REVIEW

OPEN ACCESS

The Role of Alternative Respiratory Enzymes in Photosynthetic Plant Cells Under Stress

G.B. Borovskii*, E.L. Gorbyleva, A.I. Katyshev, D.V. Pyatrikas and I.V. Fedoseeva

[1] *Siberian Institute of Plant Physiology and Biochemistry SB RAS, 664033, Irkutsk, Russia*

E-Mail: borovskii@sifibr.irk.ru

In recent years, it has become clear that for mitochondria in photosynthetic plant cells, the main role of buffer capacity is becoming, allowing to keep under control the balance of ATP production, regulation of the level of pyridine nucleotide reduction, generation of ROS and RNS, as well as optimize the main metabolic flows, which is especially important under stress. Non-conjugated respiration is an important mechanism for achieving stable operation and maximum efficiency of photosynthetic cells. It is actively used in the light and becomes even more important under stress in lighting conditions. The most important part of these non-canonical mitochondrial functions is provided by alternative mitochondrial respiratory enzymes.

Plants have two interconnected systems of cellular energy generation – respiratory and photosynthetic. And if in heterotrophic cells the most important role in the energy supply of metabolic processes belongs to mitochondrial respiration, then in photosynthetic plant cells this function is assumed by photosynthesis and chloroplasts. However, this does not mean that mitochondria in autotrophic cells are reduced, inactive in light, or their functions are not important for cellular energy metabolism. The role of mitochondria remains paramount, but is being transformed for other tasks. In recent years, it has become clear that the main function for mitochondria in photosynthetic plant cells is the buffer function, which is expressed in maintaining the balance of ATP production, the level of pyridine nucleotide reduction, limiting the generation of ROS and RNS, as well as optimizing the main metabolic fluxes, which is especially important under stress (Popov *et al.*, 2021; Igamberdiev, Bykova, 2023).

An important part of these non-canonical mitochondrial functions is provided by alternative mitochondrial respiratory enzymes. A significant number of enzymes of alternative electron transport pathways are present in plant mitochondria, many of which are active under stress (Møller *et al.*, 2021). In *Arabidopsis thaliana*, these enzymes encode seven NAD(P)H dehydrogenase genes (*NDA1-2, NDB1–4, NDC1*), five alternative oxidase genes (*AOX1a–d, AOX2*) and three uncoupling protein genes (*UCP1-3*) (Michalecka *et al.*, 2003; Møller *et al.*, 2021; Lima *et al.*, 2022).

Alternative NAD(P)H dehydrogenases (ND II)

The work and functions in photosynthetic cells and under stressful conditions of alternative NAD(P)H dehydrogenases were initially discovered using rotenone, an inhibitor of respiratory complex I. It turned out that part of the dehydrogenase activity of mitochondria is not suppressed by this inhibitor, and in order to distinguish these enzymes from those already known, they were called type II dehydrogenases (ND II). It was found that in this case NAD(P)H is oxidized by several enzymes localized on the intermembrane and matrix surfaces of the inner membrane of mitochondria. As mentioned above, three groups of genes encoding these enzymes were found in Arabidopsis, some of these enzymes turned out to be sensitive to Ca_{2+} ions (Michalecka *et al.*, 2003; Møller *et al.*, 2021), the amount of which increases in cells under various stresses. The localization of these enzymes has been established: NDB1–NDB4 are external (located on the outer side of the inner membrane of the mitochondria), and NDA1, NDA2 and NDC1 are internal (facing the mitochondrial matrix, Elhafez *et al.*, 2006). NDA and NDB2 oxidize NADH, NADPH is used as a substrate by NDB1 and NDC1 (Møller *et al.*, 2021). It turned out that the expression of ND II genes increases under stressful conditions or under other influences in a coordinated manner with the expression of genes encoding AOX (Clifton *et al.*, 2005; Wanniarachchi *et al.*, 2018).

It is not possible to block the synthesis of all ND II in plants constitutively, since it is impossible to obtain viable seeds (Smith *et al.*, 2011), however, several works on blocking individual ND II genes have been published. There are results showing that deletion of the *NDB4* gene encoding the external NADH dehydrogenase of *A. thaliana* led to a decrease in the level of ROS generation. The authors believed that this effect could be caused by an increase in the activity of antioxidant enzymes and alternative oxidase (Smith *et al.*, 2011). Other researchers (Wallström *et al.*, 2014a; Wallström *et al.*, 2014b) studied how suppression of the expression of *NDA1, NDA2*, and *NDB1* genes encoding alternative internal and external NAD(P)H dehydrogenases of *A. thaliana* affects plant growth and metabolism, as well as changes in the expression of other genes. It has been shown that a decrease in the number of *NDA1* and *NDA2* proteins leads to a slowdown in growth and an increase in the lactate content in cells. However, no significant phenotypic differences were found between mutants and wild-type plants (Wallström *et al.*, 2014a). A decrease in the amount of NDB1 protein disrupted plant growth, but had no effect on respiratory activity. At the same time, the lack of *NDB1* significantly affected the expression of genes involved in protein synthesis, as well as in the functioning of plant signaling systems (Wallström *et al.*,

2014b). It has been shown that the activity of the *NDB2* gene plays a role in the resistance of Arabidopsis to drought in strong light (Sweetman *et al.*, 2019), and the drought-resistant soybean variety shows significantly higher expression of *NDB2* (as well as a number of other genes of alternative respiratory pathways) than plants sensitive to this stress factor (Alizadeh *et al.*, 2023). Increased expression of the *NDA1* and *NDA2* genes encoding the internal alternative NADH dehydrogenase led to a decrease in ROS generation, restored the photosynthetic system and increased the survival of seedlings under conditions of anoxia–reoxygenation (Jethva *et al.*, 2023). The effect of constitutive heterologous *NDB2* expression on plant resistance to low temperature and the rate of ROS generation were studied on transgenic tobacco plants, into whose cells the *A. thaliana NDB2 (AtNDB2)* gene was introduced (Korotaeva *et al.*, 2023). An assessment of the effect of low positive and negative temperatures in the range from +3° C to -3° C did not reveal differences in the survival rate of transgenic plants and wild-type plants (Borovskii *et al.*, 2023). At the same time, the best characteristics of the photosystem of transgenic plants functioning under low–temperature stress were shown - a lower drop in non-photochemical quenching (NPQ) and maximum quantum yield of photosystem II (Fv/Fm) in comparison with wild-type plants, as well as lower generation of ROS in leaves (Borovskii *et al.*, unpublished data). The activity of NDB1 depends on the content of free Ca_{2+} ions and low pH values (Rasmusson *et al.*, 2008). Consequently, acidification of the cytosol stimulates the oxidation of external NAD(P)H (Hao *et al.*, 2015), which logically fits into the definition of these enzymes as stressful.

It is important for plants that ND II enzymes are able to support the oxidation of NAD(P)H in conditions in which the activity of mitochondrial complex I is reduced, however, they do not create significant competition for complex I in other conditions, for example, at low concentrations of NAD(P)H. In model experiments, when ND II dehydrogenase genes were transferred to cells of species in which they are absent in the genome, the activity of external ND II arabidopsis contributed to a decrease in oxidative stress with inhibited activity of the

mitochondrial complex I (Catania *et al.*, 2019). This allows us to conclude that ND II enzymes work effectively in mitochondria that are not adapted for the functioning of alternative ETC.

Alternative oxidase (AOX)

The functional role and regulation of the activity of genes and proteins of alternative electron transport routes under stress has been studied in the most detail for AOX. AOX is a terminal oxidase of plants that branches off from the main mitochondrial respiratory chain at the ubiquinone level and, using electrons obtained from it, catalyzes the reduction of oxygen to water. It is resistant to cyanide and therefore its activity is quite simple to fix. The path of electronic transport through AOX bypasses two points of generation of an electrochemical proton gradient (complexes III and IV), and the energy of oxidation of ubiquinone by oxygen is released as heat. This reduces the energy efficiency of respiration, reduces the influence of respiratory control, which regulates the rate of formation of ATP and NADH, depending on the needs of the cell. AOX is found not only in higher plants, but also in representatives of all kingdoms (except archaebacteria): bacteria, algae, mosses, ferns, fungi, and even in sedentary or immobile animals (sponges, anemones, nematodes, mollusks, Vanlerberghe *et al.*, 2020).

It was found that although plants have several alternative oxidase genes, these genes and the enzymes encoded by them do not duplicate and cannot fully compensate for the absence of each other (Selinski *et al.*, 2018b). At the same time, different isoforms of AOX have different levels of sensitivity to pyruvate (Sweetman *et al.*, 2022), and are also activated differently by intermediates of the tricarboxylic acid cycle (Selinski *et al.*, 2018b). Posttranslational activation of AOX proteins is carried out in several ways, fine regulation is performed, among other things, by intermediates of the tricarboxylic acid (TCA) cycle, and the activity of AOX also depends on the redox status of the cell (Selinski *et al.*, 2017). Regulation of the activity of AOX enzymes is carried out with the participation of two conserved cysteine residues – CysI and CysII. The formation of a disulfide bridge between the CysI of two

AOX monomers under oxidized conditions leads to inactivation of the enzyme, their reduction in the dimer of non-covalently bound monomers converts the enzyme to the active form, and the interaction of both reduced Cys residues with pyruvate or other TCA cycle products to form thiohemiacetal leads to an even greater increase in enzyme activity (Selinski *et al.*, 2018a). Thus, fine regulation of AOX by intermediates of mitochondrial metabolism can be achieved, and activation of AOX by intermediates of photorespiration - glyoxylate and hydroxypyruvate reveals the metabolic relationship of AOX with this process, which requires the oxidation of large amounts of NADH without conjugation with ATP synthesis (Igamberdiev, Bykova, 2023). The protective role of AOX in stress conditions of photosynthetic cells is well known. For example, in cucumber, *AOX2* expression increases under cold stress, and this is associated with maintaining photosynthetic productivity (Ikkonen *et al.*, 2020). It has been shown that the functioning of this enzyme prevents an uncontrolled increase in the amount of ROS and RNS when the respiratory chain is inhibited under stress or "overflow" of the reduced pool of ubiquinones. It is known that *AOX* is involved in retrograde signaling, which leads to changes in the expression of many other genes under stress (Saha *et al.*, 2016; Garmash, 2021).

Interestingly, plants have another alternative terminal oxidase, similar in function to AOX. It is a plastid terminal oxidase (PTOX) that is found in chloroplasts. PTOX is a key factor for maintaining the redox balance of the plastoquinone pool (PQ) and functions as a "safety valve" to protect photosynthesis, obviously echoing the functions of mitochondrial AOX (Wang *et al.*, 2016). It is a stress-sensitive protein that can protect plants from various types of stress (Stepien, Johnson, 2018). In this review, we will not consider this enzyme, but its presence and functions well illustrate the idea that evolution tends to invent the same solutions to similar problems repeatedly.

Uncoupling plant proteins (UCPs)

The respiration rate of mitochondria depends on the transmembrane potential on the inner membrane of organelles. Its increase to 180 mV significantly inhibits the flow of electrons through complexes I, III and IV of the electron transfer chain generating $\Delta\mu H^+$, which leads to a decrease in the consumption of NAD(P)H and other mitochondrial substrates. One way to avoid this is to increase the activity of non-conjugated electron transport pathways (Popov *et al.*, 2021). Another way is to dissipate the potential with the help of specific proteins originally found in brown fat tissues in animals, where they participate in thermogenesis (Ricquier *et al.*, 1983). Later, uncoupling proteins (UCPs) and the uncoupling effect were discovered in plants (Vercesi *et al.*, 2006; Popov *et al.*, 2021). The uncoupling proteins of *A. thaliana* are represented by a small family of genes (*UCP1-3*), their products are integral proteins of the inner mitochondrial membrane with molecular weights of about 33 kDa. Proteins are activated by free fatty acids and ROS, and are inhibited by purine nucleotides. UCPs activity leads to a decrease in the membrane potential of the inner mitochondrial membrane (Vercesi *et al.*, 2006). The results of studies with double knockdown of various UCP genes show that *UCP2* and *UCP3* have a complementary function with *UCP1* in plant reproductive and vegetative organs/tissues, as well as in adaptation to stress. The partial redundancy between UCP isoforms suggests that functionally they can act both separately and jointly (Lima *et al.*, 2022). The mechanism by which UCP transports free fatty acids through the inner membrane of mitochondria has been the subject of debate (Ježek *et al.*, 2018). The crystal structure of UCP suggests a model of protein activity known as the mechanism of cyclic fatty acid turnover, in which, instead of transporting a soluble substrate, UCP catalyzes the inversion of ionized fatty acids distributed in the membrane, which allows the proton to be moved by fatty acids from one side of the membrane to the other (Barreto *et al.*, 2020).

The most studied function of UCPs is plant protection under such stresses as cold, hyperthermia, excessive illumination, drought, and exposure to pathogens. A probable defense mechanism is associated with a decrease in respiratory control and a decrease in ROS formation in mitochondria, since the formation of superoxide radicals depends on a high value of the transmembrane potential and increases

exponentially with its increase (Liu, Huang, 1996; Popov *et al.*, 2021). The absence of *UCP1* leads to oxidative stress, although it does not impair the plant's ability to withstand a wide range of abiotic stresses. More importantly, in such plants, there is a significant restriction of photorespiration activity with a decrease in the rate of glycine oxidation in mitochondria, which leads to a related decrease in the rate of photosynthetic carbon assimilation (Sweetlove *et al.*, 2006). Overexpression of *UCP* in plants correlates not only with adaptation to oxidative stress. It increases the productivity of photosynthesis and stimulates mitochondrial biogenesis, which correlates with changes in the expression of genes involved in energy metabolism and redox homeostasis (Laitz *et al.*, 2015). Although the physiological role of UCPs in plants is still being discussed, it is clear that thermogenesis is not the most important function of these proteins. At the same time, it is obvious that they are important for plant adaptation to stressful conditions by regulating membrane potential and reducing ROS, as well as for balancing energy flows in photosynthetic cells (Barreto *et al.*, 2020; Popov *et al.*, 2021; Igamberdiev, Bykova, 2023).

Coordination of the expression of genes of alternative ETC among themselves and with the state of the photosynthetic apparatus

With simultaneous operation of external and (or) internal ND II and AOX, the cell freely oxidizes part of NAD(P)H, converting chemical energy into thermal energy, which allows regulating the redox state of the pool of NAD(P)H, components of ETC mitochondria in a plant cell and shunting ROS generation sites in mitochondria (Popov *et al.*, 2021). Since ND II is connected to the respiratory chain through ubiquinol, then in order for the potential not to be generated in the ETC, further AOX activity is needed. In the light of these data, it is clear why the expression of the *NDB, NDA* and *AOX* genes in plants are interrelated. The expression of these genes also occurs synchronously in response to various abiotic stresses, which implies joint regulation by common promoter elements. Thus, the expression level of *AOX1a* in *A. thaliana* determines the expression level

of the *NDB2* gene under control conditions and under UV irradiation (Garmash *et al.*, 2020). Under many stresses, such as drought, almost all genes encoding proteins of alternative mitochondrial electron transport pathways are involved in plant stress response and adaptation (Yerlikaya *et al.*, 2022). In transgenic tobacco plants, *N. sylvestris* with overexpression of the potato *StNDB1* gene (*Solanum tuberosum* L.) observed an increase in the activity of tobacco's own *AOX* (Liu *et al.*, 2008). A similar effect of activation of the expression of different genes of alternative mitochondrial ETC in tobacco plants with increased expression of the *AtNDB2* gene was observed in our work (Borovskii *et al.*, 2021). During the operation of UCPs, mitochondria dissipate the potential accumulated during the operation of the cytochrome pathway (Vercesi *et al.*, 2006), which reduces respiratory control in these organelles, and such activity can serve as an alternative to the functioning of AOX, which is especially important in conditions of anoxia and hypoxia.

The expression of genes of alternative ETC is related both to each other and to the functioning of the photosynthetic apparatus. This occurs in various ways and through various metabolites. Thus, citrate, a product of the tricarboxylic acid cycle, is an activator at the transcriptional level not only for AOX, but also for NDA (Igamberdiev, Bykova, 2023). One of the possible ways combining the expression of genes of alternative ETC is retrograde signaling, when mitochondrial redox signals induce the expression of *NDA2, NDB2* and *UCP1b* together with genes of antioxidant systems (Garmash, 2021). Through the redox status of photosynthetic ETC, the regulation of genes of alternative mitochondrial ETC can also occur. The signal received from it coordinates the amount of AOX and the protein of the LHCB2 light-harvesting complex, and both proteins then contribute to maintaining the energy balance of chloroplasts, especially under stress (Chadee *et al.*, 2021; Alber, Vanlerberghe, 2021; Igamberdiev, Bykova, 2023). Light stimulates the expression of *NDA* and *NDC* (Escobar *et al.*, 2004). Strong light-activated gene expression is also observed in external NDB dehydrogenases (Michalecka *et al.*, 2003).

Coordination is necessary for photosynthetic cells, probably because in conditions where ATP and redox energy are intensively produced by light-dependent photosynthetic reactions, chloroplasts have insufficient ability to supply ATP to the cytosol. In the form of citrate, energy enters the mitochondria, where at this moment it is important to switch to the non-conjugated pathways of mitochondrial electron transport, which balances the ATP/ADP and NAD(P)H/NAD(P)$^+$ in mitochondria, cytosol and other cellular compartments. Thus, uncoupled respiration is an important mechanism for achieving stable operation and maximum efficiency of photosynthetic plant cells (Igamberdiev, Bykova, 2023). In the light, mitochondria coordinate the phosphorylation of adenylates and the reduction of pyridine nucleotides in the cytosol and other cellular compartments in order to avoid excessive energization and optimize the main metabolic flows. This function, which can be defined as thermodynamic buffering, is largely realized due to the flexibility of the mitochondrial ETS, the presence of alternative pathways in it and the possibility of uncoupled respiration. It is actively used in the light and becomes even more important under stress in the lighting conditions of the cell.

ACKNOWLEDGEMENT

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Alber N.A., Vanlerberghe G.C. (2021) The flexibility of metabolic interactions between chloroplasts and mitochondria in Nicotiana tabacum leaf. *Plant J.,* 106, 1625–1646.

Alizadeh R., Kumleh H.H., Rezadoost M.H. (2023) The simultaneous activity of cytosolic and mitochondrial antioxidant mechanisms in neutralizing the effect of drought stress in soybean. *Plant Physiology Reports*. 28, 78–91.

Barreto P., Counago R.M., Arruda P. (2020) Mitochondrial uncoupling protein-dependent signaling in plant bioenergetics and stress response. *Mitochondrion*, 53, 109-120.

Borovskii G.B., Gorbyleva E.L., Katyshev A.I., Korotaeva N.E., Polyakova E.A., Pyatrikas D.V., Fedoseeva I.V., Shigarova A.M. (2023) Effect of the overexpression of external alternative NADH dehydrogenase gene in Arabidopsis on the resistance of transformed tobacco plants to negative temperatures. *Izvestiya vuzov. Prikladnaya khimiya i biotekhnologiya = Proceedings of Universities. Applied Chemistry and Biotechnology*. 13, 516-522. (in Russian)

Borovskii G.B., Korotaeva N.E., Katyshev A.I., Fedoseeva I.V., Fedyaeva A.V., Kondakova M.A., Rikhvanov E.G., Shyshlova-Sokolovskaya A.M., Sauchyn D.G., Urbanovich O.Yu. (2021) The overexpression of the Arabidopsis NDB2 gene in tobacco plants affects the expression of genes encoding the alternative mitochondrial electron transport pathways and stress proteins. In *Plant Genetics, Genomics, Bioinformatics, and Biotechnology: Book of abstracts of the 6th International scientific conference. Novosibirsk*, 42.

Catania A., Iuso A., Bouchereau J., Kremer L.S., Paviolo M., Terrile C., Bénit P., Rasmusson A.G., Schwarzmayr T., Tiranti V., Rustin P., Rak M., Prokisch H., Schiff M. (2019) Arabidopsis thaliana alternative dehydrogenases: a potential therapy for mitochondrial complex I deficiency? Perspectives and pitfalls. *Orphanet Journal of Rare Diseases*, 14, 236.

Chadee A., Alber N.A., Dahal K., Vanlerberghe G.C. (2021) The complementary roles of chloroplast cyclic electron transport and mitochondrial alternative oxidase to ensure photosynthetic performance. *Front Plant Sci*, 12, 748204.

Clifton R., Lister R., Parker K.L. Sappl P.G., Elhafez D., Millar A.H., Day D.A., Whelan J. (2005) Stress-induced co-expression of alternative respiratory chain components in Arabidopsis thaliana. *Plant Mol. Biol.*, 58, 193–212.

Elhafez D., Murcha M.W., Clifton R., Soole K.L., Day D.A., Whelan J. (2006) Characterization of mitochondrial alternative NAD(P)H dehydrogenases in Arabidopsis: intraorganelle

location and expression. *Plant and Cell Physiology.*,47, 43–54.

Escobar M.A., Franklin K.A., Svensson A.S., Salter M.G., Whitelam G.C., Rasmusson A.G. (2004) Light regulation of the Arabidopsis respiratory chain. Multiple discrete photoreceptor responses contribute to induction of type II NAD(P)H dehydrogenase genes. *Plant Physiol.*, 136, 2710–2721.

Garmash E.V. (2021) Role of mitochondrial alternative oxidase in the regulation of cellular homeostasis during development of photosynthetic function in greening leaves. *Plant Biol.*, 23, 221-228.

Garmash E.V., Velegzhaninov I.O., Ermolina K.V., Rybak A.V., Malyshev R.V. (2020) Altered levels of AOX1a expression result in changes in metabolic pathways in Arabidopsis thaliana plants acclimated to low dose rates of ultraviolet B radiation. *Plant Science.*, 291, 110332.

Hao M.S., Jensen A.M., Boquist A.S., Liu Y.J., Rasmusson A.G. (2015) The Ca2+-regulation of the mitochondrial external NADPH dehydrogenase in plants is controlled by cytosolic pH. *PLoS One,* 10, e0139224.

Ikkonen E.N., Grabelnykh O.I., Sherudilo E.G. (2020) Salicylhydroxamic acid-resistant and sensitive components of respiration in chilling-sensitive plants subjected to a daily short-term temperature drop. *Russian J. Plant Physiol.*, 67, 60–67.

Igamberdiev A.U., Bykova N.V. (2023). Mitochondria in photosynthetic cells: Coordinating redox control and energy balance. *Plant Physiology*, 191, 2104-2119.

Igamberdiev A.U. (2020) Citrate valve integrates mitochondria into photosynthetic metabolism. *Mitochondrion*, 52, 218–230

Jethva J., Lichtenauer S., Schmidt-Schippers R., Steffen-Heins A., Poschet G., Wirtz M., van Dongen J.T., Eirich J., Finkemeier I., Bilger W., Schwarzländer M., Sauter M. (2023) Mitochondrial alternative NADH dehydrogenases NDA1 and NDA2 promote survival of reoxygenation stress in Arabidopsis by safeguarding photosynthesis and limiting ROS generation. *New Phytologist*, 238, 96-112.

Ježek P., Holendová B., Garlid K.D., Jabůrek M. (2018) Mitochondrial uncoupling proteins: subtle regulators of cellular redox signaling. *Antioxidants Redox Signal.*, 29, 667-714.

Korotaeva N.E., Shigarova A.M., Katyshev A.I., Fedoseeva I.V., Fedyaeva A.V., Sauchyn D.V., Shyshlova-Sokolovskaya A.M., Urbanovich O.Yu., Borovskii G.B. (2023) Effect of expression of the NDB2 heterologous gene of Arabidopsis thaliana on growth and respiratory activity of Nicotiana tabacum. *Russian J. Plant Physiol.*, 70, 93.

Laitz A.V., Acencio M.L., Budzinski I.G., Labate M.T., Lemke N., Ribolla P.E., Maia I.G. (2015) Transcriptome response signatures associated with the overexpression of a mitochondrial uncoupling protein (AtUCP1) in tobacco. *PLoS One*, 10, e0130744.

Lima R.P.M., Nunes-Laitz A.V., Arcuri M.D.L.C., Campos F.G., Joca T.A., Monteiro G.C., Kushima H., Lima G.P.P, de Almeida R.L.F., Barreto P., de Godoy Maia I. (2022) The double knockdown of the mitochondrial uncoupling protein isoforms reveals partial redundant roles during Arabidopsis thaliana vegetative and reproductive development. *Plant Science*, 322, 111365.

Liu S.S., Huang J.P. (1996) Coexistence of a reactive oxygen cycle with the Q cycle in the respiratory chain. A hypothesis for generating, partitioning, targeting and functioning of superoxide in mitochondria. In Parker, L, Traber, M.G., Xin W.J. (eds.), *Natural antioxidants molecular mechanism and health effects*. Champaign, IL, AOCS Press, pp. 513–529.

Liu Y.J., Norberg F.E.B., Szilágyi A., De Paepe R., Åkerlund H.-E., Rasmusson A.G. (2008) The mitochondrial external NADPH dehydrogenase modulates the leaf NADPH/NADP+ ratio in transgenic Nicotiana sylvestris. *Plant and Cell Physiology.*, 49, 251–263.

Michalecka A.M., Svensson A.S., Johansson F.I., Agius S.C., Johanson U., Brennicke A., Binder S., Rasmusson A.G. (2003) Arabidopsis genes encoding mitochondrial type II NAD(P)H

dehydrogenases have different evolutionary origin and show distinct responses to light. *Plant Physiol.*, 133, 642–652.

Møller I.M., Rasmusson A.G., van Aken O. (2021) Plant mitochondria — past, present and future. *Plant J.* 108. 912–959.

Popov V.N., Syromyatnikov M.Y., Fernie A.R., Chakraborty S., Gupta K.J., Igamberdiev A.U. (2021) The uncoupling of respiration in plant mitochondria: keeping reactive oxygen and nitrogen species under control. *Journal of Experimental Botany*, 72, 793-807.

Rasmusson A.G., Geisler D.A., Møller I.M. (2008) The multiplicity of dehydrogenases in the electron transport chain of plant mitochondria. *Mitochondrion*, 8, 47–60.

Ricquier D., Thibault J., Bouillaud F., Kuster Y. (1983) Molecular approach to thermogenesis in brown adipose tissue. Cell-free translation of mRNA and characterization of the mitochondrial uncoupling protein. *J. Biol. Chem.*, 258, 6675–6677.

Saha B., Borovskii G., Panda S.K. (2016) Alternative oxidase and plant stress tolerance. *Plant signaling & behavior.*, 11, e1256530.

Selinski J., Hartmann A., Deckers-Hebestreit G., Day D.A., Whelan J., Scheibe R. (2018a) Alternative oxidase isoforms are differentially activated by tricarboxylic acid cycle intermediates. *Plant Physiol*. 176, 1423–1432.

Selinski J, Hartmann A, Kordes A, Deckers-Hebestreit G, Whelan J, Scheibe R. (2017) Analysis of posttranslational activation of alternative oxidase isoforms. *Plant Physiol.*, 174, 2113–2127.

Selinski J., Scheibe R., Day D.A., Whelan J. (2018b) Alternative oxidase is positive for plant performance. *Trends Plant Sci.*, 23, 588–597.

Smith C., Barthet M., Melino V., Smith,P., Day D., Soole K. (2011) Alterations in the mitochondrial alternative NAD(P)H dehydrogenase NDB4 lead to changes in mitochondrial electron transport chain composition, plant growth and response to oxidative stress. *Plant cell physiol*. 52, 1222-1237.

Stepien P. Johnson G.N. (2018) Plastid terminal oxidase requires translocation to the grana stacks to act as a sink for electron transport. *Proc. Natl. Acad. Sci. USA*, 115, 9634–9639.

Sweetlove L.J., Lytovchenko A., Morgan M., Nunes-Nesi A., Taylor N.L., Baxter C.J., Eickmeie I., Fernie A.R. (2006) Mitochondrial uncoupling protein is required for efficient photosynthesis. *Proc. Natl. Acad. Sci. USA*, 103, 19587–19592.

Sweetman C., Selinski J., Miller T.K., Whelan J., Day D.A. (2022) Legume alternative oxidase isoforms show differential sensitivity to pyruvate activation. *Front. Plant Sci.* 12, 813691

Sweetman C., Waterman C.D., Rainbird B.M., Smith P.M., Jenkins C.D., Day D.A., Soole K.L. (2019) AtNDB2 is the main external NADH dehydrogenase in mitochondria and is important for tolerance to environmental stress. *Plant Physiol.*, 181, 774-788.

Vanlerberghe G.C., Dahal K., Alber N.A., Chadee A. (2020) Photosynthesis, respiration and growth: A carbon and energy balancing act for alternative oxidase. *Mitochondrion*, 52, 197-211.

Vercesi A.E, Borecký J, Maia I.G, Arruda P., Cuccovia I.M., Chaimovich H. (2006) Plant uncoupling mitochondrial proteins. *Ann. Rev. Plant Biol.* 57, 383–404.

Wallström S.V., Florez-Sarasa I., Araújo W.L., Escobar M.A., Geisler D.A., Aidemark M., Lager I., Fernie A.R., Ribas-Carbó M., Rasmusson A.G. (2014a) Suppression of NDA-type alternative mitochondrial NAD(P)H dehydrogenases in Arabidopsis thaliana modifies growth and metabolism, but not high light stimulation of mitochondrial electron transport. *Plant Cell Physiol.*, 55, 881-896.

Wallström S.V., Florez-Sarasa I., Araújo W.L., Aidemark M., Fernández-Fernández M., Fernie A.R., Ribas-Carbó M., Rasmusson A.G. (2014b) Suppression of the external mitochondrial NADPH dehydrogenase, NDB1, in Arabidopsis thaliana affects central metabolism and vegetative growth. *Mol. Plant*, 7, 356–368.

Wang D., Fu A. (2016) The plastid terminal oxidase is a key factor balancing the redox state of thylakoid

membrane. *Enzymes*, 40, 143–171.

Wanniarachchi V.R., Dametto L., Sweetman C., Shavrukov Y., Day D.A., Jenkins C.L., Soole K.L. (2018) Alternative respiratory pathway component genes (AOX and ND) in rice and barley and their response to stress. *Int. J. Mol. Sci.*, 19, 915.

Yerlikaya B.A., Ates D., Abudureyimu B., Aksoy E. (2022) Effect of climate change on abiotic stress response gene networks in Arabidopsis thaliana. In Prakash, C.S., Fiaz, S., Fahad, S. (Eds.) *Principles and practices of OMICS and genome editing for crop improvement*. Cham, Springer, pp. 149–172.