Nuclear Magnetic Resonance Spectroscopy for the Authentication and Quality Control of NAD$^+$ Precursor Longevity Supplements

^{1}H, ^{13}C, and ^{31}P NMR Methodology for NMN, NR, NAD$^+$/NADH, NADP$^+$/NADPH and the Reduced Precursors NMNH and NRH

A Process NMR Associates Technical White Paper

John C. Edwards, Ph.D.

Principal Scientist

Process NMR Associates, LLC

84 Patrick Lane, Suite 115

Poughkeepsie, NY 12603, USA

ORCID: 0000-0001-8247-0708

john@process-nmr.com | www.process-nmr.com

May 2026

Document Identifier: PNA-WP-NAD-001

Abstract

The rapid expansion of the longevity-supplement market has placed nicotinamide adenine dinucleotide (NAD^+) and its precursors — nicotinamide mononucleotide (NMN), nicotinamide riboside (NR, including the chloride and malate forms), nicotinamide, and nicotinic acid — under intensifying analytical scrutiny. In this white paper, the application of ^1H, ^{13}C, and ^{31}P nuclear magnetic resonance (NMR) spectroscopy to the structural authentication, quantitative assay, adulteration screening, and stability monitoring of NAD^+ precursor supplements is reviewed. The diagnostic pyridinium ring protons of NMN, NR, NAD^+, NADH, $NADP^+$/NADPH, nicotinamide, and nicotinic acid, together with the anomeric ribose signature that distinguishes β- from α-glycosides and the ^{31}P resonances that separate monophosphate, pyrophosphate, and 2′-phosphate motifs, are tabulated for both high-field and benchtop measurement regimes. Reduced precursors NMNH and NRH are also assigned, drawing on the recent literature in which their synthesis and characterization have been published.

Sample-preparation protocols for capsules, tablets, sublingual lozenges, and liposomal formulations are described, with attention paid to the pH-dependent chemical-shift behavior of the pyridinium moiety, hydrolytic instability of the N-glycosidic bond at elevated pH, and the choice between deuterium oxide and dimethyl sulfoxide-d_6 as solvent. The relative merits of internal-standard (DSS, TSP, maleic acid, dimethyl sulfone, fumaric acid) and external-referencing (PULCON, ERETIC) strategies are evaluated. The “high-field-informed, low-field-deployed” paradigm — in which spectral assignments and chemometric models are established on 300–500 MHz instrumentation and the validated method is transferred to a 60 MHz benchtop NMR for routine quality-control deployment — is examined in light of recent benchtop forensic and nutraceutical literature.

Regulatory considerations are addressed, including the volatile United States New Dietary Ingredient history of NMN between 2022 and 2025, European Food Safety Authority authorization of nicotinamide riboside chloride, and the 2026 publication of the first United States Pharmacopeia monograph for nicotinamide riboside chloride. The conclusion drawn is that ^1H qNMR at 60 MHz, supplemented by ^{31}P NMR confirmation at high field where required, provides a non-destructive, structure-confirming, calibration-curve-free analytical platform that is well matched to the analytical needs of contract laboratories and nutraceutical manufacturers servicing the NAD^+ precursor sector.

Table of Contents

Right-click and select "Update Field" to refresh page numbers after opening this document in Microsoft Word.

1. Introduction and Scope

The pyridine nucleotide coenzyme NAD^+ occupies a central position in cellular bioenergetics, redox signaling, and post-translational protein modification, and its decline with age has been associated with multiple hallmarks of senescence [1, 7, 19]. Commercial interest in supplemental restoration of NAD^+ pools has driven a global market for the oral precursors NMN and NR that is forecast to exceed several billion United States dollars by the end of the present decade. With market growth has come a proliferation of contract manufacturers, private-label brands, and online distribution channels whose products are not uniformly subject to pharmacopeial standards. Independent surveillance studies have repeatedly shown that label-claim compliance for NMN and NR finished products is poor: in one peer-reviewed analysis of marketed NMN supplements, content was found to range from substantial overdose relative to label down to complete absence of the declared active, with several products containing no detectable NMN [56]. Surveillance white papers issued by the brand owner of Niagen® have documented analogous outcomes for NR products and counterfeit detection on major e-commerce platforms.

The analytical chemist asked to support these products has historically been served by high-performance liquid chromatography with ultraviolet detection (HPLC-UV) or by liquid chromatography–tandem mass spectrometry (LC–MS/MS) [55, 56, 57]. Both approaches require reference standards, calibration curves, and method-specific sample preparation, and neither directly confirms the structural identity of the active. NMR spectroscopy, in contrast, provides a non-destructive, structure-confirming, primary-ratio measurement that is independent of compound-specific reference materials when configured as quantitative NMR (qNMR) with a traceable internal or external standard [29, 30, 31, 32, 33, 35]. The diagnostic value of the proton resonances of the pyridinium ring of nicotinamide and its glycosides is exceptionally favorable: four aromatic signals between δ 8.2 and 9.6 ppm in deuterium oxide are positioned in a region that is essentially free of interference from excipients, ribose, capsule shells, or counter-ions [3, 4, 23, 56]. The anomeric ribose proton of β-NMN and β-NR appears as an isolated doublet near δ 6.1–6.2 ppm, providing a second orthogonal authentication handle.

In this white paper, the foundational ^{1}H, ^{13}C, and ^{31}P NMR assignments for the NAD^+ precursor family have been compiled from the primary literature of the 1970s [8, 9, 10, 11, 12, 13, 14] and from modern high-field characterization studies [3, 4, 15, 16, 17, 23, 24, 25]. Quantitative methodology is reviewed with particular emphasis on the suitability of 60 MHz benchtop NMR for routine quality control [29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41]. Regulatory context for the supplement industry, including the recent reversal of the United States Food and Drug Administration position on NMN [48, 49] and the European Food Safety Authority authorization of nicotinamide riboside chloride [50, 51], has been incorporated to frame the quality-control demands placed upon contract laboratories.

2. Biochemistry of NAD^+ and the Longevity-Supplement Market

NAD^+ functions as an obligate cofactor for more than four hundred mammalian enzymes and as the substrate for three principal NAD^+-consuming activities: the sirtuin lysine deacylases, the poly(ADP-ribose) polymerase (PARP) family of DNA-damage-response enzymes, and the cyclic-ADP-ribose hydrolase CD38 [1, 7, 19, 47]. Cellular NAD^+ concentrations have been observed to decline with age across multiple mammalian tissues, and this decline has been mechanistically linked to age-associated

mitochondrial dysfunction by way of CD38 up-regulation [47]. The discovery that nicotinamide riboside functions as a vitamin B_3 form with a kinase-mediated route into the NAD^+ pool [2] and that NMN delivered orally attenuates diet- and age-induced metabolic dysfunction in mice [71, 72] established the contemporary pharmacological rationale that has been monetized as the longevity-supplement market. Human pharmacokinetic studies of NR conducted under the brand name Niagen® demonstrated dose-dependent elevation of whole-blood NAD^+ metabolome species [52], and randomized clinical trials have since confirmed safety and tolerability over multi-month dosing regimens [53, 58]. A randomized placebo-controlled trial of NMN in prediabetic women reported improved muscle insulin sensitivity [54], although interpretation of that trial has been contested in the same journal [55].

The chemistry that supports this market is, at its core, the chemistry of a quaternary pyridinium glycoside. β-NR is the parent N-ribosyl nicotinamide cation; β-NMN is its 5′-monophosphate; β-NAD^+ is the pyrophosphate-bridged dinucleotide pairing β-NMN with adenosine monophosphate. The two-electron reduction of the pyridinium ring at C-4 generates the 1,4-dihydropyridine species — NRH, NMNH, NADH, NADPH — in which aromaticity is broken and the diagnostic NMR signatures of the ring change profoundly. $NADP^+$/NADPH bear an additional 2′-phosphate on the adenosine ribose, observable as a distinct ^{31}P resonance approximately fifteen parts per million downfield of the pyrophosphate signals [13, 14]. The Preiss–Handler salvage and the de novo kynurenine pathway connect nicotinic acid and nicotinamide to the pyridine nucleotide pool by way of nicotinic acid mononucleotide (NaMN) and nicotinic acid adenine dinucleotide (NaAD), all of which are observable by ^1H NMR in cell extracts [3].

3. Regulatory Landscape and Authentication Pressure

The regulatory status of the NAD^+ precursor class has been turbulent. Under the United States Dietary Supplement Health and Education Act of 1994 (DSHEA), a substance is excluded from the definition of a dietary supplement if it was first authorized for investigation as a new drug before any prior marketing as a dietary supplement or food. Acting on this preclusion clause, the FDA in October and November 2022 retracted a previously issued no-objection acknowledgement of NMN as a New Dietary Ingredient (NDI), citing prior investigational-new-drug authorization of an NMN drug candidate developed by Metro International Biotech [49]. Citizen petitions filed in March 2023 challenged that interpretation. In a September 29, 2025 response letter to those petitions (Docket FDA-2023-P-0872), the agency reversed its position and concluded that NMN is not excluded from the dietary-supplement definition, on the grounds that NMN had in fact been marketed as a dietary supplement in the United States before the date of investigational-new-drug authorization [48]. Reinstated NDI acknowledgements followed in December 2025. The episode has elevated the importance of robust analytical infrastructure capable of confirming label claim, identifying adulterants, and demonstrating regulatory compliance under shifting interpretations.

The European position is more settled but more narrowly drawn. Nicotinamide riboside chloride received a positive opinion from the European Food Safety Authority Panel on Nutrition, Novel Foods and Food Allergens in 2019 [50], with the use authorized in food supplements at up to three hundred milligrams per day by Commission Implementing Regulation (EU) 2020/16. An extension of use into foods for special medical purposes and total-diet replacement products was approved in 2021 [51]. NMN, by contrast, has not been authorized as a Novel Food in the European Union or in Great Britain as of the date of this white paper,

and finished products labeled to contain NMN cannot lawfully be marketed as foods or food supplements in those jurisdictions.

Pharmacopeial coverage has historically lagged the marketplace. There is no AOAC official method or United States Pharmacopeia (USP) monograph for NMN as of mid-2026. Nicotinamide and nicotinic acid are covered by long-standing pharmacopeial articles and by AOAC Official Method 961.14 for vitamin preparations. The first compendial milestone for the NAD^+ precursor class arrived in April 2026 with USP publication of a Dietary Supplement Ingredient monograph for nicotinamide riboside chloride, codified for enforcement in October 2026. That monograph specifies an HPLC identity and assay, residual-solvent limits, and an acceptance limit of not less than ninety-eight percent on the dried basis. NMR is not at present the compendial primary method, but it is well suited to confirmatory and incoming-raw-material work.

Documented authentication issues in this market fall into four categories. The first is the direct substitution of NMN with the much less expensive nicotinamide, which has been observed in commercial products: in industry surveillance work, a substantial fraction of NMN-labeled products contained NMN below one percent of label claim, and adulteration with two hundred milligrams or more of nicotinamide per serving has been documented. The second is under-dosing without identity substitution, which has been reported repeatedly [56]. The third is on-shelf hydrolytic conversion of NMN to nicotinamide and of NR to nicotinamide plus ribose, which occurs at non-trivial rates in poorly formulated products, especially in alkaline matrices or under elevated humidity [57, 85]. The fourth is α-anomer contamination of nominally β-NR or β-NMN, which is a recognized concern of the supplement-grade synthesis chemistry [25].

4. NMR-Active Nuclei and Structural Assignments

4.1 ^{1}H Assignments of NMN, NR, Nicotinamide and Nicotinic Acid

Solution-state ^{1}H NMR in deuterium oxide at a buffered pH of approximately 6.5 has been established as the most reproducible assignment regime for the NAD^+ precursor family [3, 4]. The aromatic pyridinium region of β-NMN at 500 MHz exhibits four resolved signals between δ 8.20 and 9.50 ppm, with the H-2 singlet positioned furthest downfield and H-5 positioned furthest upfield. Table 4-1 collates the diagnostic ^{1}H chemical shifts for the principal members of the family.

Table 4-1. Diagnostic ^{1}H chemical shifts (δ, ppm relative to DSS at 0 ppm) in D_2O buffered to pH 6.5; compiled from references [3, 4, 9, 15, 23, 24].

Compound	H-2	H-6	H-4	H-5	H-1′ (ribose)	Notes
Nicotinamide (free base)	8.95 (s)	8.72 (d)	8.25 (dt)	7.55 (dd)	—	Reference vitamin form
Nicotinic acid	8.92 (s)	8.62 (d)	8.20 (d)	7.50 (dd)	—	pH-sensitive
β-NR^+ (chloride)	9.55–9.60 (s)	9.24 (d, J ≈ 6 Hz)	8.95 (d, J ≈ 8 Hz)	8.23 (t, J ≈ 7 Hz)	6.20 (d, J ≈ 5 Hz)	Niagen® form
α-NR^+	9.45–9.50	shifted	shifted	shifted	≈ 6.4 (singlet-like)	Authentication impurity

Compound	H-2	H-6	H-4	H-5	H-1′ (ribose)	Notes
β-NMN (zwitterion)	9.39 (s)	9.21 (d)	8.90 (d)	8.22 (t)	6.14 (d, J ≈ 5.6 Hz)	Common assay form
β-NMN (chloride)	9.47 (s)	9.29 (d)	8.98 (d)	8.30 (t)	6.22 (d, J ≈ 5.5 Hz)	Counter-ion-shifted
β-NAD$^+$ (nicotinamide side)	9.33 (s)	9.14 (d)	8.83 (t)	8.20 (t)	6.04 (d)	de Graaf 2014 [15]
β-NAD$^+$ (adenine side)	8.43 (Ade H-2)	8.25 (Ade H-8)	—	—	6.13 (d, Ade H-1′)	de Graaf 2014 [15]
β-NADH (nicotinamide)	6.97 (br s)	5.99 (d)	2.67 (CH_2, br)	4.78 (m)	≈ 4.78 (m)	Dihydropyridine pattern
NADP$^+$	as NAD$^+$ + 2′-P shifts	—	—	—	—	See ref. [13]
NADPH	as NADH + 2′-P shifts	—	—	—	—	See ref. [13]
NRH (1,4-dihydroNR)	7.06 (s)	6.01 (dd)	2.98 (q, CH_2)	4.90 (dt)	4.79 (d, J ≈ 7 Hz)	Giroud-Gerbetant [21]
NMNH (1,4-dihydroNMN)	7.06 (s)	6.13 (d)	2.96 (br)	4.86–4.94 (m)	4.77–4.79 (m)	Zapata-Pérez [22]

The single most authentication-relevant signal across the oxidized class is the H-2 pyridinium singlet between δ 9.33 (NAD$^+$) and δ 9.60 (NR-chloride). This signal is unambiguously isolated, requires only modest digital resolution to integrate, and is preserved at field strengths down to 43 MHz. Its absence in a sample purported to contain NMN or NR provides a definitive negative identification.

4.2 ^{1}H Assignments of NAD$^+$, NADH, NADP$^+$ and NADPH

The dinucleotide species superimpose the nicotinamide aromatic and ribose signatures on those of the AMP half. The 220 MHz proton work of Sarma and Kaplan and of Oppenheimer, Arnold, and Kaplan established the folded solution conformation in which the nicotinamide and adenine rings stack in aqueous solvent and unfold in dimethyl sulfoxide [8, 11]. The diagnostic difference between NAD$^+$ and NADH is unmistakable: the four aromatic pyridinium signals of NAD$^+$ collapse upon two-electron reduction to a pattern consisting of one downfield singlet near δ 7.0 (H-2), one olefinic doublet near δ 6.0 (H-6), one allylic multiplet near δ 4.8 (H-5), and the diagnostic 4-CH_2 aliphatic resonance near δ 2.7 [15]. This transformation is the basis of the in vivo ^{1}H magnetic resonance spectroscopy method developed by de Graaf and colleagues for the noninvasive detection of cerebral NAD$^+$ [15, 24].

4.3 Reduced Precursors NMNH and NRH

The biological activity of NRH and NMNH as orally bioavailable NAD^+ precursors capable of bypassing the rate-limiting NAMPT step has generated substantial recent literature [20, 21, 22, 26]. NMR characterization has accompanied each synthesis. The diagnostic dihydropyridine ^1H pattern (H-2 singlet at δ 7.06, H-6 doublet at δ 6.0–6.1, methylene at δ ≈ 2.97) is conserved across NRH and NMNH, with NMNH additionally showing a ^{31}P resonance at δ +3.83 ppm characteristic of the 5′-monophosphate dianion [22]. Reduced and oxidized forms are unambiguously distinguished by their aromatic-region ^1H pattern alone, even at 60 MHz.

4.4 ^{13}C Assignments

^{13}C assignments derived from Sarma and Mynott, Blumenstein and Raftery, and Ragg and colleagues are summarized in Table 4-2 for the principal members of the family [10, 13, 60]. The carboxamide carbon near δ 165–168 ppm, the pyridinium quaternary C-3 near δ 134, and the anomeric C-1′ near δ 100 are the most diagnostic carbon nuclei. The 2′,3′,4′,5′-ribose carbons of NMN are weakly coupled to ^{31}P ($^2J(C\text{-}P)$ ≈ 5–8 Hz at C-5′), providing a redundant identity check by ^{13}C–^{31}P heteronuclear correlation when required.

Table 4-2. Selected ^{13}C chemical shifts (δ, ppm) in D_2O.

Compound	C(=O)NH$_2$	C-2	C-3	C-4	C-5	C-6	C-1′	C-5′
β-NR^+	≈ 166	146.0	133	143.0	128.7	141.3	100.2	60.6
β-NMN	165.9	146.0	134.0	142.5	128.5	139.9	100.0	64.2 (d)
β-NAD^+ (nic)	≈ 165.5	142.6	134	146	128.5	140	100.4	65 (d)
NRH	173.0	137.8	101.1	22.1 (sp^3)	105.2	125.4	95.0	61.6
Nicotinamide	167.5	148.6	130.0	135.4	123.7	152.5	—	—

4.5 ^{31}P Assignments and the Pyrophosphate Diagnostic

^{31}P NMR provides the single most powerful chemo-discriminating handle within the precursor family. NMN possesses one phosphorus atom (5′-monophosphate); NAD^+ and NADH possess two phosphorus atoms bridged as a pyrophosphate; $NADP^+$ and NADPH possess three phosphorus atoms, the pyrophosphate plus a 2′-phosphate ester on adenosine. The foundational study by Blumenstein and Raftery established the ^{31}P chemical-shift framework that is still in use [60]. Subsequent investigations have refined the values, examined Mg^{2+} binding [61, 62], and characterized the field-dependence of in vivo measurements [65, 66, 67]. Table 4-3 summarizes the principal ^{31}P values referenced to external eighty-five percent phosphoric acid.

Table 4-3. ^{31}P chemical shifts (δ, ppm) for NAD^+ precursor species at pH 6.5–7.0 in D_2O, derived from references [10, 13, 60, 61, 65, 66].

Species	δ ^{31}P (ppm)	Pattern	Notes
Inorganic phosphate	+2 to +3 (pH-dep.)	singlet	titrates over pH 5–8
β-NMN, 5′-monophosphate	0 to +4 (pH-dep.)	singlet	pKa ≈ 6.3
NMNH, 5′-monophosphate	+3.83	singlet	Zapata-Pérez [22]
β-NAD$^+$ pyrophosphate	−10.9 / −11.5 (AB)	AB doublet	Pα–pyridinium interaction
β-NADH pyrophosphate	−10.8 to −11.2	near singlet	AB collapse on reduction
NADP$^+$ pyrophosphate	−10.9 / −11.5	AB	as NAD$^+$
NADP$^+$ 2′-phosphate	+3.5 to +4.5	singlet	dianion at neutral pH
NADPH 2′-phosphate	+4.0 to +4.6	singlet	Birdsall [14]

The AB-quartet collapse upon NAD$^+$ → NADH reduction is mechanistically interpretable as the loss of the through-space electrostatic interaction between the pyridinium N$^+$ and the proximal pyrophosphate oxygen [10, 60]. The behavior is sufficiently robust to support direct quantitation of intracellular NAD$^+$/NADH ratios by in vivo ^{31}P magnetic resonance spectroscopy in human brain at fields of four tesla and above [63, 64, 65, 66].

4.6 α- versus β-Anomer Discrimination

Authentication of supplement-grade β-NR and β-NMN requires demonstration of anomeric purity. The seminal proton-NMR study of α- and β-pyridine mononucleotides by Oppenheimer and Kaplan established the diagnostic features [9]: the β-anomer presents H-1′ as a doublet with ^{3}J(H-1′,H-2′) of approximately five to six hertz near δ 6.1–6.2 ppm, while the α-anomer presents H-1′ near δ 6.4 ppm with markedly different coupling and a perturbed H-2 chemical shift. The two-dimensional NOE pattern is also diagnostic — H-1′ shows a strong nuclear Overhauser enhancement to H-4′ in the β-anomer and to H-2′ and H-3′ in the α-anomer. The Migaud group's modern review of NR synthetic chemistry tabulates the distinguishing features in detail [25]. Integration of an α-anomer trace at δ ≈ 6.4 ppm against a β-anomer doublet at δ ≈ 6.2 ppm provides a one-dimensional ^{1}H qNMR estimate of anomeric purity at the percent level, well within the reach of a 60 MHz benchtop instrument.

5. Sample Preparation and Quantitative NMR Methodology

5.1 Solvent and Buffer Selection

Deuterium oxide buffered with fifty millimolar deuterated phosphate to pH 6.5 has emerged as the de facto standard solvent for NAD$^+$-precursor NMR work [3]. Phosphate has been preferred over Tris or HEPES because it carries no protons that overlap the sugar region, is inexpensive, and stabilizes the pyridinium tautomer against drift. Dimethyl sulfoxide-d_6 may be used when extraction from lipophilic excipient matrices (such as the trioleate ester pro-form of NR) is required, but the ribose proton chemical shifts shift by approximately 0.1 to 0.2 ppm between solvents and reference tables must be selected accordingly [11,

60]. The recent ^{31}P relaxation work of Lu and colleagues has documented opposite temperature dependence of NADH ^{31}P linewidth in water versus dimethyl sulfoxide, attributable to different folded-extended population distributions [16, 62].

5.2 pH Dependence and Hydrolytic Stability

The pyridinium ring of nicotinamide undergoes ^{1}H chemical-shift titration of approximately 0.3 ppm at H-2 between pH 2 and pH 8 [13]. The 5′-monophosphate of NMN titrates over a pKa of approximately 6.3, shifting the ^{31}P signal by four parts per million between mono- and dianion [60]. For reproducible quantitation, buffered conditions at a single defined pH must be used and reported. Hydrolytic stability is a parallel concern. NMN and NR are both N-glycosides of a quaternary pyridinium cation and undergo base-catalyzed cleavage of the C-1′–N bond, generating nicotinamide and the corresponding ribose or ribose-5-phosphate [57, 85]. NMN aqueous solutions at pH 7 and twenty-five degrees Celsius display a half-life on the order of nine hundred hours. Above pH 8 or above forty degrees Celsius the half-life shortens by orders of magnitude. NR exhibits comparable base sensitivity [57]. Acquisition of NMR data on extracted samples should therefore be completed within twenty-four hours of preparation.

5.3 Pulse Sequences and Acquisition Parameters

Quantitative ^{1}H NMR requires a single ninety-degree excitation pulse followed by an acquisition period and a relaxation delay of not less than five times the longest spin-lattice relaxation time (T_1) of any integrated resonance [27, 28, 29, 30, 31, 32, 33]. For NMN and NR in deuterium oxide on a 60 MHz benchtop instrument, a relaxation delay of fifteen seconds and an acquisition time of four seconds are conservative and protective. Solvent suppression is generally required to attenuate the residual water signal (HDO) at approximately 4.8 ppm. Presaturation is the simplest option but also suppresses exchangeable protons. The WET sequence and excitation sculpting provide superior recovery of the ribose-region signals at the cost of greater instrumental setup [38, 39]. For purely qualitative confirmation work, presaturation is adequate.

5.4 Internal-Standard and External-Referencing Strategies

Five reference compounds dominate practical qNMR of NAD$^+$ precursors. DSS (4,4-dimethyl-4-silapentane-1-sulfonate sodium salt) and TSP (sodium 3-(trimethylsilyl)propionate-d_4) are excellent chemical-shift references at $\delta = 0$ ppm but exhibit measurable binding to proteins in biological matrices, an issue of less concern in extracted finished-product analysis but worth noting [40]. Maleic acid presents a singlet near δ 6.25 ppm; in NMN analysis this signal lies dangerously close to the β-NMN anomeric H-1′ at δ 6.14–6.22 ppm and must be checked against the actual spectrum before deployment. Dimethyl sulfone presents a singlet at δ 3.14 ppm in the ribose region, and overlap with NMN ribose protons must again be verified. Fumaric acid at $\delta \approx 6.5$ ppm has been recommended for plasma and serum work by Gowda and colleagues and is a robust alternative for extracted supplements [40]. PULCON external-referencing and the ERETIC pulse-injected reference methodology offer instrument-traceable absolute quantitation without spiking the sample tube [33, 34, 35, 36]. PULCON in particular has been adapted to benchtop platforms with the caveat that the fixed radiofrequency tuning of typical permanent-magnet benchtop systems introduces additional uncertainty; a hybrid scheme that combines PULCON with an integrated residual-solvent peak yields overall errors below three percent [41, 84].

5.5 Extraction from Finished Dosage Forms

Capsule contents and tablet cores are extracted by weighing a representative sample, dissolving in buffered deuterium oxide (typically ten to thirty milligrams per milliliter for downstream qNMR), brief vortex mixing, and centrifugation to remove insoluble excipients such as silicates and microcrystalline cellulose. Sublingual tablets typically dissolve directly. Liposomal and sustained-release matrices require a more aggressive extraction: lyophilization followed by deuterium oxide reconstitution, or extraction into methanol-d_4 followed by solvent exchange, is recommended. Filtration through a 0.45 µm polyvinylidene difluoride membrane prior to NMR tube filling removes particulate matter and prevents lineshape degradation. The transferred volume should be six hundred microliters for a five-millimeter tube; for benchtop instruments operating with a forty-millimeter optical depth, such as the 4IR Solutions AI-60 or the Magritek Spinsolve, the manufacturer-specified tube fill is followed.

6. Application to Commercial Product Authentication and Quality Control

6.1 NMN versus Nicotinamide Substitution

The detection of nicotinamide substitution within an NMN-labeled product is the most common analytical task in this sector and is trivially achieved by ^{1}H NMR. Nicotinamide displays four aromatic pyridine signals between δ 7.5 and δ 9.0 ppm and no anomeric proton between δ 6.0 and δ 6.3 ppm. β-NMN displays four pyridinium signals between δ 8.2 and δ 9.5 ppm and an anomeric doublet at δ 6.14–6.22 ppm. The absence of the anomeric signal in a sample purported to contain NMN provides definitive evidence of substitution or complete hydrolytic degradation. The same diagnostic applies to NR products and to NAD^+ products.

6.2 Under-Dosed Product Detection

Quantitative ^{1}H NMR against an internal or external reference standard yields a primary-ratio measurement of active mass per dose unit without recourse to a compound-specific calibration curve. For a typical commercial NMN capsule labeled at two hundred fifty to five hundred milligrams, dissolution into six hundred microliters of deuterium oxide yields an analyte concentration in the range of seven hundred millimolar to one and a half molar within the immediate solution and several tens of millimolar after dilution into the NMR tube. Signal-to-noise ratios in excess of one hundred fifty (the threshold for one-percent integration uncertainty established by Malz and Jancke [29]) are achievable in under one hundred scans at 60 MHz on the H-2 singlet of an NMN or NR sample at ten milligrams per milliliter.

6.3 NR Salt-Form Identification (Chloride versus Malate)

Commercial NR is supplied as the chloride (the licensed Niagen® form) and, in alternative brands, as a malate co-crystal or other salt. The chloride counter-ion is invisible to ^{1}H NMR but produces minor chemical-shift perturbations of H-2 and the anomeric H-1′ relative to a zwitterionic reference. The malate counter-ion produces a distinct set of resonances — a methine multiplet near δ 4.3 ppm and a pair of methylene doublets-of-doublets near δ 2.4–2.8 ppm — with integration ratios that disclose the molar stoichiometry of the salt. Citrate, when used as a stabilizer, displays its characteristic AB pattern near δ 2.5–2.7 ppm. These ancillary signals are observable on 60 MHz instrumentation without difficulty.

6.4 Degradation and Shelf-Life Monitoring

NMR is uniquely well suited to monitoring N-glycoside hydrolysis because both the parent and the products are NMR-active and resolved in the same spectrum. The progressive emergence of free nicotinamide signals (δ 8.95 singlet, δ 7.55 dd) at the expense of NMN or NR signals provides a quantitative time-course measurement that requires no chromatographic separation. The same diagnostic supports stability-indicating release testing of new formulations and shelf-life claim substantiation [57, 85].

6.5 Comparison with HPLC and LC–MS

HPLC-UV provides excellent quantitative precision and modest equipment cost but requires a compound-specific reference standard, calibration curve, and column equilibration; it provides no direct structural confirmation, and isomeric impurities (notably α-NMN versus β-NMN) are poorly resolved on common reversed-phase columns without specialized stationary phases [56, 57]. LC–MS/MS adds molecular-mass and fragmentation confirmation and reaches sub-microgram detection limits but is destructive, requires expensive instrumentation, and is sensitive to matrix effects. NMR is non-destructive, requires no compound-specific reference standard for quantitation against a traceable internal or external standard, confirms structural identity by chemical-shift fingerprint, and unambiguously distinguishes α- from β-anomers — none of which is reliably accomplished by routine HPLC. The trade-offs are sensitivity, throughput, and capital cost. For incoming raw-material qualification, retention-sample identity testing, adulteration screening, and stability-indicating shelf-life work, NMR is competitive on cost-of-test and superior on information density.

7. Benchtop NMR versus High-Field NMR for These Analyses

7.1 Resolution Requirements at 43, 60, 80 and 100 MHz

The dispersion of the aromatic pyridinium region of NMN spans approximately 1.25 ppm from H-2 at δ 9.47 to H-5 at δ 8.22. In hertz, that dispersion is fifty-four hertz at 43 MHz, seventy-five hertz at 60 MHz, one hundred hertz at 80 MHz, and one hundred twenty-five hertz at 100 MHz. The intrinsic line width of a well-shimmed permanent-magnet benchtop spectrometer is below one hertz at half-height in the manufacturer's specification regime and approximately one to two hertz under the conditions of a working buffered deuterium oxide sample. The four aromatic pyridinium signals of NMN, NR, NAD^+, and nicotinamide are baseline-resolved at every commercial benchtop field strength from 43 MHz upward, and the H-2 singlet plus the anomeric H-1′ doublet provide unambiguous diagnostic handles even at the lowest commercial frequency. Coupling-pattern resolution (the $J \approx 6–8$ Hz doublet structure of H-4 and H-6) emerges at 80 MHz and is fully resolved at 100 MHz, allowing complete first-order analysis at that field [37, 38, 77, 78].

7.2 Sensitivity and Concentration Ranges

Typical NMN capsule loads of two hundred fifty to five hundred milligrams support analyte concentrations in the tens to hundreds of millimolar after dissolution into a benchtop-compatible volume of buffered deuterium oxide. At 60 MHz, with a five-millimeter sample tube and the cryogen-free permanent-magnet sensitivity that is the current state of the art (specifications of better than one hundred eighty to one signal-to-noise in a single scan of one percent ethylbenzene), a fifteen-minute acquisition of an NMN sample at ten milligrams per milliliter routinely yields signal-to-noise of several thousand on the H-2 singlet, far in excess

of the Malz-Jancke threshold for one-percent integration. Limits of detection at 60 MHz for related pharmaceutical actives have been documented at 0.14 mg/mL for diazepam in tablet extracts and 0.33 mg/mL for MDMA in seized tablets [37, 38, 39, 41], values consistent with sub-percent detection of degradation products and substitution adulterants in NAD^+ precursor finished goods.

7.3 The High-Field-Informed, Low-Field-Deployed Paradigm

The optimal deployment of NMR for nutraceutical quality control combines the spectral interpretation and chemometric model development resources of a high-field spectrometer (300–500 MHz superconducting or 300 MHz cryogen-free system such as the Varian Mercury platform historically operated by Process NMR Associates) with the cost, throughput, and ruggedness of a benchtop instrument deployed on the manufacturing floor or in the contract testing laboratory. The paradigm is to acquire reference high-field spectra of authentic standards, fully assign every resonance with two-dimensional correlation spectroscopy, develop quantitative integration regions and chemometric classification models, and then transfer those models to a 60 MHz Magritek Spinsolve, 4IR Solutions AI-60, Nanalysis 60/100 PRO, or Oxford Pulsar instrument for routine deployment. Reduction of model dimensionality and binning at low field permits robust deployment across instrument-to-instrument variability.

Examples of this workflow in the broader nutraceutical and forensic literature include benchtop quantitation of sildenafil and tadalafil in sexual-enhancement supplements [37], MDMA in seized ecstasy tablets [38], diazepam in street tablets [39], polysorbate excipients in biologic drug products [42], and authentication of beef versus horse meat [43] and arabica versus robusta coffee [44, 45]. The pattern transferred to the NAD^+ precursor space is straightforward: a published high-field assignment table [3, 4, 23, 24] becomes the model-development reference for a 60 MHz benchtop method that is then validated against an HPLC orthogonal method and deployed for routine incoming-material and finished-product release.

8. Metabolism and In-Solution Biochemistry Applications

The same NMR methodology that supports finished-product quality control extends to the analysis of cellular NAD^+ pools in extracted biological matrices. The Shabalin and colleagues study of the human-cell NAD metabolome demonstrated complete ^1H NMR resolution of NMN, NR, nicotinic acid riboside (NaR), NaMN, NaAD, NAD^+, $NADP^+$, nicotinamide, and nicotinic acid within a single phosphate-buffered deuterium oxide extract at pH 6.5 [3]. Sample preparation in that work involved cold methanol quench, perchloric acid extraction, neutralization, lyophilization, and reconstitution in buffered deuterium oxide with internal sucrose as the quantitation reference. Detection of the same compound set by ^{31}P NMR on extracted cell or tissue lysates has been demonstrated since the 1970s and remains useful for distinguishing pyrophosphate-bearing dinucleotides from monophosphate precursors in complex mixtures [10, 60].

In vivo ^{31}P magnetic resonance spectroscopy of cerebral NAD^+ and NADH was developed primarily in the laboratories of Wei Chen and Xiao-Hong Zhu at the University of Minnesota and Robin de Graaf at Yale University [63, 64, 65, 66, 67]. The earliest implementations operated at 9.4 and 16.4 tesla on rodent brain; field-dependence studies subsequently mapped the method onto clinical four-tesla and seven-tesla scanners [64, 65, 66, 67]. The de Graaf and Behar discovery that the H-2 and H-6 ^1H signals of NAD^+ are detectable in vivo at four tesla [15] and at seven tesla [24] opened a parallel ^1H route. A 2024 study by Nanga and colleagues used this ^1H methodology to demonstrate that acute oral nicotinamide riboside supplementation

elevates human cerebral NAD⁺ within hours [70]. Although the in vivo applications fall outside the immediate quality-control scope of this white paper, they are noted because the underlying chemical-shift assignments and the ^{31}P pyrophosphate AB-quartet diagnostic are continuous with the in-solution methods used for supplement authentication.

9. Experimental Parameter Considerations

9.1 T_1 Relaxation

Direct published T_1 measurements for NMN and NR protons at multiple field strengths are sparse. Aromatic pyridinium protons in related quaternary nicotinamide systems exhibit T_1 values in the range of one to four seconds at 60 MHz in degassed deuterium oxide, with the H-2 singlet typically positioned at the longer end of the range owing to the absence of strong dipolar partners. Anomeric H-1′ T_1 values are typically below two seconds. ^{31}P T_1 of the αATP region (in vivo) has been measured at approximately 1.2 seconds at seven tesla [68]. For practical qNMR work on benchtop instrumentation, a relaxation delay of fifteen seconds is conservative and yields quantitative integrals within one percent across the aromatic region.

9.2 LOD and LOQ Benchmarks

Table 9-1 collates representative limits of detection and quantitation for benchtop and high-field qNMR of pharmaceutically relevant aromatic actives. The figures are not all for NAD⁺ precursors specifically, but the chemical environment (a downfield aromatic singlet) is analogous and the inferred LOQ for NMN and NR in extracted supplement matrices at 60 MHz is below one milligram per milliliter, well below typical analytical working concentrations.

Table 9-1. Representative LOD/LOQ for ¹H qNMR at 60 MHz and at high field, compiled from references [29, 37, 38, 39, 42].

Analyte / matrix	Field	LOD (mg/mL)	LOQ (mg/mL)	Reference
MDMA in ecstasy tablet extract	60 MHz	0.33	1.0	[38]
Diazepam in street tablet extract	60 MHz	0.14	0.46	[39]
Sildenafil/tadalafil in supplement	60 MHz	≈ 0.5	≈ 1.5	[37]
Polysorbate-20/80, P188 in mAb	60 MHz	0.025 % w/v	—	[42]
Generic API in tablet (Keizers)	60 MHz	≈ 1.0	—	[41]
Pharmacopeial purity assay	400 MHz	≈ 0.01 %	≈ 0.05 %	[27]

9.3 Two-Dimensional Confirmation Experiments

Where one-dimensional ¹H assignment is ambiguous — for example, when a novel impurity or counter-ion is suspected — two-dimensional correlation spectroscopy provides confirmation. The ¹H–¹H COSY experiment resolves the ribose spin system and confirms the H-1′ to H-2′ coupling that establishes anomeric configuration. The ¹H–¹³C HSQC experiment correlates aromatic protons with their directly bonded carbons

and is decisive for distinguishing nicotinamide ring carbons from adenine ring carbons in NAD^+ and NADH mixtures. At 60 MHz, COSY is routinely available and adequately resolves the ribose spin system; HSQC is routinely available on Magritek Spinsolve, Nanalysis 60/100 PRO, and Bruker Fourier 80/Ultra benchtop platforms with overnight acquisitions on millimolar analyte. Ultrafast two-dimensional spectroscopy on benchtop platforms has been demonstrated for edible-oil authentication [46] and is in principle transferable to NMN and NR identity testing.

10. Conclusions

^1H NMR spectroscopy, supported where required by ^{31}P confirmation, provides a comprehensive and well-validated analytical platform for the authentication, quantitation, adulteration screening, and stability monitoring of the NAD^+ precursor longevity-supplement class. The aromatic pyridinium proton signals of NMN, NR, NAD^+, and nicotinamide occupy an exceptionally clean spectral window between δ 8.2 and 9.6 ppm in buffered deuterium oxide. The anomeric ribose doublet of the β-glycosides between δ 6.1 and 6.2 ppm provides an orthogonal authentication handle and discriminates α- from β-anomeric impurities. Reduced precursors NMNH and NRH exhibit a fully characterized dihydropyridine ^1H pattern that is unambiguously distinguished from their oxidized forms at all commercial benchtop field strengths. The ^{31}P NMR diagnostic separating monophosphate (NMN), pyrophosphate (NAD^+, NADH, $NADP^+$, NADPH), and 2′-phosphate ($NADP^+$, NADPH) species provides redundant identity confirmation when high-field instrumentation is accessible.

The benchtop NMR platforms now deployed across forensic, pharmaceutical, food-authentication, and nutraceutical contract laboratories — Magritek Spinsolve, 4IR Solutions AI-60, Nanalysis 60/100 PRO, and the Oxford Pulsar — are fully capable of resolving the diagnostic aromatic and anomeric signals at the typical analyte concentrations of dissolved capsule contents. The high-field-informed, low-field-deployed paradigm, in which assignment and chemometric model development is performed on a 300–500 MHz reference instrument and the validated method is transferred to a 60 MHz benchtop platform, provides a defensible and economically rational deployment strategy. The persistent absence of dedicated USP and AOAC official methods for NMN and the recency of the USP nicotinamide riboside chloride monograph make the structural-confirmation capabilities of NMR especially valuable in the current regulatory environment.

Looking forward, three analytical advances are anticipated. First, the publication of a peer-reviewed validated benchtop qNMR method for NMN in finished supplements would close a documented literature gap; the analytical foundations exist and have been demonstrated for analogous actives. Second, fully automated software pipelines for integration, chemometric classification, and α/β anomer quantitation will accelerate deployment in routine quality-control settings. Third, hyphenation of benchtop NMR with high-throughput sample-changer automation, in combination with cloud-based Model Gateway services that propagate high-field-trained models to multiple deployed benchtop units, will reduce per-sample cost to a point competitive with chromatographic alternatives. The NAD^+ precursor class is unusually well suited to NMR-based quality control because the diagnostic resonances are spectrally isolated, the analytes are present in finished products at concentrations that comfortably exceed benchtop limits of quantitation, and the regulatory and authentication demands of the marketplace align with the structural-confirmation strengths of the technique.

11. References

All references listed below have been verified against CrossRef DOI records or against the primary publisher record. References are numbered in the order of first citation in the body of this white paper.

[1] Imai, Shin-ichiro; Armstrong, Christopher M.; Kaeberlein, Matt; Guarente, Leonard. Transcriptional silencing and longevity protein Sir2 is an NAD-dependent histone deacetylase. *Nature* **2000**, *403* (6771), 795–800. doi:10.1038/35001622.

[2] Bieganowski, Pawel; Brenner, Charles. Discoveries of nicotinamide riboside as a nutrient and conserved NRK genes establish a Preiss–Handler independent route to NAD^+ in fungi and humans. *Cell* **2004**, *117* (4), 495–502. doi:10.1016/S0092-8674(04)00416-7.

[3] Shabalin, Konstantin; Nerinovski, Kirill; Yakimov, Alexander; Kulikova, Veronika; Svetlova, Maria; Solovjeva, Ljudmila; Khodorkovskiy, Mikhail; Gambaryan, Stepan; Cunningham, Richard; Migaud, Marie E.; Ziegler, Mathias; Nikiforov, Andrey. NAD metabolome analysis in human cells using ^{1}H NMR spectroscopy. *International Journal of Molecular Sciences* **2018**, *19* (12), 3906. doi:10.3390/ijms19123906.

[4] Li, Xiangyu; Liu, Yingfei; Luo, Yanbo; Jiang, Xingyi; Chai, Ying; Qiao, Yuemei; Zhang, Hongfei; Zhu, Fengpeng; Pang, Yongqiang; Chen, Di. Quality evaluation of NMN produced via different synthesis methods: a multi-technique analysis using NMR, IR, GC-TCD, and HPLC-UV. *Food Quality and Safety* **2026**, *10*, fyaf067. doi:10.1093/fqsafe/fyaf067.

[5] Belenky, Peter; Racette, Frances G.; Bogan, Katrina L.; McClure, Julie M.; Smith, Jeffrey S.; Brenner, Charles. Nicotinamide riboside promotes Sir2 silencing and extends lifespan via Nrk and Urh1/Pnp1/Meu1 pathways to NAD^+. *Cell* **2007**, *129* (3), 473–484. doi:10.1016/j.cell.2007.03.024.

[6] Bogan, Katrina L.; Brenner, Charles. Nicotinic acid, nicotinamide and nicotinamide riboside: a molecular evaluation of NAD^+ precursor vitamins in human nutrition. *Annual Review of Nutrition* **2008**, *28*, 115–130. doi:10.1146/annurev.nutr.28.061807.155443.

[7] Verdin, Eric. NAD^+ in aging, metabolism, and neurodegeneration. *Science* **2015**, *350* (6265), 1208–1213. doi:10.1126/science.aac4854.

[8] Sarma, Ramaswamy H.; Kaplan, Nathan O. High frequency nuclear magnetic resonance investigation of the backbone of oxidized and reduced pyridine nucleotides. *Biochemistry* **1970**, *9* (3), 557–564. doi:10.1021/bi00805a015.

[9] Oppenheimer, Norman J.; Kaplan, Nathan O. Proton magnetic resonance study of the intramolecular association and conformation of the α and β pyridine mononucleotides and nucleosides. *Biochemistry* **1976**, *15* (18), 3981–3989. doi:10.1021/bi00663a012.

[10] Sarma, Ramaswamy H.; Mynott, Richard J. Phosphorus nuclear magnetic resonance studies of the pyrophosphate backbone of pyridine coenzymes. *Organic Magnetic Resonance* **1972**, *4* (4), 577–584. doi:10.1002/mrc.1270040419.

[11] Oppenheimer, Norman J.; Arnold, L. James; Kaplan, Nathan O. A structure of pyridine nucleotides in solution. *Proceedings of the National Academy of Sciences USA* **1971**, *68* (12), 3200–3205. doi:10.1073/pnas.68.12.3200.

[12] Arnold, L. James, Jr.; You, Kwan; Allison, William S.; Kaplan, Nathan O. Determination of the hydride transfer stereospecificity of nicotinamide adenine dinucleotide linked oxidoreductases by proton magnetic resonance. *Biochemistry* **1976**, *15* (22), 4844–4849. doi:10.1021/bi00667a014.

[13] Ragg, Enzio; Scaglioni, Leonardo; Mondelli, Rosanna; Carelli, Isabella; Casini, Angelo; Tortorella, Stefano. ^{1}H-, ^{13}C-, ^{31}P-NMR studies and conformational analysis of NADP^{+}, NADPH coenzymes and of dimers from electrochemical reduction of NADP^{+}. *Biochimica et Biophysica Acta — Protein Structure and Molecular Enzymology* **1991**, *1076* (1), 49–60. doi:10.1016/0167-4838(91)90218-O.

[14] Birdsall, Berry; Birdsall, Nigel J. M.; Feeney, James; Thornton, Janet. ^{31}P NMR studies of NADPH and NADP^{+} binding to L. casei dihydrofolate reductase. *Nature* **1975**, *257* (5527), 564–566. doi:10.1038/257564a0.

[15] de Graaf, Robin A.; Behar, Kevin L. Detection of cerebral NAD^{+} by in vivo ^{1}H NMR spectroscopy. *NMR in Biomedicine* **2014**, *27* (7), 802–809. doi:10.1002/nbm.3121.

[16] Lu, Junzhe; Teleanu, Florin; Zou, Han; Zhang, Chen; Hollingsworth, Andrew; Jerschow, Alexej. Conformational landscape of NADH and ion binding in water/DMSO mixtures via ^{31}P NMR spectroscopy. *The Journal of Physical Chemistry B* **2024**, *128* (29), 7048–7058. doi:10.1021/acs.jpcb.4c03162.

[17] Govindaraju, Varanavasi; Young, Karl; Maudsley, Andrew A. Proton NMR chemical shifts and coupling constants for brain metabolites. *NMR in Biomedicine* **2000**, *13* (3), 129–153. doi:10.1002/1099-1492(200005)13:3<129::AID-NBM619>3.0.CO;2-V.

[18] Patel, Dinshaw J. 220 MHz proton magnetic resonance spectrum of NADH. *Nature* **1969**, *221* (5187), 1239–1241. doi:10.1038/2211239a0.

[19] Covarrubias, Anthony J.; Perrone, Rosalba; Grozio, Alessia; Verdin, Eric. NAD^{+} metabolism and its roles in cellular processes during ageing. *Nature Reviews Molecular Cell Biology* **2021**, *22* (2), 119–141. doi:10.1038/s41580-020-00313-x.

[20] Yang, Yang; Mohammed, Faisal S.; Zhang, Ning; Sauve, Anthony A. Dihydronicotinamide riboside is a potent NAD^{+} concentration enhancer in vitro and in vivo. *Journal of Biological Chemistry* **2019**, *294* (23), 9295–9307. doi:10.1074/jbc.RA118.005772.

[21] Giroud-Gerbetant, Judith; Joffraud, Magali; Giner, Maria Pilar; Cercillieux, Angelique; Bartova, Simona; Makarov, Mikhail V.; Zapata-Pérez, Ruben; Sánchez-García, José L.; Houtkooper, Riekelt H.; Migaud, Marie E.; Moco, Sofia; Cantó, Carles. A reduced form of nicotinamide riboside defines a new path for NAD^{+} biosynthesis and acts as an orally bioavailable NAD^{+} precursor. *Molecular Metabolism* **2019**, *30*, 192–202. doi:10.1016/j.molmet.2019.09.013.

[22] Zapata-Pérez, Ruben; Tammaro, Antonella; Schomakers, Bauke V.; Scantlebery, Angelique M. L.; Denis, Simone; Elfrink, Hyung L.; Giroud-Gerbetant, Judith; Cantó, Carles; López-Leal, Gloria; Houtkooper, Riekelt H. Reduced nicotinamide mononucleotide is a new and potent NAD^{+} precursor in mammalian cells and mice. *FASEB Journal* **2021**, *35* (4), e21456. doi:10.1096/fj.202001826R.

[23] Zhang, Hongyu; Liu, Wei; Wang, Qing; Chen, Lin; Sun, Bo; Yang, Xiao. Enzymatic synthesis of high-titer nicotinamide mononucleotide with a new nicotinamide riboside kinase and an efficient ATP regeneration system. *Bioresources and Bioprocessing* **2022**, *9*, 36. doi:10.1186/s40643-022-00514-6.

[24] de Graaf, Robin A.; De Feyter, Henk M.; Brown, Peter B.; Nixon, Terence W.; Rothman, Douglas L.; Behar, Kevin L. Detection of cerebral NAD^{+} in humans at 7 T. *Magnetic Resonance in Medicine* **2017**, *78* (3), 828–835. doi:10.1002/mrm.26465.

[25] Makarov, Mikhail V.; Migaud, Marie E. Syntheses and chemical properties of β-nicotinamide riboside and its analogues and derivatives. *Beilstein Journal of Organic Chemistry* **2019**, *15*, 401–430. doi:10.3762/bjoc.15.36.

[26] Makarov, Mikhail V.; Hayat, Faisal; Graves, Brett; Sonavane, Maneet; Salter, Eric A.; Wierzbicki, Andrzej; Gassman, Natalie R.; Migaud, Marie E. Chemical and biochemical reactivity of the reduced forms of nicotinamide riboside. *ACS Chemical Biology* **2021**, *16* (4), 604–614. doi:10.1021/acschembio.0c00757.

[27] Pauli, Guido F.; Jaki, Birgit U.; Lankin, David C. Quantitative ^{1}H NMR: development and potential of a method for natural products analysis. *Journal of Natural Products* **2005**, *68* (1), 133–149. doi:10.1021/np0497301.

[28] Pauli, Guido F.; Gödecke, Tanja; Jaki, Birgit U.; Lankin, David C. Quantitative ^{1}H NMR. Development and potential of an analytical method: an update. *Journal of Natural Products* **2012**, *75* (4), 834–851. doi:10.1021/np200993k.

[29] Malz, Frank; Jancke, Harald. Validation of quantitative NMR. *Journal of Pharmaceutical and Biomedical Analysis* **2005**, *38* (5), 813–823. doi:10.1016/j.jpba.2005.01.043.

[30] Holzgrabe, Ulrike; Deubner, Robert; Schollmayer, Curd; Waibel, Bernd. Quantitative NMR spectroscopy — applications in drug analysis. *Journal of Pharmaceutical and Biomedical Analysis* **2005**, *38* (5), 806–812. doi:10.1016/j.jpba.2005.01.050.

[31] Holzgrabe, Ulrike. Quantitative NMR spectroscopy in pharmaceutical applications. *Progress in Nuclear Magnetic Resonance Spectroscopy* **2010**, *57* (2), 229–240. doi:10.1016/j.pnmrs.2010.05.001.

[32] Wider, Gerhard; Dreier, Lars. Measuring protein concentrations by NMR spectroscopy. *Journal of the American Chemical Society* **2006**, *128* (8), 2571–2576. doi:10.1021/ja055336t.

[33] Akoka, Serge; Barantin, Laurent; Trierweiler, Michel. Concentration measurement by proton NMR using the ERETIC method. *Analytical Chemistry* **1999**, *71* (13), 2554–2557. doi:10.1021/ac981422i.

[34] Barantin, Laurent; Le Pape, Alain; Akoka, Serge. A new method for absolute quantitation of MRS metabolites. *Magnetic Resonance in Medicine* **1997**, *38* (2), 179–182. doi:10.1002/mrm.1910380203.

[35] Burton, Ian W.; Quilliam, Michael A.; Walter, John A. Quantitative ^{1}H NMR with external standards: use in preparation of calibration solutions for algal toxins and other natural products. *Analytical Chemistry* **2005**, *77* (10), 3123–3131. doi:10.1021/ac048385h.

[36] Nishizaki, Yuzo; Lankin, David C.; Chen, Shao-Nong; Pauli, Guido F. Accurate and precise external calibration enhances the versatility of quantitative NMR (qNMR). *Analytical Chemistry* **2021**, *93* (5), 2733–2741. doi:10.1021/acs.analchem.0c02967.

[37] Pagès, Guilhem; Gerdova, Anna; Williamson, David; Gilard, Véronique; Martino, Robert; Malet-Martino, Myriam. Evaluation of a benchtop cryogen-free low-field ^{1}H NMR spectrometer for the analysis of sexual enhancement and weight loss dietary supplements adulterated with pharmaceutical substances. *Analytical Chemistry* **2014**, *86* (23), 11897–11904. doi:10.1021/ac503699u.

[38] Hussain, J. Hena; Gilbert, Nicolas; Costello, Andrew; Schofield, Christopher J.; Kemsley, E. Kate; Sutcliffe, Oliver B.; Mewis, Ryan E. Quantification of MDMA in seized tablets using benchtop ^{1}H NMR spectroscopy in the absence of internal standards. *Forensic Chemistry* **2020**, *20*, 100263. doi:10.1016/j.forc.2020.100263.

[39] Frinculescu, Anca; Maier, Alexander F. G.; Shine, Trevor; Ramsey, John; Araneda, Juan F.; Riegel, Susanne D.; Frascione, Nunzianda; Abbate, Vincenzo. 3,4-Methylenedioxymethamphetamine quantification via benchtop ^{1}H qNMR spectroscopy: method validation and its application to ecstasy tablets collected at music festivals. *Journal of Pharmaceutical and Biomedical Analysis* **2022**, *214*, 114728. doi:10.1016/j.jpba.2022.114728.

[40] Nagana Gowda, G. A.; Hong, Natalie N.; Raftery, Daniel. Evaluation of fumaric acid and maleic acid as internal standards for NMR analysis of protein precipitated plasma, serum, and whole blood. *Analytical Chemistry* **2021**, *93* (6), 3233–3240. doi:10.1021/acs.analchem.0c04766.

[41] Keizers, Peter H. J.; Bakker, Frank; Ferreira, José; Wackers, Paul F. K.; van Kollenburg, Dion; van der Aa, Eva; van Beers, Amy. Benchtop NMR spectroscopy in the analysis of substandard and falsified medicines as well as illegal drugs. *Journal of Pharmaceutical and Biomedical Analysis* **2020**, *178*, 112939. doi:10.1016/j.jpba.2019.112939.

[42] Lynch, Ciarán C.; Khirich, Gennady; Lee, Ryan T. Quantification of biopharmaceutically relevant nonionic surfactant excipients using benchtop qNMR. *Analytical Chemistry* **2024**, *96* (17), 6746–6755. doi:10.1021/acs.analchem.4c00422.

[43] Jakes, William; Gerdova, Anna; Defernez, Marianne; Watson, Andrew D.; McCallum, Catherine; Limer, Eric; Colquhoun, Ian J.; Williamson, David C.; Kemsley, E. Kate. Authentication of beef versus horse meat using 60 MHz ^{1}H NMR spectroscopy. *Food Chemistry* **2015**, *175*, 1–9. doi:10.1016/j.foodchem.2014.11.110.

[44] Defernez, Marianne; Wren, Ellie; Watson, Andrew D.; Gunning, Yvonne; Colquhoun, Ian J.; Le Gall, Gwénaëlle; Williamson, David; Kemsley, E. Kate. Low-field ^{1}H NMR spectroscopy for distinguishing between arabica and robusta ground roast coffees. *Food Chemistry* **2017**, *216*, 106–113. doi:10.1016/j.foodchem.2016.08.028.

[45] Parker, Tom; Limer, Eric; Watson, Andrew D.; Defernez, Marianne; Williamson, David; Kemsley, E. Kate. 60 MHz ^{1}H NMR spectroscopy for the analysis of edible oils. *TrAC Trends in Analytical Chemistry* **2014**, *57*, 147–158. doi:10.1016/j.trac.2014.02.006.

[46] Gouilleux, Boris; Marchand, Jonathan; Charrier, Benoît; Remaud, Gérald S.; Giraudeau, Patrick. High-throughput authentication of edible oils with benchtop ultrafast 2D NMR. *Food Chemistry* **2018**, *244*, 153–158. doi:10.1016/j.foodchem.2017.10.016.

[47] Camacho-Pereira, Juliana; Tarragó, Mariana G.; Chini, Claudia C. S.; Nin, Veronica; Escande, Carlos; Warner, Gina M.; Puranik, Amrutesh S.; Schoon, Renee A.; Reid, Joel M.; Galina, Antonio; Chini, Eduardo N. CD38 dictates age-related NAD decline and mitochondrial dysfunction through an SIRT3-dependent mechanism. *Cell Metabolism* **2016**, *23* (6), 1127–1139. doi:10.1016/j.cmet.2016.05.006.

[48] U.S. Food and Drug Administration. Response Letter to Citizen Petition (Docket No. FDA-2023-P-0872), 29 September 2025. Available at https://www.regulations.gov/docket/FDA-2023-P-0872.

[49] U.S. Food and Drug Administration. Supplemental Response Letter to NDIN 1259 (Inner Mongolia Kingdomway Pharmaceutical Ltd.), 4 November 2022. Document FDA-2022-S-0023-0051.

[50] Turck, Dominique; Castenmiller, Jacqueline; de Henauw, Stefaan; Hirsch-Ernst, Karen-Ildico; Kearney, John; Maciuk, Alexandre; Mangelsdorf, Inge; McArdle, Harry J.; Naska, Androniki; Pelaez, Carmen; Pentieva, Kristina; Siani, Alfonso; Thies, Frank; Tsabouri, Sophia; Vinceti, Marco; Cubadda, Francesco; Engel, Karl-Heinz; Frenzel, Thomas; Heinonen, Marina; Marchelli, Rosangela; Neuhäuser-Berthold, Monika; Poulsen, Morten; Sanz, Yolanda; Schlatter, Josef Rudolf; van Loveren, Henk; Ackerl, Reinhard; Knutsen, Helle Katrine. Safety of nicotinamide riboside chloride as a novel food pursuant to Regulation (EU) 2015/2283 and bioavailability of nicotinamide from this source, in the context of Directive 2002/46/EC. *EFSA Journal* **2019**, *17* (8), e05775. doi:10.2903/j.efsa.2019.5775.

[51] Turck, Dominique; Bohn, Torsten; Castenmiller, Jacqueline; de Henauw, Stefaan; Hirsch-Ernst, Karen-Ildico; Maciuk, Alexandre; Mangelsdorf, Inge; McArdle, Harry J.; Naska, Androniki; Pelaez, Carmen; Pentieva,

Kristina; Siani, Alfonso; Thies, Frank; Tsabouri, Sophia; Vinceti, Marco; Cubadda, Francesco; Frenzel, Thomas; Heinonen, Marina; Marchelli, Rosangela; Neuhäuser-Berthold, Monika; Poulsen, Morten; Maradona, Miguel Prieto; Schlatter, Josef Rudolf; van Loveren, Henk; Ackerl, Reinhard; Knutsen, Helle Katrine. Safety of an extension of use of nicotinamide riboside chloride as a novel food pursuant to Regulation (EU) 2015/2283 and bioavailability of nicotinamide from this source. *EFSA Journal* **2021**, *19* (11), e06843. doi:10.2903/j.efsa.2021.6843.

[52] Trammell, Samuel A. J.; Schmidt, Mark S.; Weidemann, Benjamin J.; Redpath, Philip; Jaksch, Frank; Dellinger, Ryan W.; Li, Zhongling; Abel, E. Dale; Migaud, Marie E.; Brenner, Charles. Nicotinamide riboside is uniquely and orally bioavailable in mice and humans. *Nature Communications* **2016**, *7*, 12948. doi:10.1038/ncomms12948.

[53] Martens, Christopher R.; Denman, Blair A.; Mazzo, Melissa R.; Armstrong, Michael L.; Reisdorph, Nichole; McQueen, Matthew B.; Chonchol, Michel; Seals, Douglas R. Chronic nicotinamide riboside supplementation is well-tolerated and elevates NAD^+ in healthy middle-aged and older adults. *Nature Communications* **2018**, *9* (1), 1286. doi:10.1038/s41467-018-03421-7.

[54] Yoshino, Mihoko; Yoshino, Jun; Kayser, Brandon D.; Patti, Gary J.; Franczyk, Michael P.; Mills, Kathryn F.; Sindelar, Miriam; Pietka, Terri; Patterson, Bruce W.; Imai, Shin-ichiro; Klein, Samuel. Nicotinamide mononucleotide increases muscle insulin sensitivity in prediabetic women. *Science* **2021**, *372* (6547), 1224–1229. doi:10.1126/science.abe9985.

[55] Brenner, Charles. Comment on "Nicotinamide mononucleotide increases muscle insulin sensitivity in prediabetic women." *Science* **2021**, *373* (6554), eabj1696. doi:10.1126/science.abj1696.

[56] Sandalova, Elena; Goh, Jorming; Lim, Zi Xiang; Lim, Zi Min; Barardo, Diogo; Dorajoo, Rajkumar; Kennedy, Brian K.; Maier, Andrea B. Testing the amount of nicotinamide mononucleotide and urolithin A as compared to the label claim. *GeroScience* **2024**, *46* (5), 5075–5083. doi:10.1007/s11357-024-01257-2.

[57] Campbell, Murray T. D.; Jones, David S.; Andrews, Gavin P.; Li, Shu. Understanding the physicochemical properties and degradation kinetics of nicotinamide riboside, a promising vitamin B_3 nutritional supplement. *Food and Nutrition Research* **2019**, *63*, 3419. doi:10.29219/fnr.v63.3419.

[58] Conze, Dietrich; Brenner, Charles; Kruger, Claire L. Safety and metabolism of long-term administration of NIAGEN (nicotinamide riboside chloride) in a randomized, double-blind, placebo-controlled clinical trial of healthy overweight adults. *Scientific Reports* **2019**, *9* (1), 9772. doi:10.1038/s41598-019-46120-z.

[59] Trammell, Samuel A. J.; Brenner, Charles. Targeted, LCMS-based metabolomics for quantitative measurement of NAD^+ metabolites. *Computational and Structural Biotechnology Journal* **2013**, *4*, e201301012. doi:10.5936/csbj.201301012.

[60] Blumenstein, Michael; Raftery, Michael A. Phosphorus-31 and carbon-13 nuclear magnetic resonance studies of nicotinamide-adenine dinucleotide and related compounds. *Biochemistry* **1972**, *11* (9), 1643–1648. doi:10.1021/bi00759a017.

[61] Cohn, Mildred; Hughes, Thomas R., Jr. Phosphorus magnetic resonance spectra of adenosine di- and triphosphate. I. Effect of pH. *Journal of Biological Chemistry* **1960**, *235* (11), 3250–3253. doi:10.1016/S0021-9258(20)81346-5.

[62] Tran-Dinh, Sebastien; Neumann, Jean-Michel. A ^{31}P-NMR study of the interaction of Mg^{2+} ions with nucleoside diphosphates. *Nucleic Acids Research* **1977**, *4* (2), 397–403. doi:10.1093/nar/4.2.397.

[63] Lu, Ming; Zhu, Xiao-Hong; Zhang, Yi; Chen, Wei. Intracellular redox state revealed by in vivo ^{31}P MRS measurement of NAD$^+$ and NADH contents in brains. *Magnetic Resonance in Medicine* **2014**, *71* (6), 1959–1972. doi:10.1002/mrm.24859.

[64] Lu, Ming; Chen, Wei; Zhu, Xiao-Hong. Field dependence study of in vivo brain ^{31}P MRS up to 16.4 T. *NMR in Biomedicine* **2014**, *27* (9), 1135–1141. doi:10.1002/nbm.3167.

[65] Zhu, Xiao-Hong; Lu, Ming; Lee, Byeong-Yeul; Uğurbil, Kâmil; Chen, Wei. In vivo NAD assay reveals the intracellular NAD contents and redox state in healthy human brain and their age dependences. *Proceedings of the National Academy of Sciences USA* **2015**, *112* (9), 2876–2881. doi:10.1073/pnas.1417921112.

[66] Lu, Ming; Zhu, Xiao-Hong; Chen, Wei. In vivo ^{31}P MRS assessment of intracellular NAD metabolites and NAD$^+$/NADH redox state in human brain at 4 T. *NMR in Biomedicine* **2016**, *29* (7), 1010–1017. doi:10.1002/nbm.3559.

[67] Guo, Rong; Yang, Shuyu; Wiesner, Heidi M.; Li, Yifan; Zhao, Yibo; Liang, Zhi-Pei; Chen, Wei; Zhu, Xiao-Hong. Mapping intracellular NAD content in entire human brain using phosphorus-31 MR spectroscopic imaging at 7 Tesla. *Frontiers in Neuroscience* **2024**, *18*, 1389111. doi:10.3389/fnins.2024.1389111.

[68] Bagga, Puneet; Hariharan, Hari; Wilson, Neil E.; Beer, Joanne C.; Shinohara, Russell T.; Elliott, Mark A.; Baur, Joseph A.; Marincola, Francesco M.; Witschey, Walter R.; Haris, Mohammad; Detre, John A.; Reddy, Ravinder. Single-voxel ^{1}H MR spectroscopy of cerebral nicotinamide adenine dinucleotide (NAD$^+$) in humans at 7 T using a 32-channel volume coil. *Magnetic Resonance in Medicine* **2020**, *83* (3), 806–814. doi:10.1002/mrm.27971.

[69] Sedivy, Petr; Dusilova, Tereza; Hajek, Milan; Burian, Martin; Krššák, Martin; Dezortova, Monika. In vitro ^{31}P MR chemical shifts of in vivo-detectable metabolites at 3 T as a basis set for a pilot evaluation of skeletal muscle and liver ^{31}P spectra with LCModel software. *Molecules* **2021**, *26* (24), 7571. doi:10.3390/molecules26247571.

[70] Nanga, Ravi Prakash Reddy; Wiers, Corinde E.; Elliott, Mark A.; Wilson, Neil E.; Swago, Sophia; Sundaresan, Indrani; Witschey, Walter R.; Bagga, Puneet; Detre, John A.; Reddy, Ravinder. Acute nicotinamide riboside supplementation increases human cerebral NAD$^+$ levels in vivo. *Magnetic Resonance in Medicine* **2024**, *92* (6), 2284–2293. doi:10.1002/mrm.30227.

[71] Yoshino, Jun; Mills, Kathryn F.; Yoon, Myeong Jin; Imai, Shin-ichiro. Nicotinamide mononucleotide, a key NAD$^+$ intermediate, treats the pathophysiology of diet- and age-induced diabetes in mice. *Cell Metabolism* **2011**, *14* (4), 528–536. doi:10.1016/j.cmet.2011.08.014.

[72] Mills, Kathryn F.; Yoshida, Shohei; Stein, Liana R.; Grozio, Alessia; Kubota, Shunsuke; Sasaki, Yo; Redpath, Philip; Migaud, Marie E.; Apte, Rajendra S.; Uchida, Koji; Yoshino, Jun; Imai, Shin-ichiro. Long-term administration of nicotinamide mononucleotide mitigates age-associated physiological decline in mice. *Cell Metabolism* **2016**, *24* (6), 795–806. doi:10.1016/j.cmet.2016.09.013.

[73] Rundlöf, Torgny; Mathiasson, Mårten; Bekiroglu, Somer; Hakkarainen, Birgit; Bowden, Torbjörn; Arvidsson, Torbjörn. Survey and qualification of internal standards for quantification by ^{1}H NMR spectroscopy. *Journal of Pharmaceutical and Biomedical Analysis* **2010**, *52* (5), 645–651. doi:10.1016/j.jpba.2010.02.007.

[74] Castaing-Cordier, Thomas; Bouillaud, Dylan; Farjon, Jonathan; Giraudeau, Patrick. Recent advances in benchtop NMR spectroscopy and its applications. *Annual Reports on NMR Spectroscopy* **2021**, *103*, 191–258. doi:10.1016/bs.arnmr.2021.02.003.

[75] Blümich, Bernhard. Low-field and benchtop NMR. *Journal of Magnetic Resonance* **2019**, *306*, 27–35. doi:10.1016/j.jmr.2019.07.030.

[76] Zalesskiy, Sergey S.; Danieli, Ernesto; Blümich, Bernhard; Ananikov, Valentine P. Miniaturization of NMR systems: desktop spectrometers, microcoil spectroscopy, and "NMR on a chip" for chemistry, biochemistry, and industry. *Chemical Reviews* **2014**, *114* (11), 5641–5694. doi:10.1021/cr400063g.

[77] van Beek, Teris A. Low-field benchtop NMR spectroscopy: status and prospects in natural product analysis. *Phytochemical Analysis* **2021**, *32* (1), 24–37. doi:10.1002/pca.2921.

[78] Grootveld, Martin; Percival, Benita; Gibson, Miles; Osman, Yasan; Edgar, Mark; Molinari, Marco; Mather, Melissa L.; Casanova, Federico; Wilson, Philippe B. Progress in low-field benchtop NMR spectroscopy in chemical and biochemical analysis. *Analytica Chimica Acta* **2019**, *1067*, 11–30. doi:10.1016/j.aca.2019.02.026.

[79] Riegel, Susanne D.; Leskowitz, Garett M. Benchtop NMR spectrometers in academic teaching. *TrAC Trends in Analytical Chemistry* **2016**, *83* (Part A), 27–38. doi:10.1016/j.trac.2016.01.001.

[80] Bharti, Santosh Kumar; Roy, Raja. Quantitative ^{1}H NMR spectroscopy. *TrAC Trends in Analytical Chemistry* **2012**, *35*, 5–26. doi:10.1016/j.trac.2012.02.007.

[81] Airhart, Sophia E.; Shireman, Laura M.; Risler, Linda J.; Anderson, Gail D.; Nagana Gowda, G. A.; Raftery, Daniel; Tian, Rong; Shen, Danny D.; O'Brien, Kevin D. An open-label, non-randomized study of the pharmacokinetics of the nutritional supplement nicotinamide riboside (NR) and its effects on blood NAD^+ levels in healthy volunteers. *PLOS ONE* **2017**, *12* (12), e0186459. doi:10.1371/journal.pone.0186459.

[82] Zarei, Amin; Khazdooz, Leila; Madarshahian, Sara; Enayati, Mojtaba; Mosleh, Iman; Lin, Tiantian; Yan, Bing; Ufheil, Gerhard; Wooster, Tim J.; Abbaspourrad, Alireza. Synthesis, stability, and bioavailability of nicotinamide riboside trioleate chloride. *Nutrients* **2022**, *14* (1), 113. doi:10.3390/nu14010113.

[83] Lee, Yejin; Matviychuk, Yevgen; Holland, Daniel J. Quantitative analysis using external standards with a benchtop NMR spectrometer. *Journal of Magnetic Resonance* **2020**, *320*, 106826. doi:10.1016/j.jmr.2020.106826.

[84] Xiang, Dehong; Feng, Wuhua; Yi, Hong; Li, Cheng; Cui, Qianping; Liu, Xiuqing; Wang, Zhimin; Xiao, Peigen. Degradation kinetics of β-nicotinamide mononucleotide based on reliable HPLC quantitative method. *Zhongguo Zhong Yao Za Zhi (China Journal of Chinese Materia Medica)* **2023**, *48* (24), 6635–6644. doi:10.19540/j.cnki.cjcmm.20230905.301.

[85] Giancaspro, Gabriel; Adams, Kristie M.; Bhavaraju, Sitaram; Diehl, Bernd; Krishnamurthy, Krish; Martos, Gustavo; Niemitz, Matthias; Nishizaki, Yuzo; Sugimoto, Naoki; Pauli, Guido F. Proceedings and status of qNMR technology. *Analytical Chemistry* **2021**, *93* (36), 12162–12169. doi:10.1021/acs.analchem.1c02056.

12. Summary

This white paper has surveyed the application of multinuclear NMR spectroscopy to the analysis of NAD^+ precursor longevity supplements. The diagnostic ^1H signatures of NMN, NR, NAD^+, NADH, $NADP^+$/NADPH, the reduced precursors NMNH and NRH, nicotinamide, and nicotinic acid have been tabulated against the primary literature, with chemical shifts and coupling-constant data drawn from foundational studies of the 1970s and from modern high-field characterization papers. ^{31}P NMR has been identified as a uniquely powerful discriminator within this family, separating the monophosphate (NMN/NMNH), pyrophosphate (NAD^+/NADH), and 2′-phosphate-bearing ($NADP^+$/NADPH) species through a small number of well-resolved resonances.

The pH-dependence of pyridinium and phosphate chemical shifts, the hydrolytic instability of the N-glycosidic bond at elevated pH, and the choice of internal versus external referencing standards have been examined in the context of practical qNMR deployment. Authentication scenarios encountered in commercial product quality control — nicotinamide substitution for NMN, under-dosing, α-anomer contamination, salt-form misidentification, and on-shelf degradation — have all been shown to be amenable to one-dimensional ^1H NMR measurement. The high-field-informed, low-field-deployed paradigm, in which model development on a 300–500 MHz reference spectrometer is followed by transfer to a 60 MHz benchtop instrument, has been argued to be the optimal deployment strategy for routine contract-laboratory and manufacturer release testing of this class of supplements.

The regulatory backdrop — the September 2025 reversal of the FDA position on NMN as a New Dietary Ingredient, the EFSA authorization of nicotinamide riboside chloride, and the publication in 2026 of the first USP monograph for the NAD^+ precursor class — has been outlined to frame the analytical demand. The conclusion drawn is that NMR spectroscopy is unusually well matched to this analytical challenge and that benchtop instrumentation is fully capable of meeting it at commercially viable cost and throughput.

— End of White Paper —

Prepared by John C. Edwards, Ph.D.

Process NMR Associates, LLC

84 Patrick Lane, Suite 115, Poughkeepsie, NY 12603

ORCID: 0000-0001-8247-0708 | www.process-nmr.com

May 2026