx.doi.org/10.1016/S1369-5266(03)00005-0).
- [45] Robert Penchovsky and Dimitrios Kaloudas. Molecular factors affecting tomato fruit size. *Plant Gene*, 33:100395, March 2023. ISSN 2352-4073. doi: 10.1016/j.plgene.2022.100395. URL <http://dx.doi.org/10.1016/j.plgene.2022.100395>.
- [46] Markus Ralser. ptretight2 (plasmid #19407) sequencing result. Addgene plasmid repository, 2008. URL <https://www.addgene.org/browse/sequence/181154/>. Sequencing result #181154 for the empty-backbone plasmid pTREtight2, available from Addgene since 15 October 2008:contentReference[oaicite:1]index=1.
- [47] Satyabrata Sahoo, Shib Sankar Das, and Ria Rakshit. Codon usage pattern and predicted gene expression in arabidopsis thaliana. *Gene*, 721:100012, 2019. ISSN 0378-1119. doi: 10.1016/j.gene.2019.100012. URL <http://dx.doi.org/10.1016/j.gene.2019.100012>.
- [48] Mikal E. Saltveit. Effect of ethylene on quality of fresh fruits and vegetables. *Postharvest Biology and Technology*, 15(3):279–292, March 1999. ISSN 0925-5214. doi: 10.1016/s0925-5214(98)00091-x. URL [http://dx.doi.org/10.1016/S0925-5214\(98\)00091-X](http://dx.doi.org/10.1016/S0925-5214(98)00091-X).
- [49] A. Sarrión-Perdigones, M. Vazquez-Vilar, J. Palaci, B. Castelijns, J. Forment, P. Ziarsolo, J. Blanca, A. Granell, and D. Orzaez. Goldenbraid 2.0: A comprehensive dna assembly framework for plant synthetic biology. *PLANT PHYSIOLOGY*, 162(3):1618–1631, May 2013. ISSN 1532-2548. doi: 10.1104/pp.113.217661. URL <http://dx.doi.org/10.1104/pp.113.217661>.
- [50] Ina Schlathölter, Anna Dalbosco, Michael Meissle, Andrea Knauf, Alex Dallemulle, Beat Keller, Jörg Romeis, Giovanni A. L. Broggini, and Andrea Patocchi. Low outcrossing from an apple field trial protected with nets. *Agronomy*, 11(9):1754, August 2021. ISSN 2073-4395. doi: 10.3390/agronomy11091754. URL <http://dx.doi.org/10.3390/agronomy11091754>.
- [51] Helmut K. Seitz and Felix Stickel. Acetaldehyde as an underestimated risk factor for cancer development: role of genetics in ethanol metabolism. *Genes & Nutrition*, 5(2):121–128, October 2009. ISSN 1865-3499. doi: 10.1007/s12263-009-0154-1. URL <http://dx.doi.org/10.1007/s12263-009-0154-1>.
- [52] Shoot Gardening. *Malus domestica 'winston'*. Shoot Gardening plant profile, 2026. URL <https://www.shootgardening.com/plants/malus-domestica-winston>. Accessed: 2026-02-11.

- [53] Specialty Produce. Winston apples. Specialty Produce produce profile, 2026. URL https://specialtyproduce.com/produce/Winston_Apples_22027.php. Accessed: 2026-02-11.
- [54] Piotr Szymczyk and Małgorzata Majewska. Plant synthetic promoters. *Applied Sciences*, 14(11):4877, June 2024. ISSN 2076-3417. doi: 10.3390/app14114877. URL <http://dx.doi.org/10.3390/app14114877>.
- [55] UniProt Consortium. LexA repressor - escherichia coli (strain k12), n.d. URL <https://www.uniprot.org/uniprotkb/P0A7C2/entry>. UniProtKB reviewed (Swiss-Prot) entry for LexA repressor (gene: *lexA*) from *Escherichia coli* strain K12:contentReference[oaicite:0]index=0. Accessed 11 February 2026.
- [56] Sybille B Unsicker, Grit Kunert, and Jonathan Gershenson. Protective perfumes: the role of vegetative volatiles in plant defense against herbivores. *Current Opinion in Plant Biology*, 12(4):479–485, August 2009. ISSN 1369-5266. doi: 10.1016/j.pbi.2009.04.001. URL <http://dx.doi.org/10.1016/j.pbi.2009.04.001>.
- [57] Irina Ivanova Vaseva, Enas Qudeimat, Thomas Potuschak, Yunlong Du, Pascal Genschik, Filip Vandenbussche, and Dominique Van Der Straeten. The plant hormone ethylene restricts arabidopsis growth via the epidermis. *Proceedings of the National Academy of Sciences*, 115(17), April 2018. ISSN 1091-6490. doi: 10.1073/pnas.1717649115. URL <http://dx.doi.org/10.1073/pnas.1717649115>.
- [58] Marta Vazquez-Vilar, Alfredo Quijano-Rubio, Asun Fernandez-del Carmen, Alejandro Sarrión-Perdigones, Rocio Ochoa-Fernandez, Peio Ziarsolo, José Blanca, Antonio Granell, and Diego Orzaez. Gb3.0: a platform for plant bio-design that connects functional dna elements with associated biological data. *Nucleic Acids Research*, page gkw1326, January 2017. ISSN 1362-4962. doi: 10.1093/nar/gkw1326. URL <http://dx.doi.org/10.1093/nar/gkw1326>.
- [59] Takamitsu Waki, Shunsuke Miyashima, Miyako Nakanishi, Yoichi Ikeda, Takashi Hashimoto, and Keiji Nakajima. A <scp>gal</scp>4-based targeted activation tagging system in <scp>a</scp>rabidopsis thaliana. *The Plant Journal*, 73(3):357–367, November 2012. ISSN 1365-313X. doi: 10.1111/tpj.12049. URL <http://dx.doi.org/10.1111/tpj.12049>.
- [60] Miaomiao Wang, Nan Jiang, Jiale Wang, Xiaotong Hu, Qizhe Li, Wanyu Xu, Tuanhui Bai, Jian Jiao, Jiangli Shi, Yu Liu, Ran Wan, Kunxi Zhang, Pengbo Hao, Yujie Zhao, Liu Cong, Yawen Shen, and Xianbo Zheng. Genome-wide identification of apple expansins and functional evidence for mdexpa17 in postharvest fruit ripening. *Horticulturae*, 12(2): 130, January 2026. ISSN 2311-7524. doi: 10.3390/horticulturae12020130. URL <http://dx.doi.org/10.3390/horticulturae12020130>.
- [61] Shuo Wang, Li-Xian Li, Zhen Zhang, Yue Fang, Dan Li, Xue-Sen Chen, and Shou-Qian Feng. Ethylene precisely regulates anthocyanin synthesis in apple via a module comprising mdeil1, mdmyb1, and mdmyb17. *Horticulture Research*, 9, 2022. ISSN 2052-7276. doi: 10.1093/hr/uhac034. URL <http://dx.doi.org/10.1093/hr/uhac034>.
- [62] World Health Organization Regional Office for Europe. No level of alcohol consumption is safe for our health. News release, 2023. URL <https://www.who.int/europe/news/item/04-01-2023-no-level-of-alcohol-consumption-is-safe-for-our-health>. Accessed: 2026-02-11.
- [63] Mengbo Wu, Kaidong Liu, Honghai Li, Ying Li, Yunqi Zhu, Dan Su, Yaoxin Zhang, Heng Deng, Yikui Wang, and Mingchun Liu. Gibberellins involved in fruit ripening and softening by mediating multiple hormonal signals in tomato. *Horticulture Research*, 11(2), December

2023. ISSN 2052-7276. doi: 10.1093/hr/uhad275. URL <http://dx.doi.org/10.1093/hr/uhad275>.
- [64] Ryohei Yagi, Franz Mayer, and Konrad Basler. Refined lexa transactivators and their use in combination with the drosophila gal4 system. *Proceedings of the National Academy of Sciences*, 107(37):16166–16171, August 2010. ISSN 1091-6490. doi: 10.1073/pnas.1005957107. URL <http://dx.doi.org/10.1073/pnas.1005957107>.
 - [65] Rui Yan, Tianle Zhang, Yuan Wang, Wenxiu Wang, Rahat Sharif, Jiale Liu, Qinglong Dong, Haoan Luan, Xuemei Zhang, Han Li, Suping Guo, Guohui Qi, and Peng Jia. The apple mdga2ox7 modulates the balance between growth and stress tolerance in an anthocyanin-independent manner. *Plant Physiology and Biochemistry*, 212:108707, July 2024. ISSN 0981-9428. doi: 10.1016/j.plaphy.2024.108707. URL <http://dx.doi.org/10.1016/j.plaphy.2024.108707>.
 - [66] Pengtao Yue, Qian Lu, Zhi Liu, Tianxing Lv, Xinyue Li, Haidong Bu, Weiting Liu, Yaxiu Xu, Hui Yuan, and Aide Wang. Auxin-activated mdarf5 induces the expression of ethylene biosynthetic genes to initiate apple fruit ripening. *New Phytologist*, 226(6):1781–1795, March 2020. ISSN 1469-8137. doi: 10.1111/nph.16500. URL <http://dx.doi.org/10.1111/nph.16500>.
 - [67] Sara Zenoni, Stefania Savoi, Nicola Busatto, Giovanni Battista Tornielli, and Fabrizio Costa. Molecular regulation of apple and grape ripening: exploring common and distinct transcriptional aspects of representative climacteric and non-climacteric fruits. *Journal of Experimental Botany*, 74(20):6207–6223, August 2023. ISSN 1460-2431. doi: 10.1093/jxb/erad324. URL <http://dx.doi.org/10.1093/jxb/erad324>.
 - [68] Bei Zhang, Madhusudhan Rapolu, Sandeep Kumar, Manju Gupta, Zhibin Liang, Zhenlin Han, Philip Williams, and Wei Wen Su. Coordinated protein co-expression in plants by harnessing the synergy between an intein and a viral 2a peptide. *Plant Biotechnology Journal*, 15(6):718–728, March 2017. ISSN 1467-7652. doi: 10.1111/pbi.12670. URL <http://dx.doi.org/10.1111/pbi.12670>.
 - [69] Junxin Zhang, Xihuan Yan, Tiran Huang, Huan Liu, Fang Liu, Meixia Yang, MingFeng Yang, and Lanqing Ma. Overexpressing 4-coumaroyl-coa ligase and stilbene synthase fusion genes in red raspberry plants leads to resveratrol accumulation and improved resistance against botrytis cinerea. *Journal of Plant Biochemistry and Biotechnology*, 32(1):85–91, June 2022. ISSN 0974-1275. doi: 10.1007/s13562-022-00784-3. URL <http://dx.doi.org/10.1007/s13562-022-00784-3>.
 - [70] Songwen Zhang, Christopher Gottschalk, and Steve van Nocker. Genetic mechanisms in the repression of flowering by gibberellins in apple (*malus x domestica* borkh.). *BMC Genomics*, 20(1), October 2019. ISSN 1471-2164. doi: 10.1186/s12864-019-6090-6. URL <http://dx.doi.org/10.1186/s12864-019-6090-6>.
 - [71] Meiliang Zhou and Johan Memelink. Jasmonate-responsive transcription factors regulating plant secondary metabolism. *Biotechnology Advances*, 34(4):441–449, July 2016. ISSN 0734-9750. doi: 10.1016/j.biotechadv.2016.02.004. URL <http://dx.doi.org/10.1016/j.biotechadv.2016.02.004>.
 - [72] Matthew H. Zinselmeier, J. Armando Casas-Mollano, Jonathan Cors, Savio S. Ferreira, Daniel F. Voytas, and Michael J. Smanski. Towards engineering hybrid incompatibility in plants. *Plant Biotechnology Journal*, 23(7):2752–2754, April 2025. ISSN 1467-7652. doi: 10.1111/pbi.70096. URL <http://dx.doi.org/10.1111/pbi.70096>.

- [73] Jianru Zuo, Peter D. Hare, and Nam-Hai Chua. *Applications of Chemical-Inducible Expression Systems in Functional Genomics and Biotechnology*, pages 329–342. Humana Press, 2006. ISBN 1597450030. doi: 10.1385/1-59745-003-0:329. URL <http://dx.doi.org/10.1385/1-59745-003-0:329>.

Appendix

A Modelling

In the interest of modelling simplicity, some assumptions were made. Firstly, this model assumes proteins are not passively degraded – only proteins that contain PEST tags are actively degraded. This is because the fruit cells in ripened fruit divide very slowly ([45]), resulting in negligible protein dilution. A global transcription and translation rate is also assumed. Furthermore, in this simulation, the accumulation of ethanol does not lead to reduced cell viability.

To model our system, we first sought to show that our system is induced only when the apple is picked from the tree – when ethylene is high and gibberellin is low.

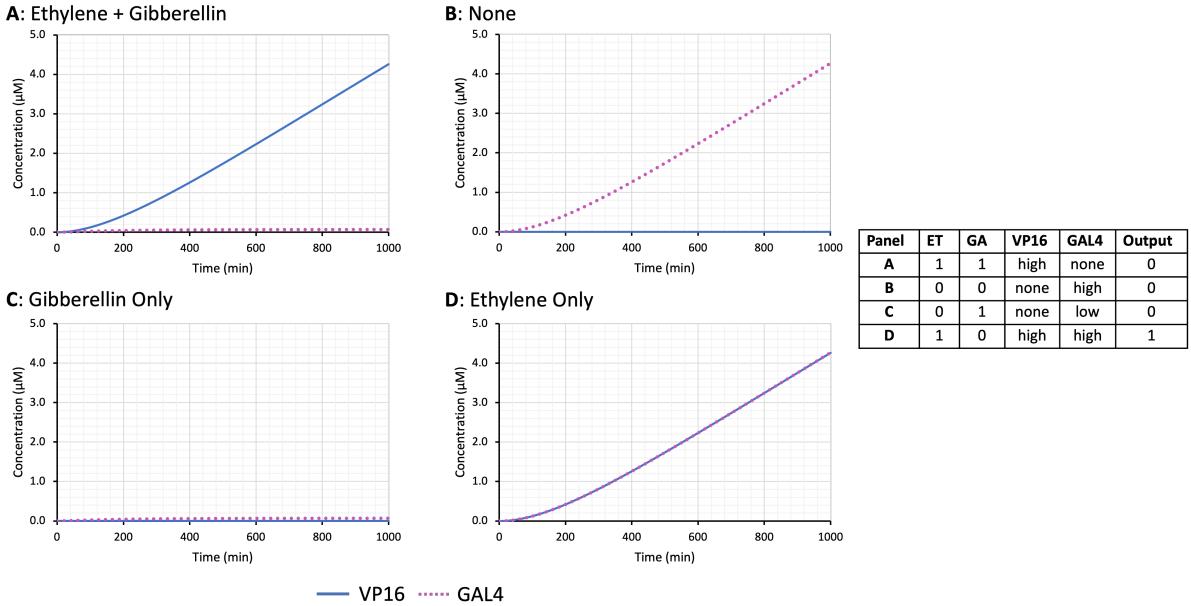


Figure 7: **Production of VP16 and GAL4 in different conditions.** ET: ethylene. GA: gibberellin.

While the complete absence of ethylene or gibberellin in fruit cells is biologically unlikely, for simplicity of modelling, we assumed binary input states, representing the presence or absence of each hormone. In the presence of both hormones, only VP16 is produced (Figure 7A), and in the absence of both hormones, only GAL4 is produced (Figure 7B). If only gibberellin is present, neither VP16 nor GAL4 is produced (Figure 7C), while in the presence of only ethylene, both VP16 and GAL4 are produced (Figure 7D).

This shows that the system is only able to produce VP16 and GAL4 when the apple is ripening. As both VP16 and GAL4 are required to induce downstream processes, alcohol production is only possible when the fruit begins to ripen.

Next, we simulated the production of ADH and PDC over 20,000 minutes, or approximately two weeks. The extended timescale was chosen to capture the long-term gene expression dynamics.

To model the production of these enzymes, we accounted for the fact that their expression is regulated by both an activator, VP16–GAL4, and a repressor, LexA. However, a well-established kinetic expression describing transcription under simultaneous activation and repression was not available. As a result, we employed an approximate formulation that combines the effects of activation and repression, as described below, where k_{trans} is the global transcription rate, K_{m_R} is the repression coefficient, K_{m_A} is the activation coefficient, and R and A are the repressor and activator concentrations, respectively.

$$\frac{d[\text{mRNA}]}{dt} = \frac{k_{\text{trans}} (K_{m_R})^n}{(K_{m_R})^n + R^n} \cdot \frac{k_{\text{trans}} A^n}{(K_{m_A})^n + A^n}.$$

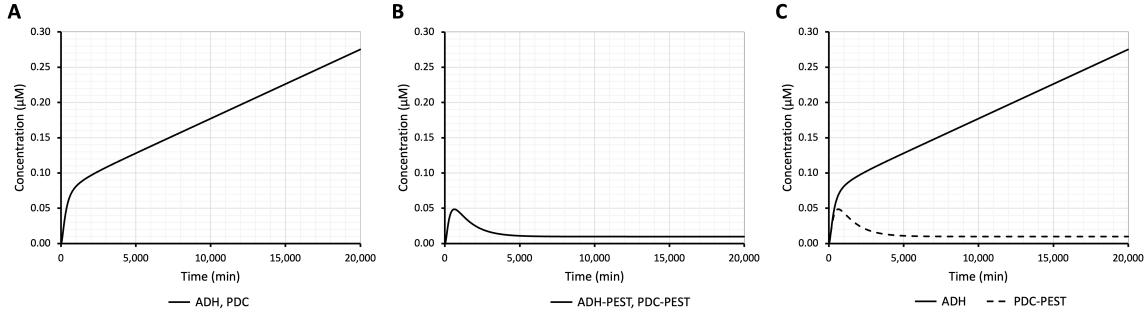


Figure 8: Production of ADH and PDC over time. (A) ADH and PDC without PEST tags. (B) ADH and PDC with PEST tags. (C) ADH without a PEST tag and PDC with a PEST tag.

As seen in Figure 8C, ADH and PDC initially increase sharply in concentration. However, ADH concentration continues to increase while PDC concentration falls before plateauing.

During the development of the model, it was found that if neither ADH nor PDC was actively degraded (Figure 8A), alcohol production would occur very quickly due to the continuous conversion of pyruvate by PDC. However, if both ADH and PDC were actively degraded, via addition of a PEST tag (Figure 8B), there would be accumulation of the intermediate acetaldehyde. As a result, in our final simulation, only PDC is actively degraded (Figure 8C), making the pyruvate to acetaldehyde conversion the rate-determining step.

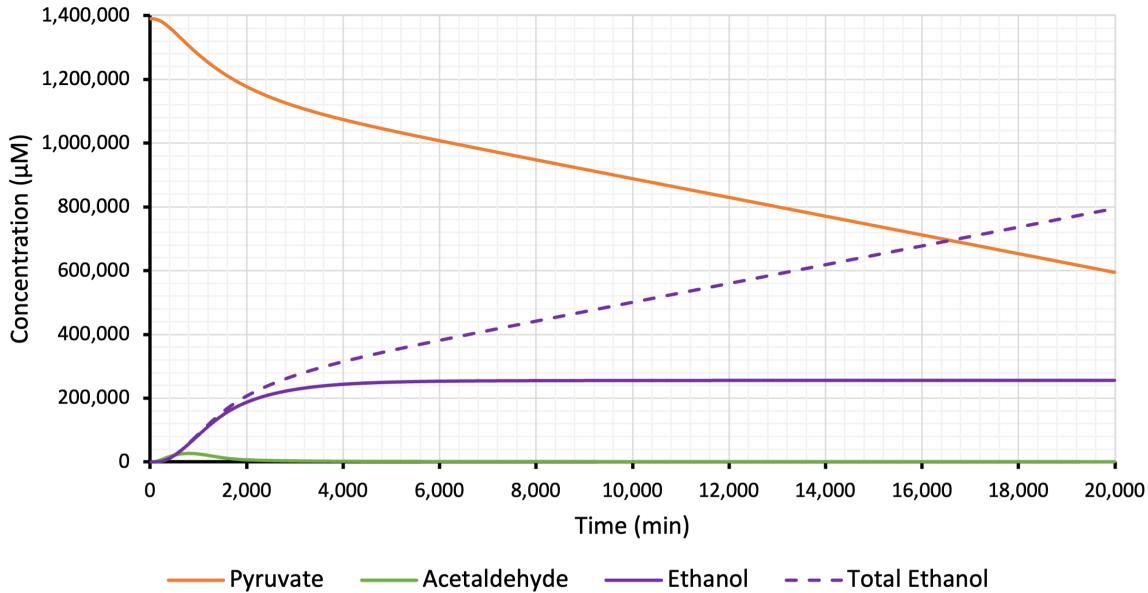


Figure 9: Production of acetaldehyde and ethanol from pyruvate. Ethanol: concentration of ethanol in the apple. Total ethanol: total concentration of ethanol, including evaporated ethanol.

As shown in Figure 9, the concentration of pyruvate is estimated to be 1.39 M, which is the total concentration of glucose and fructose in apples [6]. This is assuming that all the glucose and fructose in the apple is available to be converted to pyruvate.

Ethanol concentration reaches a steady state at around 255 mM, which corresponds to around 1.5% alcohol content in the apple. This occurs after 6,000 minutes, or around four days, and is when rate of ethanol production is equal to rate of evaporation from the apple.

Next, we tried simulating different levels of ethylene spikes (Figure 10A) and showed that the resulting ethanol production was similar (Figure 10B). This shows that our system is robust to variations in ethylene levels, allowing for a fixed final ethanol concentration in apples exhibiting different intensities of ethylene spikes.

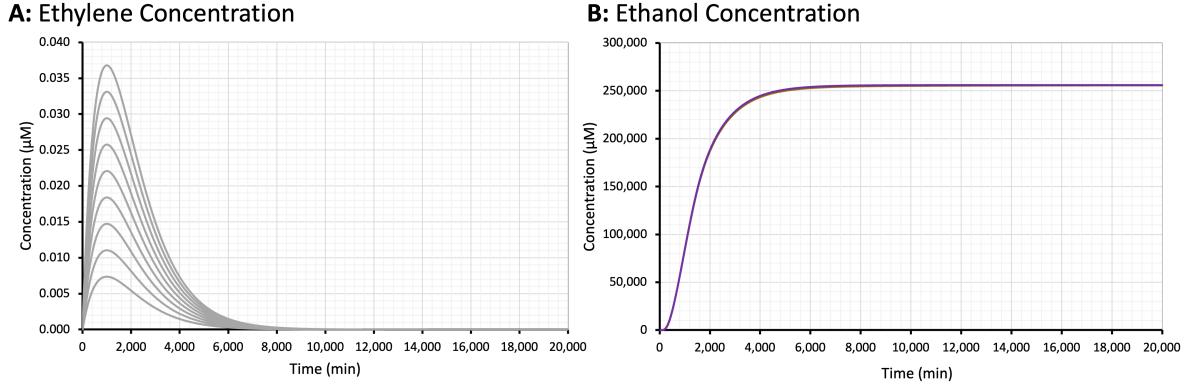


Figure 10: Ethanol production at different ethylene concentrations. (A) Different levels of ethylene spikes simulated over time. (B) The resultant changes in concentration of ethanol over time.

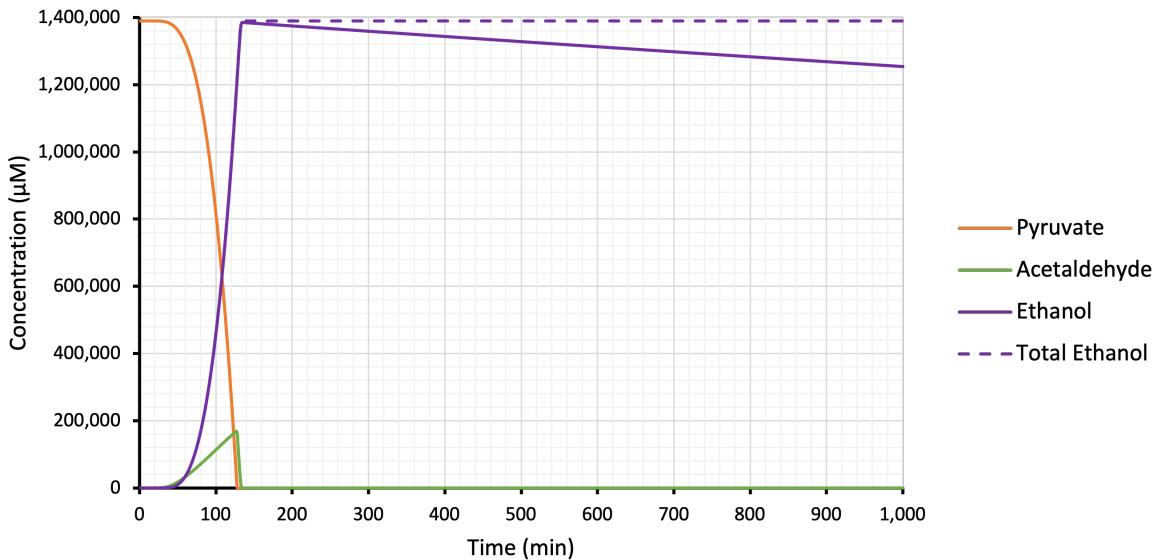


Figure 11: Unregulated conversion of pyruvate to ethanol over time. Ethanol: concentration of non-evaporated ethanol in the apple. Total ethanol: total concentration of ethanol, including evaporated ethanol.

Finally, to test the importance of negative regulation in the system, we removed the repressor module and simulated the conversion of pyruvate to ethanol over time, as shown in Figure 11. After a short delay, pyruvate was rapidly depleted to form acetaldehyde, which was subsequently converted to ethanol. This behaviour is likely driven by the self-amplification of VP16-GAL4 as well as the high catalytic efficiency of the enzymes ADH1 and PDC.

However, the rapid and complete depletion of pyruvate is biologically unrealistic, as it as-

sumes that all available carbon derived from glucose and fructose is funnelled exclusively toward ethanol production. In reality, protein expression is energy intensive and is dependent on aerobic respiration. As pyruvate is central to aerobic respiration, it cannot be solely consumed to synthesise ethanol without severely compromising cellular viability. However, while the timescale and complete depletion of pyruvate derived from the model are biologically unrealistic, these results highlight the necessity of negative regulation in maintaining physiologically realistic metabolic dynamics.

B Codon Optimization Script and CellDesigner Files

The codon optimization script and CellDesigner files used for modelling are available in the GitHub repository: <https://github.com/icider/icider>.